



**SUSTAINABILITY**

# Chemistry-enabled sustainable composites

A joint technical report by the Royal Society of Chemistry and Sustainable Composites, a partnership between the National Composites Centre and CPI



# Introducing our perspectives series

In a world where global challenges and advances in technology bring both uncertainty and new possibilities, the chemical sciences have a critical role to play. But what will that role be? How can we maximise the impact we make across academia, industry, government and education? And what actions should we take to create a stronger, more vibrant culture for research that helps enable new discoveries?

Our perspectives series addresses these questions through four lenses: talent, discovery, sustainability and research culture. Drawing together insights and sharp opinion, our goal is to increase understanding and inform debate – putting the chemical sciences at the heart of the big issues the world is facing.

## Sustainability

Our planet faces critical challenges – from plastics polluting the oceans, to the urgent need to find more sustainable resources. But where will new solutions come from? How can we achieve global collaboration to address the big issues? And where can the chemical sciences deliver the biggest impacts?



## Talent

Talent is the lifeblood of the chemical sciences. But how do we inspire, nurture, promote and protect it? Where will we find the chemical scientists of the future? And what action is required to ensure we give everyone the greatest opportunity to make a positive difference?



## Discovery

Chemistry is core to advances across every facet of human life. But where do the greatest opportunities lie? How will technology and the digital era shape the science we create? And what steps should we take to ensure that curiosity-driven research continues to unlock new opportunities in unexpected ways?



## Research Culture

Globally, scientific research in academia and industry fuels both progress and innovation. But how do we create more inclusive, diverse and vibrant environments for research, that lead to better, more open science? And how should we recognise the breadth and diversity of the people, contributions and achievements that enable new discoveries?



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# 1 About this report

**This report explores the role of chemistry in sustainable composites. It captures the findings from an investigation conducted by the Royal Society of Chemistry and Sustainable Composites, a partnership between the National Composites Centre (NCC) and CPI. In consultation with academia and industry, the investigation provides an overview of the opportunities to bring chemistry-based solutions into the UK composites supply chain for the purposes of delivering sustainability within the sector.**



## **About the Royal Society of Chemistry**

The Royal Society of Chemistry is an international organisation connecting chemical scientists with each other, with

other scientists, and with society as a whole. Founded in 1841 and based in London, UK, we have an international membership of over 50,000.

We use the surplus from our global publishing and knowledge business to give thousands of chemical scientists the support and resources required to make vital advances in chemical knowledge.

We develop, recognise and celebrate professional capabilities, and we bring people together to spark new ideas and new partnerships.

We support teachers to inspire future generations of scientists, and we speak up to influence the people making decisions that affect us all. We are a catalyst for the chemistry that enriches our world.



## **About the Sustainable Composites partnership**

### **About Sustainable Composites**

Sustainable Composites is the national hub promoting and delivering the sustainable use of composite materials.

Our aim is to accelerate the development of net zero impact composites, processes and technologies, bringing together the UK's composites expertise to quickly turn research breakthroughs into industrial applications.

Led by the National Composites Centre (NCC) and CPI – two of the seven High Value Manufacturing Catapult centres – Sustainable Composites brings together unique expertise: from formulation, development and scaling up of the materials manufacturing processes (CPI) to knowing how to design with these materials, how they must perform in use, and understanding the challenges associated with end of life (NCC).



### About the National Composites Centre (NCC)

The NCC is the UK's world-leading composite research and development facility: where innovators come when they need to make things lighter, stronger, smarter and more sustainable. Its key focus areas are composites, digital engineering, hydrogen and sustainability. With access to 'beyond' state-of-the-art technology and the best composites engineering capabilities in the world, the NCC collaborates with customers to solve the most complex engineering challenges of our time.

Part of the High Value Manufacturing Catapult, the NCC works across all manufacturing sectors and has forged strong links with aerospace, energy, defence, space, construction, infrastructure, auto, rail, marine and biomedical. It works with organisations across the board from micro enterprises and SMEs to disrupters, the supply chain and OEMs, providing businesses with a de-risked environment to design, develop, test and scale their ideas and get them to market fast.



### About CPI

CPI connects the dots within the innovation ecosystem to make great ideas and inventions a reality to benefit people, places and our planet. We're a pioneering social enterprise that accelerates the development, scale up and commercialisation of deep tech and sustainable manufacturing solutions. Through our incredible innovation experts and infrastructure, we look beyond the obvious to transform healthcare and drive towards a sustainable future.

As a trusted partner of industry, academia, government, and the investment community, we're the catalyst for delivering smart AgriFoodTech, energy storage, HealthTech, materials, and pharma innovations. We believe by working together we can build a better collective future and, as part of the High Value Manufacturing Catapult, we facilitate access to world-class organisations to deliver transformation across industries.

Creating lasting global impact from the North of England and Scotland, we invest in people and disruptive technologies to invigorate economies, create circular supply chains and make our world a better place.

### Acknowledgements

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## 2 Foreword



**Composites already play an important role in driving decarbonisation due to being lightweight, strong and durable. Their unique properties make them a critical enabler in delivering a secure and sustainable future. Without them we will not be able to reimagine products to reach zero emission transport, secure low-cost green energy or achieve the government’s legal commitment to achieve net zero emissions by 2050. Composites are also acknowledged as an important driver of economic growth in the UK. However, there is more that we need to do.**

While composites enable net zero products and technologies, a significant transition is needed across the materials supply chain to maximise the opportunity for the UK. Currently there are limited options for recycling, with processes that often degrade the performance of materials. We need to invest in new ways to reduce and remove carbon emissions from what we produce and how we consume it: from concept, design, and manufacture to end-of-life recycling and disposal.

This presents us with the opportunity to explore the role of chemistry as both a barrier and an aid in overcoming challenges in developing sustainable composites. It will determine where the development of new chemical solutions can help to transform the composites industry.

Composites have made a critical contribution when it comes to meeting net zero ambitions, from renewable energy to sustainable transportation. However, products have been designed for maximum performance with little consideration of the impact of production or waste. It is the pioneering development of the chemistry of composite constituent parts that has enabled the UK to become a global leader in the advanced composite materials marketplace. The same chemistry that leads to the challenge of recycling materials at end-of-life is a game changer when it comes to capitalising on opportunities for the future, and reducing environmental impact.

The National Composites Centre is leading the way to tackle these challenges in collaboration and partnership with academia and industry. One initiative, the Sustainable Composites partnership, was set up in 2020 by the NCC and CPI to ensure that the UK is leading the way in tackling these challenges. Our strategic programme with the Royal Society of Chemistry is playing an important part towards our aim to accelerate the development of net zero impact composites, processes and technologies. It is supporting efforts to build materials chemistry capabilities and catalyse multidisciplinary collaborations, leading to investment and funding opportunities that will benefit both the chemical science community and composites industry. The UK has the opportunity to take the lead in the development of sustainable composites, but we need to act now, together. This report highlights the important steps that we can take to redefine a new generation of products that will create a greener, cleaner future for all.

### **Richard Oldfield**

Chief Executive Officer, National Composites Centre





**Composites can make a considerable difference to our collective effort to build a more sustainable world. Everything from major public infrastructure and transportation down to many items around the home rely on these versatile materials. Electric cars, wind turbine blades, and hydrogen fuel tanks are all produced using fibre-reinforced composites, as are the likes of doors, chairs and window frames.**

Thanks to the strong, lightweight, and durable nature of these materials, demand for them is increasing. Composites also have the potential to reduce humanity's impact on the environment thanks to their usage in the wind and hydrogen energy sectors and the growing electric vehicle market. However, they are often challenging to recycle or have opportunities to be manufactured more sustainably.

Chemistry plays an important role in creating composites and the properties that make these materials so valuable. The composites industry is making advancements in creating more environmentally friendly products, but to make composites more sustainable, chemists must be at the heart of the process. From design to manufacture, application and end-of-life – chemistry can contribute throughout the entire lifecycle of a composite.

We could make significant long-term progress by furthering research and skills development, and by working with partners in industry. The Royal Society of Chemistry has made sustainability a core organisational commitment – and we want to support and encourage our community to join in and tackle this global challenge. Our collaboration with the National Composites Centre and CPI is based on exploring new opportunities with shared ideals in mind, so we would encourage our communities to work with these partners for a more prosperous future.

There are challenges when striking a balance between practical matters, such as cost and effectiveness, and sustainability goals. This report highlights these issues but also showcases some of the efforts already being made by several companies to tackle them directly. We want this report to serve as a catalyst, inspiring others to step forward and use science to create better composites, capable of building a more sustainable future.

**Jo Reynolds**

Director of Science and Communities

# 3 Executive summary

**Composite materials play a vital role in delivering key technologies for renewable energy, lightweighting transport to reduce carbon dioxide (CO<sub>2</sub>) emissions, and extending the lifetime of infrastructure. As such, they are critical to the UK's delivery of net zero emissions by 2050 and their use is predicted to grow considerably.**

To fully contribute to net zero, the composite sector must address sustainability issues in the supply chain. So far, little focus has been on the role of chemistry in improving composite sustainability. This report is an important step towards enabling this.

## **The UK market is expected to grow**

The UK composite market is valued at £4 billion and they are used in a wide range of sectors due to their light weight, strength and durability. Their continued use and growth into new markets is important to the UK economy and the UK's legal commitment to achieving net zero emissions by 2050. Fibre-reinforced composites (FRPs), the focus of this report, are helping to drive the move to a carbon-neutral world through the production of high-strength structures. FRPs are used in the production of wind turbine blades, and to lightweight parts produced for the automotive, aerospace and defence sectors, among others. This decreases emissions, and enhances durability, increasing product lifetime.

## **The supply chain faces sustainability challenges**

More than 95% of FRPs are made from virgin materials derived from fossil fuels. This problem is compounded by the fact only 15% of waste is sent for recycling at the end of life and just 6% of composite materials are reused. These factors contribute to an industry that is linear in nature with significant volumes of high-value materials being lost from the supply chain each year. While this is a problem recognised by the industry and work is ongoing to solve these issues, there is much to be done.

Fundamentally, the behaviour of all FRPs is driven by the chemistry of their constituent parts. The strong chemical bonds within a resin are what gives them durability and the interaction between the fibre and the polymer resin is what allows for such high strength. This same chemistry leads to the challenge of recycling at end of life.

Until now, FRPs have been designed for maximum performance with little consideration of the impact of production or waste. Through further development of the chemistry that dictates their behaviour a more sustainable industry can be achieved: FRPs produced with a lower environmental impact, with increased durability and a clear end-of-life pathway.

## **Chemistry's role in enabling sustainability**

This report aims to explore the role of chemistry as both a barrier and an aid in overcoming sustainability challenges. It will determine where the development of new chemical solutions can help to transform the FRP industry. These opportunities could come in the form of increased cooperation with other industries, collaboration between industry and academia or existing solutions which could be more widely adopted.

It is recognised that the challenges facing the FRP industry are wide-ranging and complex and will be solved by many different approaches, not just solutions through chemistry or chemical processing.

### Scope and methodology

This report focuses on the sustainability challenges and opportunities surrounding the composite materials sector. It focuses on polymer matrix composites (PMCs), which are referred to by the broader composites term throughout this report. Many of the sustainability challenges exhibited by PMCs may also be relevant to metal matrix composites (MMCs), ceramic matrix composites (CMCs) and other filled polymers.

In the context of this report, and the industries surveyed, the composites considered include particle, flake and continuous and discontinuous fibre-reinforced polymer (FRP) systems. They are typically used across structural and semi-structural applications for their specific properties.

The composites supply chain has been explored to provide a comprehensive assessment of sustainability-focused challenges and where chemistry may provide a solution. There are four categories that composite companies fall into:

- feedstocks used to produce the materials used in composites
- the manufacturing of composites
- the use phase of composites and their durability
- the end-of-life recycling approaches for composites.

The report focuses on the UK market and, therefore, the engagement carried out was largely with UK academic and industrial stakeholders through two online workshops. It is acknowledged that the composite supply chain is a global one and relies on many stakeholders outside the UK. For example, the UK imports many of the raw materials used in the composite industry. Included in this report are opportunities that would positively impact the UK composite market but would largely need to be actioned elsewhere.

The workshop outputs were used to guide the topics explored. The data in this report is largely from peer-reviewed journals and industrial papers, as well as insight from the workshops and subsequent discussions. The opportunities identified are summarised in **Section 8**.

## 4 Glossary

Term	Definition
<b>Additives</b>	Essential formulation components used in composite manufacture to aid processability and manufacture, as well as optimise the resin/matrix properties and adapt the reinforcements for applications
<b>Adhesive</b>	A binding substance used to join two surfaces together. It is typically used to construct assemblies by joining thermosetting composite parts, components, fixtures and fittings and whole structures
<b>Automated fibre placement</b>	The classification of manufacturing processes whereby continuous fibre tape is rolled onto the surface, typically by an automated robot or gantry system, to build up a layered composite form with high levels of precision and repeatability
<b>Bio-derived feedstocks</b>	Materials wholly or partly derived from biomass, e.g. corn, sugarcane wastes and waste wood chip
<b>Braiding</b>	The manufacturing process of continuous, mechanically interlocked fibres into rope, fabrics and typically tube-like structures
<b>Carbon capture and storage</b>	A way of reducing carbon emissions by capturing CO <sub>2</sub> produced by power generation or industrial activity, transporting it and storing it in a long-term storage facility
<b>Composite</b>	A material composed of at least two materials that combine to give properties superior to those of the individual constituents. These can be classified according to their matrix: metal, ceramic, and polymer composites
<b>Compression moulding</b>	The manufacturing process of a part that has been pressed or formed into a heated cavity that subsequently provides its shape
<b>Consumables</b>	Materials consumed during manufacturing, for example, mould release reagents, vacuum bagging, breather fabrics
<b>Cores</b>	Cellular materials commonly sandwiched between layers of composite material. Cores add stiffness to composite panels while minimising weight
<b>Creep resistance</b>	Resistance to deformation that tends to occur slowly over long-term exposure to a level of stress and under environmental conditions (typically elevated temperature)
<b>Dry fabrics/formats</b>	Woven, non-woven and unidirectional fabrics that have no resin content
<b>Fibre</b>	Natural (derived from plants including wood, hemp and bamboo fibres) or synthetic fibres (including carbon fibre and glass fibres) which are embedded in a polymer matrix to make a composite
<b>Fibre-matrix interface</b>	The connection between fibre and matrix where load is transferred. The interface dictates the mechanical behaviour and lifetime of the composite. A weak interface typically increases fracture toughness but reduces overall strength
<b>Fibre-reinforced polymer</b>	A subset of polymer matrix composites (PMCs) consisting of reinforcing fibre (e.g. glass or carbon) impregnated with a polymer matrix

Table 1: List of definitions

Table 1: List of definitions (continued)

Term	Definition
<b>Filament winding</b>	The manufacturing process whereby fibres are wound under tension around a form (mandrel) to produce open (e.g. cylinders) or closed end structures (e.g. pressure vessels, tanks)
<b>Formulation</b>	The process of combining components (monomers, additives) to create, in the context of this report, a polymer
<b>Hand lay-up</b>	A moulding method for fabricating composites through stacking layers of fibre (e.g. woven, pre-impregnated, banded) into defined orientations by hand in or onto a form
<b>Infusion</b>	The drawing of liquid resin through a stack of dry fabric, typically by vacuum, to create an impregnated laminate
<b>Load</b>	Applied force on an object
<b>Moulding</b>	The shaping of the preform into a tool (interchangeably referred to as a mould)
<b>Non-renewable feedstocks</b>	Any feedstock derived from oil, natural gas, coal and nuclear energy
<b>Out-life</b>	The time remaining for a reactive curing polymer system when at room temperature prior to gelation or a change in. "Out" referring to when "out" of the freezer
<b>Polymer</b>	A large (macro) molecule comprised of multiple repeating subunits (monomer) chemically linked in a molecular chain format
<b>Polymer matrix composite</b>	A polymeric based system containing solids such as inorganic particles or fibres to impart, for example, mechanical or physical properties
<b>Preform</b>	Partially formed or arranged fabric architecture ready for final processing. Examples are a braided sock or dry fabric prior to liquid moulding, a stack of reinforced thermoplastic plies prior to consolidation, or a pre-impregnated form shaped with a tool prior to cure
<b>Prepregs</b>	Fabric that has been either pre-impregnated with a reactive (thermoset) matrix or fully consolidated with a thermoplastic matrix. Thermoset matrices are most often refrigerated or frozen prior to processing to maintain/prevent gelation and cure of reactive chemistry
<b>Pultrusion</b>	A continuous manufacturing process where reinforcing fibre is pulled through a tool or die and combined with a polymer to create a continuous, typically constant cross-section, composite
<b>Resin transfer moulding</b>	The drawing of liquid resin through a stack of dry fabric, typically by vacuum, to create an impregnated laminate that is shaped or moulded within a closed tool with a fixed cavity
<b>Resin</b>	A formulated mixture primarily comprising organic polymer(s), monomers and other additives. Its role in composites is encapsulation of the fibre, transferring load between the fibres, holding fibres in place and providing protection from damage/degradation
<b>Sizing (fibres)</b>	Commonly used to protect fibres during processing (e.g. weaving) and to improve the fibre bonding to resin (fibre-matrix interface)

Table 1: List of definitions (continued)

Term	Definition
Spray lay-up	A method of applying resin and reinforcement to an open mould through the use of a pressurised spray
Thermoforming	A method of moulding and consolidating thermoplastic and reinforcement at elevated temperature into a shaped surface (i.e. the tool)
Thermoplastic resin	A resin type used in FRP that does not have covalent (strong) chemical bonds between polymer chains, meaning that these resins can be reformed i.e. become plastic on heating. Common examples include polypropylene and polyamide
Thermoset resin	Resin used in FRP that has strong chemical cross-linking between polymer chains to form a very stable (non-reformable) matrix. Common examples include epoxy and unsaturated polyester
Tooling	Gives composite parts their surface geometry. Aids their moulding to desired shapes

Abbreviation	Term
ABS	Acrylonitrile-butadiene-styrene
AFP	Automated fibre placement
ASA	Acrylonitrile styrene acrylate
ATL	Automated tape laying
BisA	Bisphenol A
BMC	Bulk moulding compound
CCS	Carbon capture and storage
FRP	Fibre-reinforced polymer
GHG	Greenhouse gas
PA6	Polyamide produced from caprolactam (with six carbon atoms)
PA66	Polyamide produced from hexamethylenediamine / adipic acid (both with six carbon atoms)
PBT	Polybutylene terephthalate
PC	Polycarbonate
PE	Polyethylene
PP	Polypropylene
PVC	Polyvinyl chloride
RTM	Resin transfer moulding
SMC	Sheet moulding compound
UPR	Unsaturated polyester resin
VARTM	Vacuum assisted resin transfer moulding
WPCs	Wood plastic composite

Table 2: List of abbreviations

# 5 The UK composites sector

**This section outlines the UK's fibre-reinforced polymer (FRP) sector. It highlights the key markets, supply chain and future trends which are key to ensuring intervention from the chemistry community has the potential for delivering the highest impact to a future sustainable composites industry.**

## 5.1 Overview

The UK composites market is valued at £4 billion and is expected to grow at a compound annual growth rate (CAGR) of 6 to 9% from 2019 to 2035. The key markets that use composites are aerospace, automotive, construction and infrastructure, defence, marine, oil and gas, rail, and wind.

In addition to these well-established sectors, there is a growing opportunity for composites in the emerging hydrogen market. While its size has not been quantified, it is expected to place considerable demand on carbon fibre supplies in the coming years.

**Table 3** outlines the market size of these sectors and the materials commonly used in them.

- 1 Lightweighting (fuel efficiency/speed)
- 2 Lightweighting (ease of installation)
- 3 Impact toughness/resistance
- 4 Low temperature performance
- 5 Environmental resistance (UV, biological)
- 6 Environmental resistance (low moisture)
- 7 High temperature resistance
- 8 Fire resistance/retardancy
- 9 Specific performance (stated)
- 10 Low cost
- 11 High strength/stiffness
- 12 High strength/stiffness (structural components only)
- 13 Excellent durability
- 14 Gaseous barrier

Sectors and requirements	Market size (£), 2019	Common fibres	Common resins	Additional critical materials	Typical manufacturing	Common composite parts
<ul style="list-style-type: none"> <li>1</li> <li>11</li> <li>2</li> <li>4</li> <li>8</li> <li>5</li> </ul> <b>Aerospace</b>	£889m	<ul style="list-style-type: none"> <li>Carbon (structural)</li> <li>Glass (interiors/panelling)</li> </ul>	<ul style="list-style-type: none"> <li>Epoxy prepreg and resin</li> </ul>	<ul style="list-style-type: none"> <li>Copper anti-lighting strike within composite structure</li> </ul>	<ul style="list-style-type: none"> <li>Autoclave</li> <li>AFP/ATL</li> <li>Liquid moulding techniques (e.g. RI, RTM)</li> </ul>	<ul style="list-style-type: none"> <li>Wing structures</li> <li>Trailing edge wind spar</li> <li>Seatbacks and components</li> <li>Radomes</li> <li>Cockpit floor panels</li> <li>Ailerons, elevators and spoilers</li> </ul>
<ul style="list-style-type: none"> <li>1</li> <li>2</li> <li>3</li> <li>11</li> <li>5</li> <li>9</li> </ul> <b>Wind</b>	£242m	<ul style="list-style-type: none"> <li>Glass</li> <li>Carbon (spar caps)</li> </ul>	<ul style="list-style-type: none"> <li>Epoxy, PVC, PE, VE</li> <li>SMC and BMC</li> </ul>	<ul style="list-style-type: none"> <li>Cores (balsa/PET foam)</li> <li>PU coatings/adhesives/sealants</li> </ul>	<ul style="list-style-type: none"> <li>Resin infusion (some VARTM and prepreg lay-up)</li> <li>Pultrusion (spar caps)</li> </ul>	<ul style="list-style-type: none"> <li>Wind blades</li> <li>Spar caps</li> </ul>
<ul style="list-style-type: none"> <li>1</li> <li>2</li> <li>10</li> <li>12</li> <li>8</li> <li>9</li> </ul> <b>Automotive</b> <ul style="list-style-type: none"> <li>Various chemical resistance</li> <li>Dampening properties (interiors)</li> </ul>	£505m	<ul style="list-style-type: none"> <li>Long, short and powdered glass (non-structural interior and trims)</li> <li>Carbon (structural chassis, roof, body panels etc.)</li> </ul>	<ul style="list-style-type: none"> <li>Thermoplastics, commonly PP, PA6, ABS, ASA, PBT, PA66, PC etc.</li> <li>Epoxy</li> <li>UPR</li> </ul>	<ul style="list-style-type: none"> <li>ESD additives</li> <li>Fire retardant core</li> </ul>	<ul style="list-style-type: none"> <li>Compression moulding</li> <li>Injection moulding</li> </ul>	<ul style="list-style-type: none"> <li>Bumpers/bonnets</li> <li>Some body panels</li> <li>Interior trim</li> <li>Headliners</li> <li>Chassis</li> </ul>
<ul style="list-style-type: none"> <li>1</li> <li>2</li> <li>3</li> <li>11</li> <li>5</li> <li>7</li> </ul> <b>Hydrogen</b> <ul style="list-style-type: none"> <li>High pressure resistance (Type IV tanks)</li> </ul>	-	<ul style="list-style-type: none"> <li>Carbon (SM and IM)</li> </ul>	<ul style="list-style-type: none"> <li>Toughened epoxy</li> </ul>	<ul style="list-style-type: none"> <li>Thermoplastic liners (PA-6)</li> <li>Insulation materials</li> </ul>	<ul style="list-style-type: none"> <li>Filament Winding</li> </ul>	<ul style="list-style-type: none"> <li>Tanks and pipes</li> </ul>
<ul style="list-style-type: none"> <li>1</li> <li>13</li> <li>5</li> <li>7</li> <li>12</li> <li>9</li> </ul> <b>Defence</b> <ul style="list-style-type: none"> <li>EM shielding</li> <li>Embedded functionality (e.g. sensors)</li> </ul>	£579m	<ul style="list-style-type: none"> <li>Carbon</li> <li>Kevlar</li> </ul>	<ul style="list-style-type: none"> <li>Prepreg</li> <li>Epoxy, BMI and other high temperature/performance systems</li> </ul>	<ul style="list-style-type: none"> <li>Protective layers e.g. metal sheeting</li> </ul>	<ul style="list-style-type: none"> <li>Prepreg processes</li> <li>AFP/ATL</li> <li>Autoclave</li> </ul>	<ul style="list-style-type: none"> <li>Land systems</li> <li>Military aircraft</li> <li>UAVs</li> <li>Naval vessels</li> <li>Weapons</li> <li>Protective equipment</li> </ul>
<ul style="list-style-type: none"> <li>1</li> <li>13</li> <li>5</li> <li>7</li> <li>12</li> <li>8</li> <li>9</li> </ul> <b>Marine</b> <ul style="list-style-type: none"> <li>Salinity resistance</li> </ul>	£194m	<ul style="list-style-type: none"> <li>Glass</li> <li>Some carbon</li> <li>Some aramid</li> </ul>	<ul style="list-style-type: none"> <li>UPR and epoxy</li> </ul>	<ul style="list-style-type: none"> <li>Cores</li> </ul>	<ul style="list-style-type: none"> <li>Hand lay-up</li> <li>VARTM</li> <li>Autoclave</li> </ul>	<ul style="list-style-type: none"> <li>Hull</li> <li>Deck</li> <li>Masts</li> <li>Keel and bow sections (Kevlar)</li> </ul>
<ul style="list-style-type: none"> <li>1</li> <li>2</li> <li>3</li> <li>12</li> <li>8</li> <li>9</li> </ul> <b>Construction and infrastructure</b> <ul style="list-style-type: none"> <li>Radio transparency</li> <li>Low thermal/electrical conductivity</li> <li>Blast resistance/sound insulation</li> </ul>	£139m	<ul style="list-style-type: none"> <li>Glass</li> <li>Carbon</li> <li>Wood fibres (WPCs)</li> </ul>	<ul style="list-style-type: none"> <li>UPR and vinyl ester</li> <li>PP, PE, PVC (WPCs)</li> </ul>	<ul style="list-style-type: none"> <li>Insulation and core materials</li> </ul>	<ul style="list-style-type: none"> <li>Pultrusion</li> <li>Compression moulding</li> <li>Injection moulding</li> </ul>	<ul style="list-style-type: none"> <li>Load bearing and infill panels</li> <li>Pressure pipes</li> <li>Tank liners</li> <li>Roofs</li> <li>Foot, road and rail bridge</li> <li>Aesthetic linings, cladding, decking (WPCs)</li> <li>Window frames (WPCs)</li> </ul>
<ul style="list-style-type: none"> <li>2</li> <li>7</li> <li>5</li> <li>4</li> <li>14</li> <li>9</li> </ul> <b>Rail</b> <ul style="list-style-type: none"> <li>Various chemical resistance</li> <li>Dampening properties (interiors)</li> </ul>	£60m	<ul style="list-style-type: none"> <li>Glass</li> <li>Carbon</li> </ul>	<ul style="list-style-type: none"> <li>UPR, phenolic, modified epoxy (fire resistant) prepreps and SMCs</li> </ul>	<ul style="list-style-type: none"> <li>Fire retardant foam cores</li> </ul>	<ul style="list-style-type: none"> <li>RTM</li> <li>Hand lay-up</li> <li>Pultrusion</li> </ul>	<ul style="list-style-type: none"> <li>Rail interiors</li> <li>External body panels</li> <li>Carriage underbody</li> </ul>
<ul style="list-style-type: none"> <li>1</li> <li>3</li> <li>14</li> <li>12</li> <li>8</li> <li>9</li> </ul> <b>Oil and gas</b> <ul style="list-style-type: none"> <li>High pressure resistance</li> </ul>	£21m	<ul style="list-style-type: none"> <li>Carbon</li> <li>Glass</li> </ul>	<ul style="list-style-type: none"> <li>Epoxy (for carbon)</li> <li>UPR and vinyl ester (for glass)</li> </ul>	-	<ul style="list-style-type: none"> <li>Filament winding</li> <li>Pultrusion</li> </ul>	<ul style="list-style-type: none"> <li>Pipes</li> <li>Buoyancy modules</li> <li>Top-side applications, e.g. decking, grates, handrails</li> <li>Pressure vessels</li> </ul>

Table 3: Summary of composite market sectors and the needs<sup>1</sup>



## 5.2 Supply chain

FRPs were first developed in the early 20th century, mainly in relation to aerospace and defence applications. The UK played a leading role in this with the development of the first carbon fibre composite materials. As the industry grew, there was a rapid evolution in the availability of synthetic polymers and resins associated with the growth of the petrochemicals industry. This enabled new composites which were both high performance and affordable for a variety of applications.

In the early days, several chemical companies integrated composite materials within their supply chains, supplying formulated resins and polymer compositions to end users. This structure rapidly evolved and, by the end of the 20th century, fully integrated chemical suppliers no longer dominated the supply chain. Instead, more specialised companies sourcing chemicals from across the chemical industry now primarily provide the materials and formulations tailored to the needs of manufacturers of composite parts and structures.

Today, the chemical producers who supply the raw materials usually do not supply directly to composite manufacturers but other formulators in the supply chain. Composites manufacturers are generally dependent on the complex supply chains of chemicals and materials manufacture which serve industry in general. Figure 1 summarises the composite supply chain and the different types of companies involved.

Addressing the sustainability challenges within the composites industry will likely require clear industry sector demand, and collaboration across the entire composite supply chain. As such, this report includes a critical review of the future direction for a selection of composite industry sectors to identify likely impacts and opportunities for the composite material supply chain.

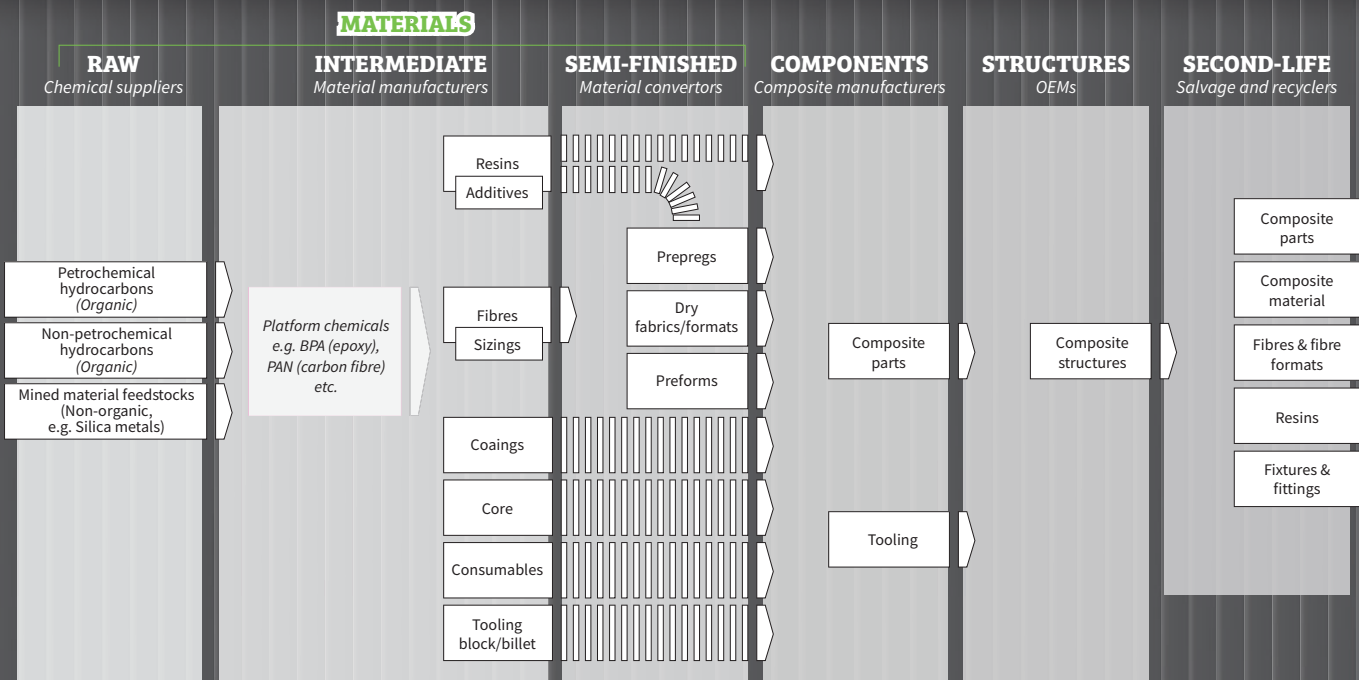


Figure 1: Schematic representation of the composite supply chain (credit: NCC)

## 5.3 Market sector spotlights

### 5.3.1 Offshore wind

The UK wind sector composite supply chain was worth £242 million in 2019. An increase in onshore and offshore UK wind capacity to 75 GW by 2030 has resulted in a continual trend for larger wind turbines to deliver the efficiency requirements that meet economic and logistical limits imposed by wind farm density. Over 130 million wind blades are needed with performance requirements that can only be met by FRP composite. Aurora Energy Research found that one turbine must be installed every weekday of the 2020s to achieve the government's goal, equating to £50 billion in investment. Meeting the annual carbon fibre demands for just the UK wind sector equates to over 4% of the entire global supply of carbon fibre in 2019.<sup>1</sup>

The significant growth in demand for renewable wind power results in one of the highest growth predictions for composite use at over 9% CAGR. There are two main approaches forming. A practical approach to delivering the highest power output with current technologies, and a parallel, sustainable approach to deal with decommissioning and developing more sustainable materials, designs and end-of-life solutions. Opportunities for new composite developments are prevalent, especially those that extend life or ease waste issues at the point of decommissioning through to the reuse/second life of recovered materials.

### 5.3.2 Automotive

The UK automotive industry had a turnover of £82 billion in 2018 and produced approximately 1.5 million cars and 85,000 commercial vehicles. The main players were BMW/Mini, Nissan, Toyota, Vauxhall and Jaguar Land Rover. The composite supply chain was worth £505 million in 2019.<sup>1</sup> The automotive industry has international supply chains and a significant amount of the value of each vehicle is provided by overseas suppliers. In addition, there are several extremely high value/low volume manufacturers such as Aston Martin, Bentley, Lotus, McLaren, Morgan and Nobel.

The automotive industry is highly sensitive to material cost, resulting in a historical preference for high rate, low cost manufacturing processes, such as sheet and bulk moulding compounds for battery housings, cosmetic panels, underbody protection, seat back frames and spare wheel pans.<sup>2</sup> The transition to electric and hydrogen propulsion is expected to see an increase in composite use, as the power-to-weight ratio and range anxiety further restricts the design envelope, leading to a push towards lightweighting. This will likely see composite use expand into primary structures opening up opportunities for high-performance carbon fibre composite systems.

E4Tech forecasts that, in 2030, 69,000 hydrogen powered passenger vehicles will be produced. Although this will be a small market share, when considered in global terms, this results in a significant opportunity for the UK to take a lead on hydrogen pressure vessel manufacture and supply.<sup>3</sup>

The automotive industry is a heavy user of relatively high volume, rapidly processable thermoplastic-based composite materials. The industry is seeing a rapid transition towards zero emissions at tailpipe technologies, coupled with increasingly stringent end-of-life targets in place via the End-of-Life Vehicle Directive. With the increasing adoption of hydrogen technologies and optimised structures required for electric vehicles there is likely to be opportunities for sustainably sourced materials, either through bio-based, natural, or recycled routes. An exponential demand for carbon fibre presents further opportunities for the development of new materials, and of end-of-life and circular supply chains.

### 5.3.3 Aerospace

The UK aerospace composite supply chain was worth £889 million in 2019<sup>1</sup> and is a world leader in the application of composites for the industry, producing complex and high value components such as wings. Growth will be through industry transformation towards new technologies and sustainability. Airbus have made significant investments in future technologies like hydrogen for zero-emission aircraft to be in service by 2025.<sup>4</sup>

Composites will play a huge role in developing tank infrastructure and increasing the amount of lightweight aircraft parts. Other new uses of composites are expected to increase in future generations of aircraft while new, smaller forms of air vehicles, such as delivery drones and air taxis, will be highly dependent on their power-to-weight and strength characteristics.<sup>5</sup>

The demand for composite material is typically performance driven, with high strength and stiffness carbon fibre and predominately toughened epoxy matrices. The barrier to entry for new chemistries within aerospace composites is often the complex and costly qualification process whereby adherence to standards must be met at all design stages: from materials, component, subcomponent through to assembly. The current supply chain is, therefore, dominated by multinational material suppliers. As a result, the composite market for aerospace is highly reliant on the import of raw materials.

The aerospace industry is projected to represent 24% of global CO<sub>2</sub> emissions by 2050 at current growth rates. Relying on efficiency improvements alone forecasts this to improve to 19%. Aerospace is therefore at a crossroads and must look at step-change technologies, including hydrogen. Three of the five top barriers for hydrogen in aerospace, defined by consultancy firm Roland Berger, are directly related to composites:<sup>6</sup>

- hydrogen storage: storage is a key driver of hydrogen's success. The low energy density means there is a huge need to develop step-change tank technology such as cryogenic tanks
- sustainable hydrogen production: sustainable green hydrogen production via electrolysis on offshore windfarms is essential to define hydrogen as a truly sustainable fuel. Composites are key, therefore, to both the production and use of green hydrogen
- infrastructure: fuel delivery infrastructure is not currently at the level needed for the aviation industry. Composites will enable hydrogen storage and transport infrastructure to be rolled out, and enable hydrogen aircraft, but investment is required to develop this technology to a suitable level.

Aerospace (and defence) dominate the UK composites market by value. Both sectors are intensive consumers of carbon fibre and high-performance resin systems. Growth in composite use is primarily performance driven for existing structures, the development of future aircraft and through the adoption of new (hydrogen based) propulsion technologies.

The growth drivers in aerospace lead to significant sustainability challenges across the composites industry. The production and sustainability of high performance and typically highly resistant/persevering materials presents intrinsic challenges at end of life. Simultaneously, the demand for hydrogen technologies currently requires energy intensive production routes and a significant volume of cost and energy intensive carbon fibre without an end-of-life supply chain. The development of new and sustainable material systems with an embedded end-of-life supply chain is needed.

### 5.3.4 Hydrogen

Hydrogen serves two purposes in the future UK commitment to net zero:

- energy storage to meet the needs of a balanced electricity grid otherwise unpredictable due to its reliance on renewables; and
- as a fuel with zero CO<sub>2</sub> emissions for heat and transportation.

At present, hydrogen is predominately produced from fossil fuels (methane) with concomitant CO<sub>2</sub> production. Therefore, significant investment is being made in both CO<sub>2</sub> capture and renewable energy-powered electrolysis methods to produce green hydrogen that could eliminate emissions completely.

One of the major disadvantages of hydrogen as a fuel is its low energy density and the requirement to store it under high pressures and/or at cryogenic temperatures. The only material capable of constraining the 100 to 700 bar pressures required for lightweight hydrogen storage vessels is carbon fibre polymer composite.

Irrespective of source, the hydrogen demand is growing significantly and it is expected that 210,000 pressure vessels will be required for passenger cars and light commercial vehicles alone. This will put significant pressure on the supply of carbon fibre over the next 10 years.

## 5.4 Sustainability trends

An overview of the market and the rapid growth of disruptive technologies such as hydrogen will present a considerable shift in the demand for sustainability within the composite material supply chain. Consultation with industry and academic experts highlighted six broad topics covering the production, use phase and end of life:

1. Low carbon feedstocks
2. Efficiency of energy and materials in manufacture
3. Increasing composite lifetime
4. Repair and reuse
5. Chemical recycling technologies for legacy materials
6. Inherently recyclable composite materials.

These topics are discussed in more detail in **Section 7**.

# 6 Sustainability in the composites sector

**This section provides an introduction into sustainability in the composites sector and the key principles that will be discussed throughout this report.**

## 6.1 Overview

Sustainability is a broad term and can be defined in many ways. The ISO definition of sustainability is ‘the state of the global system, which includes environmental, social and economic subsystems, in which the needs of the present are met without compromising the ability of future generations to meet their own needs.’<sup>7</sup>

The key environmental driver of the 2015 Paris Agreement is a global commitment to reduce global average temperatures (aiming for a less than 1.5 °C increase compared to pre-industrial levels) to prevent more severe climate change effects. The UK has a legal commitment to achieve net zero greenhouse gas (GHG) emissions by 2050 and, as a result, most policies related to sustainability centre around decarbonisation with a focus on:

- the reduction of emissions through wide-ranging mitigations, such as reduced gas power generation in favour of renewable wind
- the removal of emissions through natural or technology-based processes.<sup>8</sup>

GHG emissions represent only one of 15 environmental impact categories that need to be maintained to ensure environmental sustainability. While decarbonisation sets a clear direction for mitigations, the technologies, themselves, should also be sustainable and minimise impact across their entire supply chain. When applied to composites this means reducing their impact across all categories without limiting their ability to deliver current needs, especially where they can be enablers for sustainable technologies.

A more focused way to view the composites supply chain in terms of sustainability is to consider linear versus circular economy models. The industry needs to move away from a linear economy that relies on non-sustainable feedstock and landfilling of material. Instead, a circular economy needs to be developed in which sustainably sourced materials are fed into a closed loop with minimal subsequent losses during manufacture and at end of life.

The term ‘sustainability’ creates a challenging dichotomy where composite materials are concerned. Their high performance, exceptional durability and environmental resistance are all required for net zero energy and green technologies, but they are exceptionally challenging to manage at end of life. In 2019, approximately 110,000 tonnes of fibre-reinforced composites were produced in the UK, with only 15% sent for recycling at end of life and just 6% reused in secondary applications. In addition, over 98% of polymer matrix materials and 95% of reinforcement fibres are derived from non-renewable resources.

By 2050, wind turbine waste is predicted to reach roughly two million tonnes globally, a figure that is the same volume of composite material produced by all of Europe in 2020.<sup>9</sup> For the UK, SusWind has forecast that glass fibre waste from wind turbines alone could reach as high as 30,000 tonnes per year by 2044.<sup>10</sup>

This presents a challenge. The continued use of composite materials in delivering net zero requires a fundamental change in the sustainability of the material itself and its supply chain. This report looks at the challenges industry faces in making composites sustainable and the corresponding opportunities for chemistry and chemical processing industries in resolving them.

The future utopian state of complete decarbonisation across energy production and its use will require an overhaul of the underpinning technologies and the materials that they rely on. Evaluation of the predicted growth of a selection of these areas indicates an increasing reliance on new advanced materials and therefore a risk if the sourcing and sustainability of these materials and resources are not considered.

## 6.2 Key principles

This report assesses the challenges and opportunities in the composites industry using three key sustainability principles: waste hierarchy, circular economy, and decarbonisation.

### Waste hierarchy

The **EU waste hierarchy** ranks waste management options according to what is best for the environment. This is set out in Article 4 of the revised EU Waste Framework Directive. The UK has used this framework to set out guidance for any business or public body generating, handling, and treating waste. Figure 2 outlines the six steps: prevention, reduction, reuse, recycling, recovery (anaerobic digestion or other process with energy recovery) and disposal.



Figure 2:  
the EU waste hierarchy

## Circular economy

The circular economy is a systems concept to eliminate waste and keep products, materials, and services in use, therefore reducing the amount of finite resources required as an input. This is opposite to the current situation in the composites sector, which follows a linear economy based on ‘take-make-dispose’.

The Ellen MacArthur Foundation provides three principles for how a circular economy should work, with principles 1 and 2 being the most relevant to the composites sector:

1. Design out waste and pollution
2. Keep products and materials in use
3. Regenerate natural systems<sup>11</sup>

Figure 3 describes how a circular economy could look for composites, where materials must retain their value as they move from recycle back to manufacture. The Circular Economy Package is one way that the UK has introduced a legislative framework to help identify steps for reducing waste and establishing an ambitious and credible long-term path for waste management and recycling.<sup>12</sup>

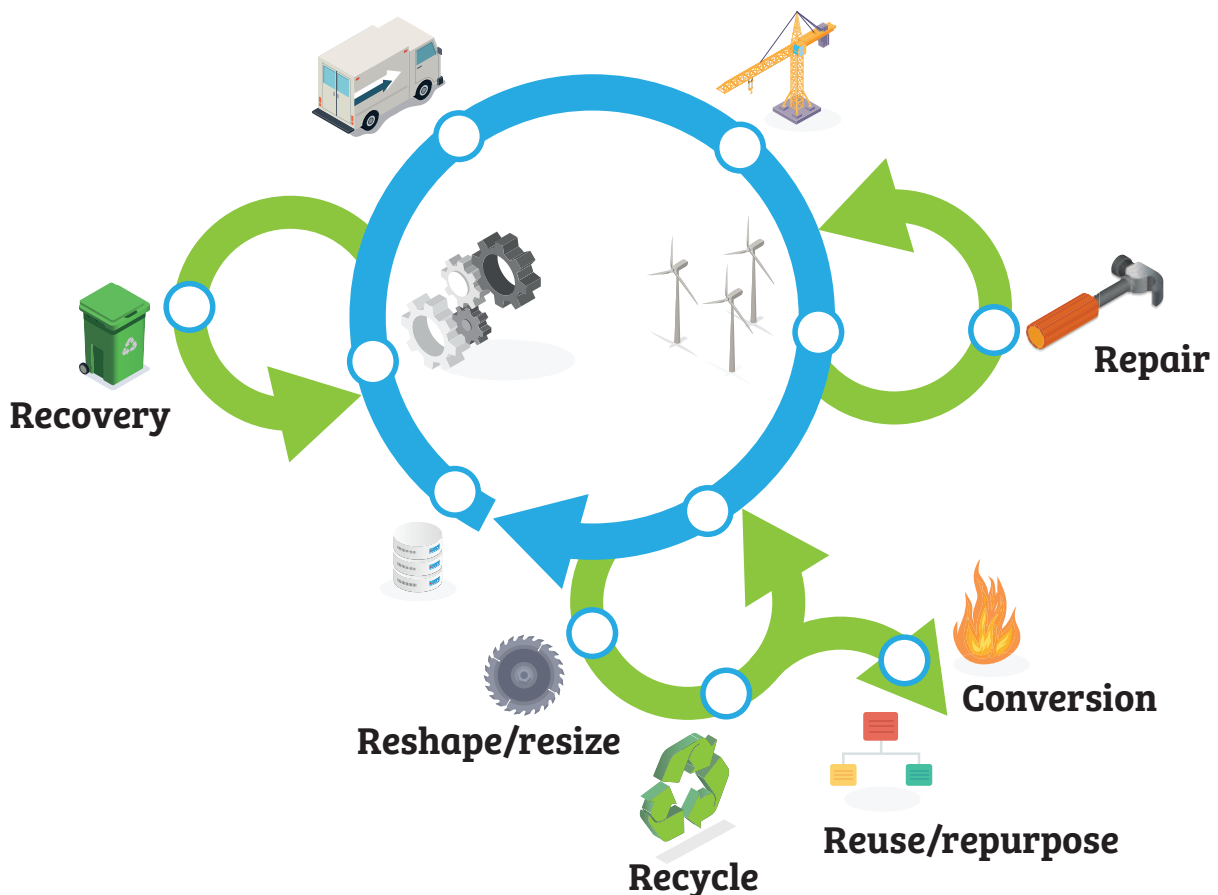


Figure 3: The future circular economy model for wind turbines, created within the [SusWind programme](#) and based on the Ellen MacArthur Foundation's three principles<sup>9</sup>

## Decarbonisation

Decarbonisation or a low carbon economy is based on energy sources that produce low levels of GHG emissions. The driver behind decarbonisation is to reduce human contribution to global warming and climate change through the reduction of GHGs that cause a warming effect. While multiple gases are known to cause warming to varying degrees, the effect caused by carbon dioxide is well quantified as a key contributor and therefore used as the base metric for calculation. Decarbonisation, therefore, is one of the key methods in achieving the removal or reduction of carbon dioxide (and other gases) in the atmosphere.

The UK's Industrial Decarbonisation Strategy sets out how industry can decarbonise in line with UK legislation to achieve net zero emissions by 2050, while remaining competitive and without pushing emissions overseas.<sup>13</sup> There are a variety of approaches set out in the strategy, but they broadly focus on investment, consumers, and industrial processes. This includes deploying low-regret technologies such as hydrogen and carbon capture, use and storage (CCUS), improving efficiency and accelerating the innovation of low carbon technologies.

A crucial aspect to the decarbonisation of the materials supply chain is the classification of GHG emissions into the three broad buckets of: Scope 1 (emissions a company is directly responsible for); Scope 2 (emissions a company is indirectly responsible for resulting from its activities); and, Scope 3 (emissions from up and down the supply chain associated with a company's product or service).



# 7 Analysis: sustainability trends

**The following section analyses the sustainability trends identified by industry and academic experts, highlighted in Section 5.4. Some trends have a greater focus on chemistry than others, therefore we indicate the relevance to the chemical sciences at the beginning of each section so that readers can rapidly identify areas of interest.**

Each of these sections detail current practices used by the industry, the sustainability challenges facing the supply chain and progress towards overcoming them. A final section is included to highlight underpinning tools that will be important for the composites industry in moving towards a sustainable future.

## 7.1 Low carbon feedstocks

This section highlights low carbon pathways to major material types currently used in the composites industry. These are derived from low carbon sources but are chemically equivalent to feedstocks derived from conventional sources. This section also discusses the opportunities bio-derived materials provide in accessing chemistry not easily available from petrochemical sources. Since all these material types are not exclusively used by the composites industry, they present an opportunity for collaboration with other chemistry-using sectors, plastics and textiles for example, to develop sustainable raw materials at scale and competitive cost.

**Table 13** in the Appendix summarises the workshop discussions in this section.

### 7.1.1 Introduction

There are two main sources of embodied carbon in the polymers and fibres used in FRPs:

- the base materials at the start of the supply chain
- the processes used to convert the base materials to the polymers, resins and other components that are used in the final formulated product prior to conversion to a composite part or structure.

The chemical industry is already evolving to decarbonise the processes used to convert base materials to formulated products: this applies as much to existing materials as to new materials. Data from the European Chemical Industry Council (CEFIC) shows that, since 1990, GHG emissions from chemicals manufacture have decreased by 59%, despite output having increased.<sup>14</sup> Typical approaches to this include:

- making chemical processes more efficient by increasing the yield of a reaction
- making process more efficient by reducing the energy required to both carry out a reaction and purify the product (usually heat, often currently provided by oil or gas-fired boilers)
- reducing the occurrence of side products requiring energy-expensive processes and treatment to eliminate them in an environmentally acceptable way.

These are immediately beneficial to both chemicals' producers and the composite supply chain since they enable more efficient material use and reduced operating costs. However, adopting new technologies to improve on the above, and the associated capital expenditure, can present challenges.

Increasingly, chemical companies are investing in or are considering future investment in:

- replacing heat from the combustion of hydrocarbons with electrical heating derived from green sources
- capturing CO<sub>2</sub> emitted from chemical processes, either for use in another application, or as carbon capture and storage (CCS).

These are more contentious within the industry because of the relative cost of electricity compared to hydrocarbon fuels. Switching energy source can be challenging, technically, as well as requiring significant up-front investment, especially for CCS.

All leading global chemicals companies, many of which service the composites industry, have announced plans to make their businesses net zero by 2050 at the latest, and some significantly before. Global chemical companies such as Huntsman, BASF and INEOS are working to lower greenhouse gas emissions, deliver circular economy solutions and use carbon sequestration and storage technologies.<sup>15,16,17</sup> These will directly benefit the composites industry as a downstream user. The change to UK law regarding full disclosure of the carbon footprint associated with a company's entire value chain will make investment in low carbon materials more attractive.<sup>18</sup>

These approaches do not, however, address the sustainability of the carbon used in the end-materials. The majority of polymer feedstocks (98%) and fibre feedstocks (95%) used in the composites industry are derived from non-renewable sources which introduces new carbon into the environment. In the long term, this will create additional issues as petrochemical sources are depleted and subject to increased price volatility.

Several companies are therefore exploring alternative sources of carbon that are relevant to the composites industry.<sup>19</sup> Prime examples of these are:

- naturally derived sources, including bio-feedstocks such as ethanol derived from sugar cane and certain grasses and bio-waste from agriculture, forestry and wider societal sources
- the use of waste materials, such as polymers and plastics, within a circular economy model
- the conversion of CO<sub>2</sub> itself to useful materials and products, using green hydrogen.

**Mass balance is a generic approach used to reduce the up-front cost of investment required in manufacturing plants to process new sustainable raw materials. It is adopted by multiple chemical companies for both bio- and waste-derived materials, and for recycle in a circular economy model. Figure 4 outlines the mass balance approach which feeds sustainably derived feedstocks into existing manufacturing assets used to process petrochemical-based feedstocks. It tracks the amount and sustainability characteristics of circular and/or bio-based content in the value chain. It is viewed by the industry as an important step on the way from our current petrochemical-based linear supply chains to a more sustainable model built around the potential of the circular economy and the bioeconomy.**

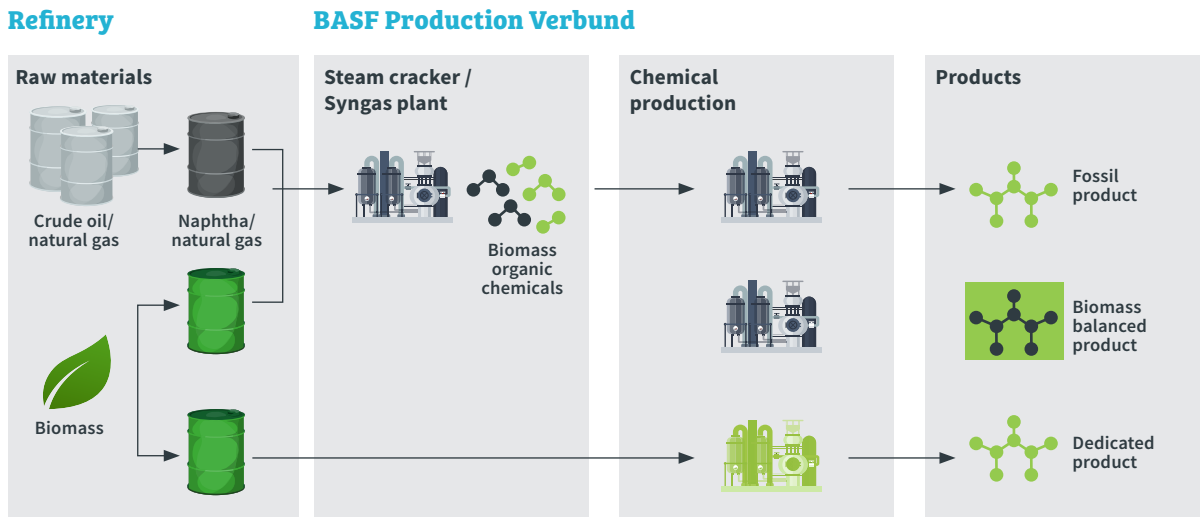


Figure 4: In the mass balance approach, fossil resources are replaced by sustainable biomass at the start of production. The share of renewable resource is then allocated to the final product.<sup>20</sup>

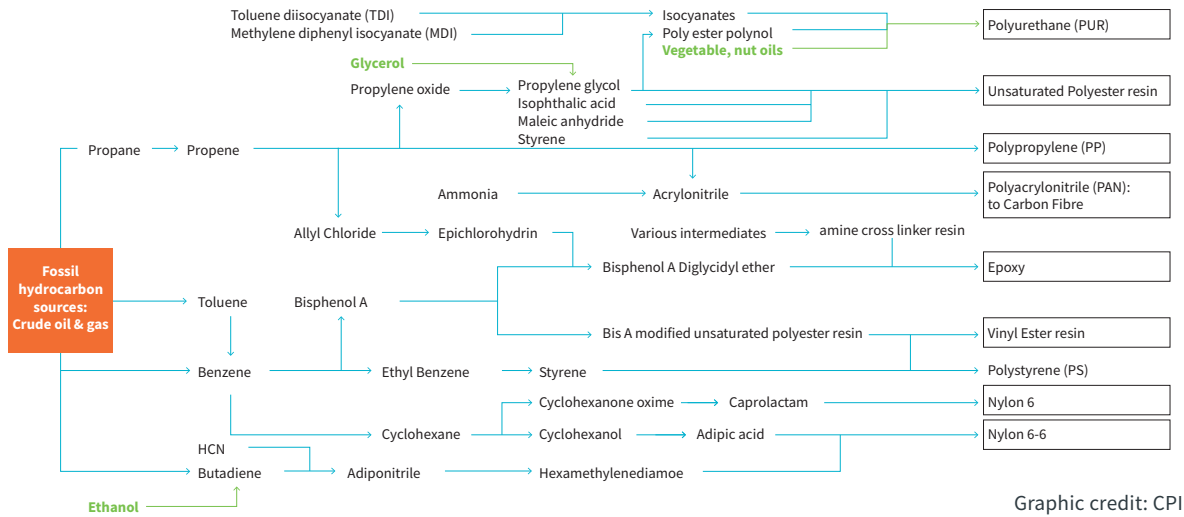


Figure 5: A summary of the major organic chemical types involved in the supply chain of precursors and composites production.

Figure 5 highlights the major chemical types currently involved in the polymer and fibre supply chains in the composites industry. All the chemicals identified are used more widely in applications outside of the composites industry in applications as diverse as plastics and packaging, coatings, adhesives, and textiles. There are broadly two types of material used in composites: thermoplastics (dominated by polypropylene and polyamides) and thermosets (dominated by epoxies and unsaturated polyesters).

## 7.1.2 Pathways to low carbon thermoplastics

Of the currently available technologies to reduce carbon emissions, several credible options are emerging, albeit with a significant cost premium in the short term.

### 7.1.2.1 Polypropylene

SABIC has announced an investment in its Teesside cracker,<sup>21</sup> which will reduce CO<sub>2</sub> emissions by 60% to produce the monomer, propylene, for polypropylene manufacture. Although this will still use non-sustainable feedstocks it will reduce the Scope 1 and 2 emissions in the monomer manufacture. Companies are also introducing bio-derived raw materials at the front end of processes; for example, SABIC launched in 2021 under the TRUECIRCLE brand.<sup>22</sup> To avoid the cost of setting up a dedicated small manufacturing unit, the bio-feedstock is fed into a large-scale manufacturing plant, and the bio-credits are allocated to the specific product type in line with feedstock inputs using the so-called 'mass balance' approach.

### 7.1.2.2 Polyamide

Similarly, advances are being made in decarbonising the manufacture of polyamide precursors; for example, DSM claims at least a 28% reduction in embodied carbon of caprolactam, used for Nylon 6 manufacture.<sup>23</sup> This is in part due to a close collaboration with supplier Fibrant, which manufactures caprolactam monomer and now also offers a bio-based caprolactam monomer with minimal embodied carbon, EcoLactam Bio®.<sup>24</sup> There are some low carbon polyamides commercially available, such as the PA11 resin Rilsan® from Arkema and Ultramid® S Balance, a polyimide 6.10 from BASF, both of which are partially derived from castor oil.<sup>25,26</sup>

### 7.1.3 Pathways to low carbon thermosets

Thermosets are multicomponent systems, composed of matrix forming oligomers and monomers combined with cross-linking agents and catalysts to effect cure. As a result, the situation for thermoset resins is more complex than the previously discussed thermoplastics. Low carbon routes for the supply of common chemicals used in polyester and epoxy resins are described below.

#### 7.1.3.1 Unsaturated polyester resins

The reactive diluent monomer component in polyester resins is principally styrene. Styrene monomer has a poor health and safety profile for use as a reactive diluent due to its potential toxicity and odour.<sup>27</sup> However, the industry has largely adapted to this via careful handling controls, and it is now seen as the most cost-effective option for widespread use. Low carbon routes to styrene monomer are being explored by INEOS, who recently developed styrene monomer using a bio-waste-derived syngas feedstock for input into existing petrochemical manufacturing.<sup>28</sup> They have now developed polymers based on this low carbon styrene replacing all the fossil fuel derived materials.<sup>29</sup>

Recent developments in polystyrene recycling are now also leading to the availability of recycled styrene monomer from polymer waste and INEOS is developing this technology.<sup>30</sup> Alternatives to styrene with an improved toxicology profile, and in some cases bio- or waste-derived, have been developed: for instance, 4-vinylphenol analogues derived from lignin.<sup>31,32</sup>

The main molecular components used in the oligomer component of unsaturated polyester resins are propylene or ethylene glycols with aromatic diacids such as phthalic or maleic anhydrides. Importantly, many of these polyester building blocks will be relevant to other industry sectors: for example, polymers in liquid formulations used in personal care, coatings and cleaning products. Bio-routes to glycols and anhydrides have been created, with some that are commercially available.

**Glycols:** There are many global suppliers of petrochemical-derived ethylene glycols (EGs), using a range of processes with varying levels of selectivity. More efficient processes are used. For example, the Shell OMEGA ('Only MEG Advantage') process is where mono ethylene glycol (MEG) is produced in a two-step process which involves the oxidation of ethylene to ethylene oxide. This is followed by the hydrolysis of ethylene oxide via an ethylene carbonate intermediate. This intermediate, produced via the reaction of ethylene oxide with carbon dioxide, eliminates side reactions between the ethylene glycol product and ethylene oxide, ultimately removing the need for energy intensive purification. The OMEGA process is reported to be over 99% selective for mono ethylene glycol.<sup>33,34</sup>

Bio-derived ethylene glycols are commercially available from an increasing number of suppliers. At present, there are two high volume suppliers, India Glycols Ltd and Croda, with other manufacturers moving from pilot to commercial scale. India Glycols Limited (IGL) manufactures 99.5% pure bio-MEG from bio-based ethanol derived from sugar cane molasses, with worldwide distribution. Croda's ECO MEG is produced in the USA from biomass ethanol, with the plant using a "high proportion" of renewable energy.<sup>35</sup>

UPM is a Finnish company with origins based in the paper industry, but which is more recently branching out into biofuels, biochemicals and biocomposites.<sup>36,37</sup> They have recently invested 550 million euros in a new industrial scale biorefinery in Leuna, Germany, with a capacity of 220,000 tonnes across the product range, including bio-MEG. The company extracts the sugars from waste wood (70% of which would normally be burnt) and waste streams from sawmills, converting it into products including bio-MEG and MPG (mono propylene glycol). The wood is locally sourced from 100% sustainably managed forests; therefore, the carbon footprint is anticipated to be considerably (at least 50%) lower than other bio-glycol sources and could eventually be carbon neutral.

In collaboration with UPM, and under the EU funded project ValChem, Metabolic Explorers has been using bacterial biochemistry to synthesis propylene glycol.<sup>38,39</sup> The Belgian company Oleon also synthesis propylene glycol at 20 kt per annum.<sup>40</sup>

**Anhydrides:** At present, maleic anhydride is produced by oxidising butane in the presence of a vanadium oxide catalyst with CO/CO<sub>2</sub> evolved as a by-product.

Routes to maleic anhydride from bio sources have been reported: for instance, high yield synthesis from sugar-derived levulinic acid, shown in Figure 6, or from renewable furfural but there are no commercial sources at this time.<sup>41,42,43</sup>

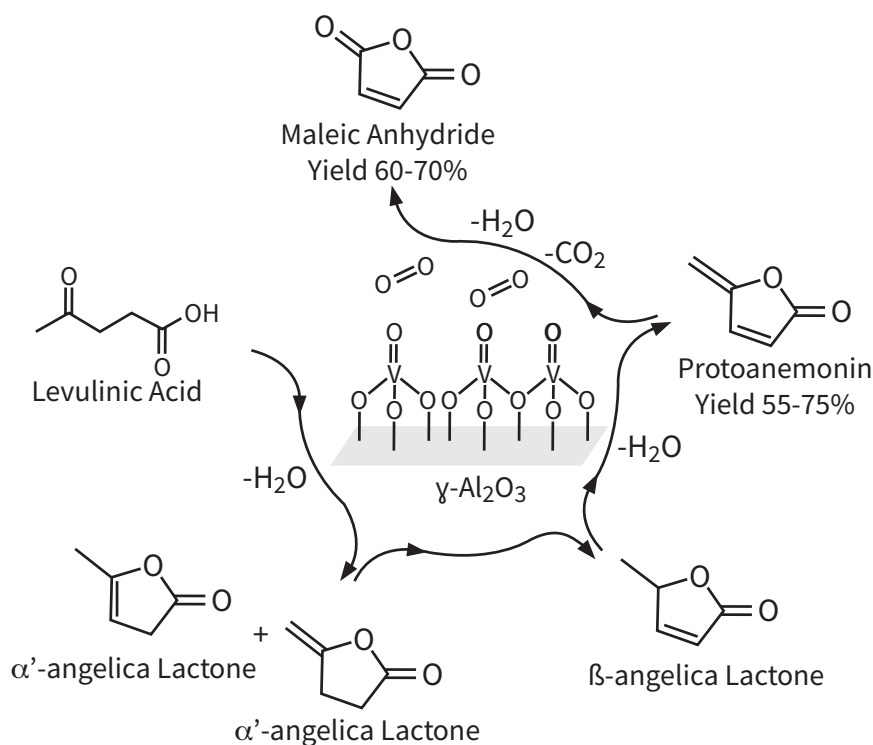


Figure 6: Synthesis route for maleic anhydride from bio-sourced levulinic acid<sup>40</sup>

Similarly, researchers have worked to identify viable routes to bio-based phthalic anhydride. However, none are yet commercialised and so it continues to be synthesised through the catalytic oxidation of fossil-refined *o*-xylene or naphthalene. While the main market is for plasticiser use, the market for phthalic anhydride was estimated to be more than 5,000 kt, of which 900 kt are used in unsaturated polyester resins. By replacing 500 kt of the petrochemical source,  $\text{CO}_2$  emissions could be reduced by almost 1,000 kt.<sup>44</sup>

Jia et al<sup>260</sup> report a one-pot synthesis route using bio-sourced materials to give furfural and 5-hydroxymethylfurfural, which then react together to give the phthalic anhydride using catalysts based on molybdenum oxide and copper nitrate. This is illustrated in Figure 7.

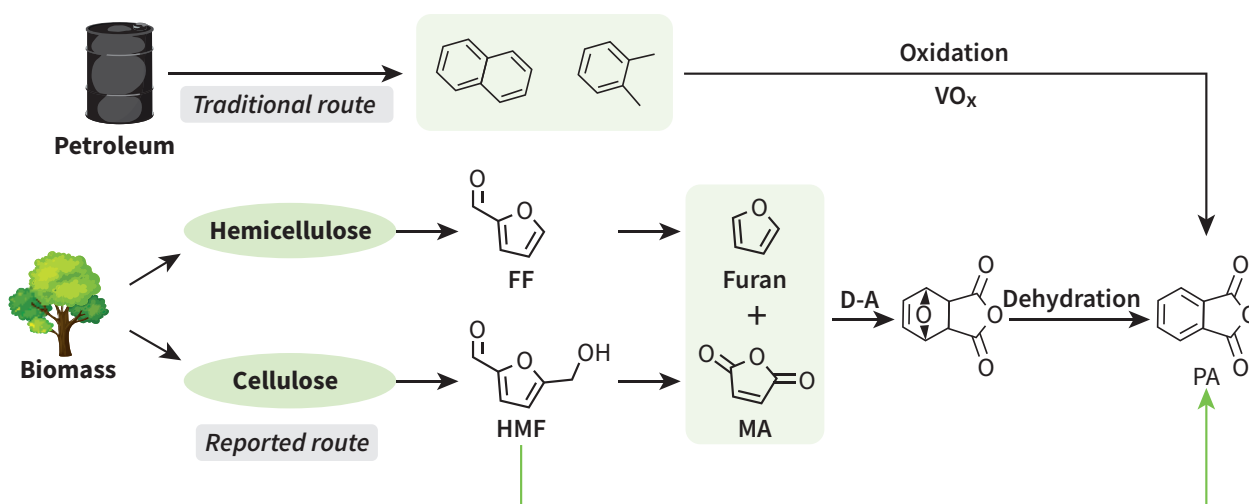


Figure 7: Bio-renewable synthesis route for phthalic anhydride<sup>256</sup>



Recently, based on research undertaken through Biorizon, TNO established a spin-off company called 'Relement' to scale up furan-derived 3-methylphthalic anhydride (MPA) as a replacement for fossil phthalic anhydride. In October, the first sample production campaign produced 25 kg of MPA at 99.5% purity. A study by CE Delft indicated that using this bio-derived MPA will lead to the equivalent reduction of 3.1 kg CO<sub>2</sub> per kg of phthalic anhydride.<sup>45,46,47</sup>

### 7.1.3.2 Epoxy resins

Figure 8 shows that the principal component of the most widely used epoxy resins is the bisphenol A-derived diglycidyl ether ('BADGE').

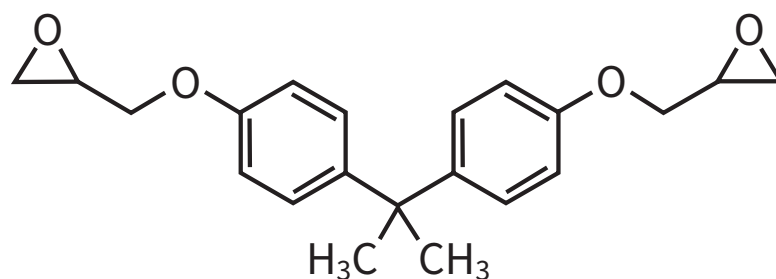


Figure 8: Chemical structure of 'BADGE'

Bio-based epichlorohydrin, derived from vegetable glycerol, is now commercially available from AGC Group under the product name Epicerol, at 120 kt per annum, which forms the epoxy groups in BADGE.<sup>48</sup> Figure 9 highlights the sustainability credentials of Epicerol versus petrochemical based EPI.

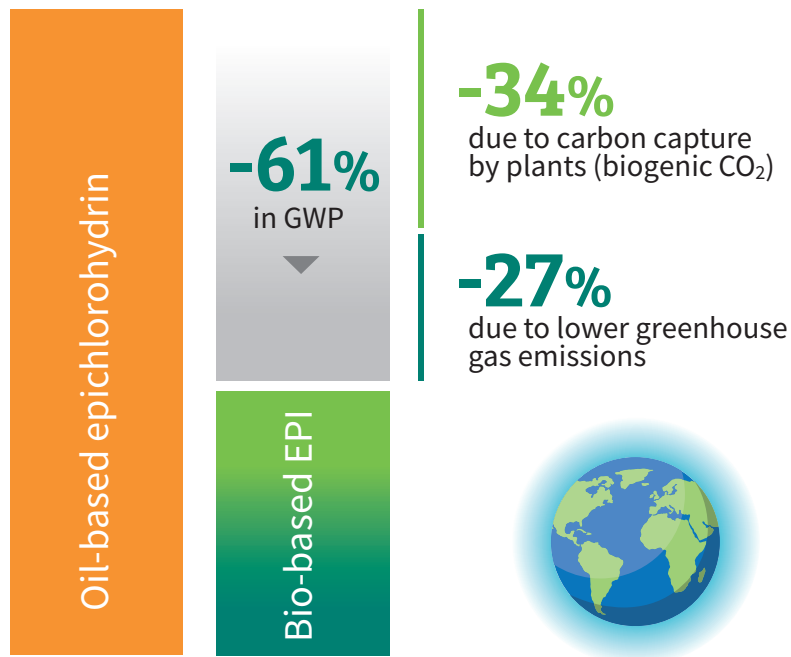


Figure 9: For each kg consumed (vs petrochemical-based EPI) the carbon footprint of Epicerol is lowered by 2.56 kg CO<sub>2</sub>, equivalent to 6.1% reduction including biogenic CO<sub>2</sub><sup>49</sup>

The situation for the bisphenol A (BisA) component in the epoxy resin is more complex, since there is evidence that the BisA molecular structure can lead to long-term health problems, even when present at only trace levels in the environment.<sup>50,51</sup> Although of limited relevance to high-performance engineering applications, concerns regarding toxicity have resulted in substantial investment in replacements for BisA materials with different molecular structures and therefore reduced toxicity. Therefore, there has been very limited investment in direct drop-in replacements for the BisA component.

The new materials that have been developed, however, do not offer the same cost performance profile as current mainstream BisA epoxy resins.<sup>52,53</sup> The main feedstock streams for BisA are:

- benzene for the main oligomer backbone (taken from the benzene/toluene/xylene (BTX) product stream in a petrochemical cracker and transformed via phenol into the condensate bisphenol A)); and
- propylene (converted via allyl chloride to epichlorohydrin for introduction of the epoxy groups of BADGE).

There are developments in the supply chain which could help with reducing the carbon footprint of BisA, as technology is becoming available to manufacture the phenol precursor from bio/waste sources.<sup>54</sup> A new bio-derived BisA based resin was recently announced by Mitsui and Teijin which will start to address this gap.<sup>55</sup>

The amine crosslinkers used in epoxy composite formulations also present substantial challenges, since a significant component are based on aromatic amines related to aniline. Aromatic amines, (such as 4-diaminodiphenylsulfone (4,4-DDS), 3,3-diaminodiphenylsulfone (3,3-DDS) 4,4-diaminodiphenyl methane (DDM), methylenedianiline (MDA) or diethyl methyl benzene diamine (DETDA) (Huntsman, n.d.)) are preferred for many applications to aliphatic. This is because they give higher glass transition temperatures ( $T_g$ ) and considerably higher heat distortion temperatures in comparison to aliphatics.

**Multifunctional amines based on natural feedstocks have recently been claimed as an alternative for high-performance materials, but these are at low technology readiness level (TRL).**

**Derived from the reaction of pentosan-rich biomass with an amine, Bitrez offers furalkamine as an alternative curing agent.**

**It is REACH compliant and reported to have at least 25% bio content.**

Amine curing systems with higher aliphatic amine content are preferred in some applications. For example, with wind energy, room temperature cure is required due to the size of the wind turbine parts being built, and high temperature performance is of lesser concern. There are examples of phenalkamine curing agents based on cardanol (derived from cashew nuts), phenol, aldehydes and polyamines, which are commercially available with bio content of up to 68%.<sup>57,58</sup> While mainly considered for use in coatings, they are offered for use in composite systems.<sup>59</sup>

Anhydrides based on methyltetrahydrophthalic anhydride (MTHPA), methyl nadic anhydride (MNA) and methylhexahydrophthalic anhydride (MHHPA), are also used to effect cross-linking in epoxy resins used in fibre-reinforced composite systems. They tend to be liquid systems formulated into a package to include catalysts.<sup>60,61,62</sup> There do not appear to be any low CO<sub>2</sub> options commercially available, but there is research into inherently recyclable carbon fibre composites based on epoxy-anhydride covalently adaptable network (CAN), which involves synthesis of, for example, MHTPA and MHHPA from bio-derived maleic anhydride.<sup>63</sup>

#### 7.1.4 Bio-derived resins

Bio-derived resins can offer new chemical approaches to deliver composite performance at acceptable cost. Most bio-derived resins are derived from biomass feedstocks.<sup>64</sup>

For example:

- **plant oils.** Plant oils are long chain fatty acids. Their unsaturated sites are ideal for functionalisation but their levels will vary depending on the crop, for example, epoxidation into monomers for epoxy resin synthesis
- **lignocellulosics and plant-based polysaccharides.** Starch and lignocellulose are the two main types for polymer production. Lignocellulosic biomass contains cellulose (34–54%), hemicellulose (19–34%), and lignin (11–30%).<sup>65</sup> Lignin is of interest as a polyaromatic structure as it provides a good baseline to mimic the aromatic structures used in petrochemical-based materials
- **sugars from waste biomass.** Cellulose can be converted into glucose and key platform chemicals such as 2,5-furan dicarboxylic acid and hydroxymethylfurfural (HMF);<sup>66</sup> hemicellulose can be converted into C5 sugars which then give C5 furans including furfural and furfuryl alcohol.

A multitude of resins and materials can be synthesised from these feedstocks. Many have been demonstrated at an academic level and have been extensively reviewed.<sup>63,67,68,69</sup> Three of the most industrially promising are described below.

### 7.1.4.1 Polyfurfuryl alcohol

Polyfurfuryl alcohol (PFA) has been the most widely adopted bio-derived matrix material to date in the composites industry. It is an excellent example of a bio-based polymer which has desirable properties that exceed its petrochemical equivalent: for example, high glass transition temperature and its fire, smoke and toxicity (FST) performance. Production of furfuryl alcohol is well established. Approximately 300,000 tonnes of furfural are produced annually and of that 70% is converted into furfuryl alcohol.<sup>70</sup>

There are some challenges during composite manufacture. The cure mechanism is a condensation reaction meaning water is released. Products on the market so far are in prepreg form where the material is already part cured which minimises any water release. This limits their application in areas such as high value components for aerospace applications. Approaches that enable PFA resins to be processed in larger volumes, for example in resin infusion, would increase the opportunity for their use.

### 7.1.4.2 Polylactic acid (PLA)

PLA is a thermoplastic with similar mechanical properties to polypropylene and has begun to be used as a replacement for other polymers in the packaging industry. Polylactic acid (PLA) is produced from glucose-derived lactic acid by the polycondensation of lactic acid or by ring-opening polymerisation of lactide.<sup>71</sup> Higher molecular weight grades can also be produced for more demanding applications and may be appropriate in composite applications.<sup>72</sup> PLA composites have been demonstrated by various sources although these largely remain demonstrator parts rather than parts put in service.<sup>73</sup>

### 7.1.4.3 Polybenzoxazines

Polybenzoxazines are thermosets with a very high glass transition temperature (up to 250°C) which have been explored as potential replacements for phenolic resins in the aerospace industry. Their aromatic structure means they have a high glass transition temperature as well as low shrinkage and a high mechanical strength.<sup>72</sup> They are formed through the ring-opening polymerisation of benzoxazine.<sup>74</sup>

Benzoxazine resins can be derived from a number of biomass derived sources including cardanol, vanillin and eugenol. When derived from cardanol, unlike benzoxazines from petrochemicals, the resin contains a long alkyl group which aids flexibility and reduces some of the brittleness seen with petrochemically derived polybenzoxazines.<sup>75</sup>

### 7.1.5 Bio-derived, low carbon and natural fibres

The principal route to carbon fibre manufacture is petrochemical-based, using acrylonitrile monomer (ACN). ACN is polymerised and then spun into fibre before a multi-stage pyrolysis process removes any functionalisation leaving usable carbon fibre. This is a costly and energy intensive process and multiple approaches are in development to reduce the associated carbon footprint such as that being developed by Lemond.<sup>76</sup>

In addition, bio-derived routes to acrylonitrile monomer are now becoming available commercially with Trillium and Solvay committing to develop the supply chain for bio-based ACN.<sup>77,78,79,80</sup> These developments align well with broader industry interests related to textile manufacture, where sustainable sourcing of materials is also a key consumer issue. There are multiple options in development to develop a bio-derived drop-in replacement for the polyacrylonitrile (PAN) fibre used in subsequent carbon fibre manufacture, including lignin as a waste product from the paper industry.<sup>81,82</sup>

The growth of the circular economy will generate alternative sources of waste materials with the potential to be used as feedstock for materials manufacture. Alongside the widespread adoption of carbon capture technology, sequestered CO<sub>2</sub> could be transformed into polymers.<sup>83</sup> An example is practiced by Eonic in the manufacture of polycarbonate polyols for use in polyurethane block copolymers.<sup>84</sup>

Technology for the conversion of mixed consumer waste streams to hydrocarbon oils and gases is now being commercialised for the biofuels industry.<sup>85</sup> Once cost barriers have been addressed, these products will also be viable as feedstocks for materials manufacture. Tata Steel is also exploring the transformation of steel manufacturing waste gases, including both CO<sub>2</sub> and CO, into chemical building blocks such as acetic acid and fatty acids.<sup>86,87</sup> As these types of industrial symbioses become established and are incorporated into chemical industry supply chains, they could provide a route for low embodied CO<sub>2</sub> composite materials.

Many natural fibres have been explored as alternatives to conventional fibre, mainly as replacements to glass fibre rather than carbon. This is because of the high strength of carbon fibre which is hard to replicate. These natural fibres can be classified into two categories:

- **primary fibres** are those which are grown directly for their use as reinforcing fibres such as sisal, hemp, bamboo and flax.
- **secondary fibres** with are by-products of crops grown for other purposes such as palm, pineapple, banana and fique.<sup>66</sup>

Secondary fibres have the advantage of maximising use from otherwise unused material whereas crops for primary fibres may need to compete with land used for other purposes including food production.

Table 4 shows the global production of various natural fibre types which are already produced in large volumes. Flax and hemp are of particular interest to the UK market as they grow well in the European climate and there is increasing land dedicated to them across Europe.<sup>88</sup>

Fiber type	Origin	Species	Largest producer countries	World production (10 <sup>3</sup> tons)
Coir	Fruit	<i>Cocos nucifera</i>	India, Vietnam, Sri Lanka	100
Kenaf	Stem	<i>Hibiscus cannabinus</i>	India, Bangladesh, United States	970
Flax	Stem	<i>Unum usitatissimum</i>	Canada, France, Belgium	830
Bamboo	Stem	(> 1,250 species)	China, India, Indonesia	30,000
Abaca	Leaf	<i>Musa textilis</i>	Philippines, Ecuador, Costa Rica	70
Jute	Stem	<i>Corchorus capsularis</i>	India, Bangladesh	2,500
Sisal	Leaf	<i>Agave sisalana</i>	Tanzania, Brazil, Kenya	378
Ramie	Stem	<i>Boehmeria nivea</i>	China, Brazil, Philippines	100
Cotton	Seed	<i>Gossypium sp.</i>	China, India, United States	25,000
Banana	Leaf	<i>Musa indica</i>	Brazil, India	200
Silk	Animal	Silkworms, honeybee	China, India, Europe	202
Wool	Animal	Sheep, alpaca, camel	Australia, New Zealand, China	2,000
Hemp	Stem	<i>Cannabis sativa</i>	China, France, Philippines	2,115
Pineapple	Leaf	<i>Ananas comosus</i>	Philippines, Thailand, Indonesia	74
Agave	Leaf	<i>Agave fourcroydes</i>	Colombia, Cuba, Mexico	56
Kapok	Fruit	<i>Ceiba pentand ra</i>	China, India	3,116
Bagasse	Stem	–	Brazil, India, China	75,000

**Table 4: Production weights of natural fibres.**

Natural fibres have some advantages over conventional fibres. They are low density, biodegradable and are low cost. However, they have some disadvantages, principally their moisture uptake and surface compatibility with matrix materials. There is also the perception of variability: how repeatable are the mechanical properties across different growing conditions and therefore a concern how the supply chain can consistently supply fibre with the required properties. If the performance variability is larger compared to conventional fibres, then increased safety factors will be required. This would remove some of the benefits of introducing bio-fibre in the first place.

Natural fibres have a hydrophilic surface owing to the density of alcohol groups on their surface. This means they are more prone to absorb moisture when compared to more chemically inert glass and carbon fibres. This is a concern for the long-term durability of natural fibres. As water is incorporated into the composite it can promote hydrolysis and lead to increased chain scission in both the resin and fibre.

The polar, hydrophilic nature of natural fibres also leads to a poor resin-to-fibre interface. A poor interface between fibre and resin leads to a composite with poor mechanical properties as any mechanical load cannot be shared across the composite. As a result, there is a likelihood of delamination. To overcome their hydrophilicity and poor interface properties, natural fibres can be chemically treated to change their surface properties. Many approaches to this have been explored including using alkaline reagents, silanes, acetylating agents, benzoylating agents and peroxides.<sup>90</sup>

### 7.1.6 Conclusion

While there is a movement towards lower embodied CO<sub>2</sub> materials in the composites industry, there are multiple challenges that need to be addressed. The major issues are:

- the relative cost and availability at scale of the new source of raw material
- the cost of associated processing to platform chemicals (where processing is different from the current petrochemical base)
- the up-front investment required in the manufacturing plant to process the new raw materials.

The FRP industry constitutes a small part of the overall plastics industry by volume. As all the segments of the plastics industry look to reduce the carbon footprint of their products, there will be competition: a) for bio- and/or waste-derived materials, b) over-demand of the necessary building block chemicals and subsequent increases in costs. Therefore, to meet the scale of demand, the supply chain for sustainably sourced materials must be of sufficiently comparable size and cost competitiveness to that of petrochemical-derived materials.

The source of the sustainable biomass also needs to be considered. The biomass needs to be derived as a secondary source, i.e. from waste streams rather than using arable land to grow crops purely as a supply of feedstock. For example, lignin feedstock that was originally grown in sustainably managed forests has been obtained from the waste generated from the pulping industry.

Due to environmental and toxicological concerns with BisA, most research has been directed into identifying safer alternatives rather than how to make it in a sustainable manner. While these alternatives may be suitable for many applications, they do not impart the required mechanical properties for direct replacements in composite systems. Without further investment in this area, making appropriate, sustainably sourced epoxy resins will be difficult to achieve.



By delivering drop-in replacements that are interchangeable with existing petrochemical-derived materials, there should be no loss in performance, which should enable a straightforward adoption into the composite market. The major advantage of targeting an existing building block and associated polymers and resins is to reduce or deliver negative carbon content by changing only the origin of the base material. Consequently, the performance of bio-based products is directly compared to those of petrochemical derivation. As more sustainable alternative materials become competitive and widely available, it is critical that the mindset surrounding them changes from “not being equivalent” to “good enough” to achieve more sustainable products that are fit for purpose in a net zero world.

There are several opportunities to create synergies across wider industrial sectors, rather than focusing purely on the niche application of polymers for use within FRP. An example is developing sustainably sourced materials with applications across multiple market sectors such as bio-based ACN for use in both textiles and as a precursor for carbon fibre in composites. Likewise, sustainable polyester building blocks for unsaturated polyester resins represent a common need with materials used in polymers in liquid formulations (PLFs).<sup>91</sup> Another example is the use of waste materials, such as sequestered carbon dioxide, from one sector (steel manufacture, for example) in the synthesis of chemicals and materials for other sectors. This type of sustainability-driven industrial symbiosis is still in its early stages but is gaining momentum and will be an active area for future developments.

The chemicals supply chain, which supplies resins for the composites industry, is highly internationalised. Carbon taxes are designed to incentivise businesses to reduce CO<sub>2</sub> emissions and their introduction is beginning to address the varying recognition of net zero across the supply chain. However, the global tax system is complicated and unequal; one tonne of carbon emissions in Sweden costs \$137 in tax, but less than \$1 in Poland.<sup>92</sup> Further inclusion of Scope 1, 2 and 3 of the Greenhouse Gas Protocol would ensure that all GHG emissions associated with a company’s value chain are included. The UK was the first G20 country to enshrine into law mandatory climate-related financial disclosures for over 1,300 of the UK’s largest companies.<sup>17</sup> This could drive a rise in regulators and companies developing environmental, social and governance frameworks directly aimed at improving sustainability and helping investors and businesses to understand the financial impacts of their exposure to climate change.<sup>93</sup>

Economic change and price volatility of fossil-derived feedstocks can make the production of higher bio content materials more financially attractive. Increased competition for crude oil, combined with carbon taxes, will make investing in the transition to lower carbon footprint materials increasingly attractive for businesses.

Ultimately, the design of end products will need to be based on the properties of the sustainably sourced materials, rather than their fossil-derived cousins. While this will naturally happen over time as lower CO<sub>2</sub> materials become more available, the conversion will likely be slow. Universities are offering PhD placements to work in the area and EU Horizon programmes include requirements for composites to contain at least 50% sustainable, bio-based materials.<sup>94,95</sup> Making a minimum bio content a stipulation of funded competitions for composites will drive research and development. This will enable industrial suppliers and designers the freedom to work together and develop the necessary protocols, reducing risks to ultimately enable earlier adoption of these materials.

## 7.2 Manufacturing efficiency

This section discusses the processes and techniques used in the manufacturing of composites to improve energy and materials efficiency. These include curing, out-life, process enablers, consumables and manufacturing waste. This section highlights how chemistry can influence manufacturing processes, particularly in the selection of resins, sizings, adhesives, coatings, and additives.

**Table 14** in the Appendix summarises the workshop discussions in this section.

### 7.2.1 Introduction

Composite manufacturing is often a complex process and there are many different manufacturing techniques. It involves high energy processes that contribute significantly to the embodied carbon of a composite part. Common manufacturing approaches to most composites are:

- resin and fibre combination through processes such as manual lay-up, infusion, and spray
- consolidation, typically with the form under vacuum to remove entrapped gas and compressed with applied pressure (for example, through autoclave, or within a press)
- curing (if using a thermoset).

Figure 10 summarises some of the main manufacturing approaches used in their production.

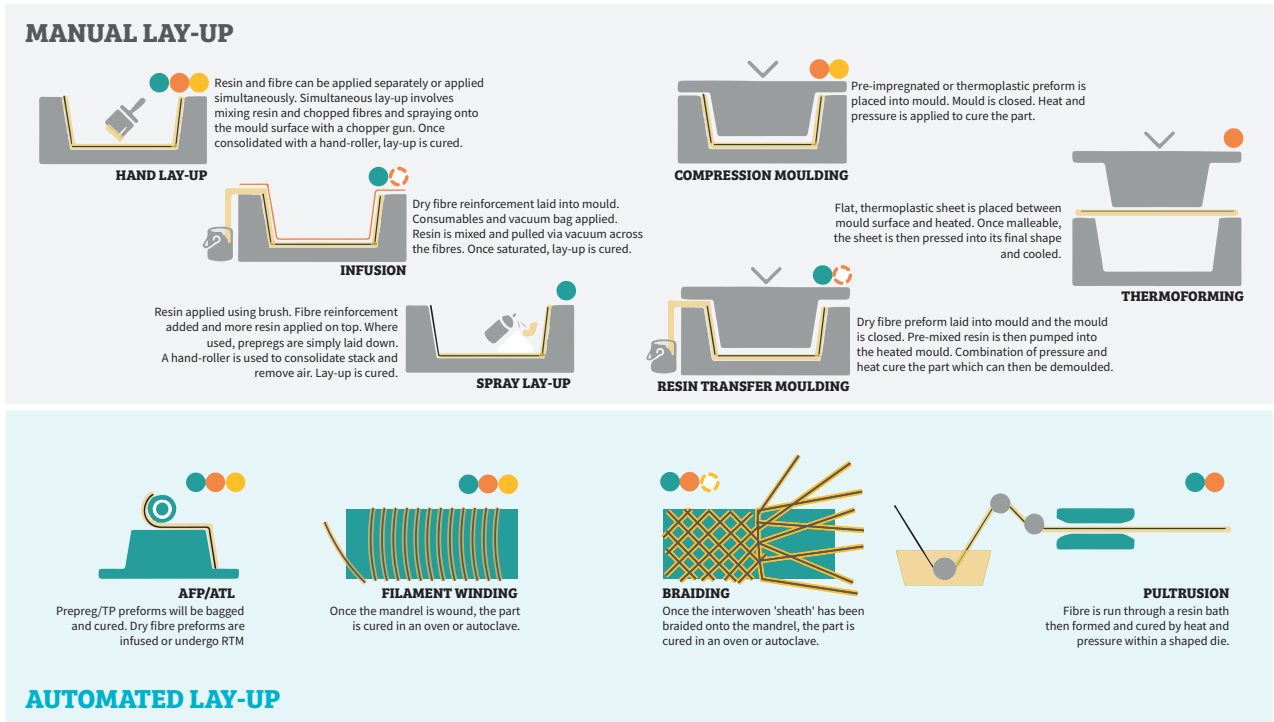


Figure 10: Manufacturing approaches in composite production (credit: NCC)

## 7.2.2 Curing

A large amount of the energy produced from a composite polymer part cradle-to-gate, is used during the curing phase. Although there are low temperature cure materials available, these are not always appropriate for the application when high strength and high glass transition temperature ( $T_g$ ) are required. If this amount of energy could be reduced, the embodied carbon of a part will follow.

Curing is a high contributor to the energy used during the manufacture of composites, but some ways that chemistry can reduce this is by designing systems that can be activated by other triggers such as ultraviolet radiation and through the development of fast curing resins to optimise thermal curing processes.

### 7.2.2.1 Ultraviolet radiation curing

Ultraviolet cured polymer composites have been in development for the past 60 years. However, the technology has not gained the same popularity as thermal cure resins. UV radiation allows almost instant curing of liquid resin to solid polymer at ambient temperatures. Cure time is reduced and, as the heating of the whole component is not required, the energy is far lower than thermal curing.<sup>96</sup>

However, UV radiation cures only the portion of the material that it comes into direct contact with, and only if it absorbs UV rays. Therefore, UV radiation is traditionally used for transparent and thin film cures less than 1mm thick. This process has limitations for coloured constituents of a component and thick parts by preventing UV rays from reaching photoinitiators.

The use of photosensitisers reportedly helped cure using sunlight by absorbing longer wavelengths and transferring energy to the photoinitiators and ultimately curing the resin. One example is Bis-acylphosphine oxide (BAPO), which has become the main solution to UV curing thicker laminates. Used in applications such as cure-in-place piping, filament winding, pultrusion and gel-coats, this technology is seeing uptake within the manufacture of an increasing number and variety of applications.

Gurit has developed a resin system called RENUVO™ which cures in minutes using portable LED lamps. Used for both prepregs and single component resins for ease of use, these materials can be handled at temperatures of 5–30 °C. A laminate up to 3 mm thick will fully cure within 80–190 seconds using 300–2000 mW/cm<sup>2</sup> UV lamps. To ensure full and correct cure across a large part, a lamp mounting system has been developed to index the lamp over the part properly. This resin system requires only room temperature storage, also reducing out-life energy consumption. **Read the Gurit case study.**

While UV curing has been tried and tested over the years, challenges remain for industry-wide uptake. These include the initial capital expenditure and the requirement for individual cure parameters to be investigated and developed for every new part, geometry, laminate and material.

### 7.2.2.2 Optimised thermal curing

For many applications, thermal curing will still be the only way to achieve a fully cured part. However, conventional methods can take many hours to heat up tools and reach high temperatures, with the ovens using significant amounts of energy. If materials that achieve the necessary strength can be cured at either lower temperatures, or for shorter dwell periods, this energy can be significantly reduced. There are limitations to the process window to which cure can be achieved. Care is needed to prevent runaway reaction resulting in exotherm that can elevate the temperature beyond its degradation or, more dangerously, its smoke or flash point. [Table 5](#) outlines the differences between the two main low energy approaches.

Approach	Fast curing resins	Low temperature curing
<b>Description</b>	Fast curing resins have been developed for high volume manufacture and used successfully over the past decade. Materials can be assembled easily, cured for short amounts of time and demoulded while hot for faster production cycles.	Although a lot of epoxy resins will reach their best mechanical properties when cured at high temperatures, there are many that are developed to gain reasonably good physical strength and $T_g$ at faster, low temperature cures.
<b>Examples</b>	<p>Snap cure prepreg such as Hexcel® M77 is a fast curing resin whose chemistry could lend itself to other processes if adapted, for a lower energy process.</p> <p>Multi-part systems such as Telene's polydicyclopentadiene (PDCPD) comprising two parts peroxides, a catalyst and a monomer solution to produce a thermoset with high toughness.</p>	A methylimidazole hardener was added to epoxy resins for high-throughput automotive composite parts with the aim to create a resin system with high $T_g$ , that cures within minutes. <sup>98</sup> A challenge of this system was a relatively low shelf life due to being highly reactive to fast cure. However, if hardeners can be successfully incorporated into epoxy resin systems (which mean short cure times) at mid-range temperatures, energy consumption can be reduced.

Table 5: Low energy curing approaches

### 7.2.3 Out-life

The storage life of resin systems is a significant factor when selecting a material for industrial use. Cost effective in large volumes, a long shelf life is beneficial to buying in and storing large quantities for long periods of time. Conversely, if this storage requires a freezer, or even a fridge, this increases the energy use and cost of the part. Ambient temperature storage may work well for high temperature cure resins, however, with the focus shifting to lower temperature cure systems, the difference between storage temperature and gel temperature comes closer.

Storage temperatures may also activate the curing process. A non-thermal curing method such as UV or microwave radiation may overcome this and negate the need for fridges and freezers to extend the material life beyond a few weeks. As discussed earlier in this report, these types of cures have their challenges to become commercially viable. But, if successful, they would be a solution to longer life ambient storage and simplify the logistics required for sub-ambient transportation.

## 7.2.4 Process enablers

In addition to out-life, out-of-autoclave cure, additive manufacturing and automated fibre placement processes enable a more sustainable material to be used in order to reduce the embodied carbon of the product.

### 7.2.4.1 Out-of-autoclave cure

Autoclave curing, a high energy process, is integral to many composite manufacturing processes by applying heat and pressure throughout cure. Moving to a vacuum-bag-only approach, with just an oven, could significantly reduce this energy consumption.

Researchers have developed a vacuum-bag-only cure of unidirectional flax fibre tape with polypropylene thermoplastic for flax/epoxy composites in naval shipyards.<sup>99</sup> This has the potential to enable further future opportunities for more sustainable processes within a renewable material technology.

However, there are some challenges. An autoclave typically operates under high pressure (8 to 13 bar). This aids the reduction of porosity within the resin through the compression of internal gases, but also aids the vacuum in drawing out gas from within the system. Many aerospace resins have been qualified for flight based on specific manufacturing processes and requalification can be expensive and time intensive. As a result, manufacturers choose proven materials and processes over novel approaches. If out-of-autoclave technology can prove itself to deliver equivalent quality, uptake could see significant opportunities for improving the carbon footprint of products.

### 7.2.4.2 Additive manufacturing

Additive manufacturing (also known as 3D printing) for composites parts has grown over the past 10 years, along with its applications. Initially depositing thermosets with short fibre reinforcements, the process has developed into continuous fibre reinforcement of thermoplastics, with two different methods for 3D printing.

- **In situ fusion** is the mixing of dry continuous fibres with melted resin during the printing process.
- **Deposition of pre-impregnated fibre** enables better bonding between constituent parts.

Various studies show the possibilities of 3D printing continuous fibres, and the opportunities to use low waste processes for manufacturing complex geometries that require structural properties. Reaching high strength still requires a thermal cure under vacuum, but this still provides potentially better options than traditional alternatives.

There has also been successful 3D printing of biocomposites through continuous flax fibres in PLA which resulted in tensile properties in the same range as continuous glass/polyamide printed composites.<sup>100</sup>

### 7.2.4.3 Automated fibre placement

Automated fibre placement (AFP) is a highly accurate automated process that results in low waste: fibres are only deposited where required and impregnated with resins before deposition. Natural fibres are renowned for being temperature sensitive and cannot withstand the higher temperatures that come with AFP. However, research has been successful at developing AFP processes with flax fibres and a thermoplastic with a minimised time at temperature to avoid degradation of the natural fibres.<sup>101</sup>

The manufacturing of composites is renowned for having a relatively high waste or scrap amount. In part, this is down to its in-process consumables and waste, but also any manufacturing inconsistencies or faults. Both waste and consumables add to the embodied carbon of the part.

Consumables are used in nearly every composite manufacture, which are traditionally single use and not designed with sustainability in mind. These include vacuum bags, breather, peel ply, inlet and outlet pipes. Many are not able to be recycled due to being contaminated with raw materials and resins. Carbon neutral consumables, natural fibre breathers and reusable vacuum bags offer more sustainable and reusable options during manufacture. However, until these become a viable option across the industry, thousands of tonnes of consumables will continue to end up in landfill.

- Plaswire takes nylon breather fabric that has not been contaminated with other textiles and PET vacuum bagging material waste, and is working on ways to recycle these back into the supply chain.<sup>102</sup>
- Techlan recycle rolls of used silicone backing paper from prepreg manufacture. By cleaning the paper, it can then be reused in numerous industries including composites. They also purchase prime grade materials which are surplus to requirements or quality rejected such as siliconised films, papers and uncoated polyester films.<sup>103</sup>
- Aptec specialise in recycling aramid fibres, processing over 100 tonnes per year. They also reprocess other types of fibre into lengths of 4–70 mm in length. Applications for the recyclate include carding and spinning, needlefelt manufacture, silencer films, friction material reinforcement and construction and infrastructure.

If material cannot be repurposed, it can still be useful in energy recovery: for example, used to produce energy in cement kilns. Even with processes that use the least amount of material possible, waste is still a significant output of the composite industry with limited commercial provision for reprocessing composite waste for reintroduction to the supply chain. The more awareness that the industry has of the challenge and opportunities to develop and support the introduction of commercial offerings, the more waste will be recycled or repurposed instead of ending in landfill.

### 7.2.5 Conclusion

There are many opportunities to reduce the embodied carbon of composite parts through the choice of material and supporting processes. Fast curing resins or low temperature cures reduce the energy required to run ovens. Out-of-autoclave processes use vacuum only for consolidation and have had successful results with comparable mechanical properties to autoclave cures. However, the benefits of an autoclave such as mitigating human error in lay-up, wrinkles and faults, are not easily transferred to out-of-autoclave curing.

UV curing has proven itself in some areas, including in aerospace and energy (for example, for wind turbine blade repair or cure). However, design relevant UV-curable materials are not nearly as available as thermal cure systems. Additives, however, also have been developed to provide hybrid thermo-UV cures that can be added to thermal cure resins.

Out-life is an important factor, with the refrigeration of resins and prepregs not only costing financially but also using a lot of energy. Ambient storage prepreg is currently under development but not yet widely used. UV cure would avoid the need for refrigeration for storage as long as the product was kept away from UV.

Processes that reduce the waste or use the least amount of material necessary are also beneficial for sustainable production. Automated fibre placement and 3D printing are two examples of this, both having been proven with natural or sustainable materials such as flax and thermoplastics. The main limitation of these processes is that the high mechanical properties of conventional processing does not always follow. For the right application, these processes will provide a more sustainable option.

The underlining obstacles are high capital expenditure for new processes and limited material options available that meet the mechanical properties of those already available. The supply chain's tendency towards what is proven over taking risks with novel technologies is also a barrier. Readily available information to educate engineers on the impact of materials and processes on the environment could significantly accelerate the development and adoption of solutions. With improved education on LCAs, material properties, and process optimisation, each part of a manufacturing process can be optimised for the least amount of waste, material, or energy, and sustainability will be at the forefront of all product development.



## 7.3 Increasing composite lifetime

This section describes how chemistry enables inherent durability of fibres and polymer matrices used in composites. Chemistry also plays an important role in the use of coatings and additives to protect composites, to increase their resistance to environmental and in-service wear, and in enabling fire resistance.

[Table 15](#) in the Appendix summarises the outputs of workshop discussions related to this area.

### 7.3.1 Introduction

An important part of increasing the sustainability of composite systems is to make current and emerging materials more durable to a wide variety of environmental and in-service factors. This in turn will lead to an increase in the in-service lifetime of the composite structures and a reduction in the need to renew and replace. Factors that affect the long-term effectiveness of composite materials include:

- temperature, both high and very low (cryogenic) and thermal cycling
- chemical exposure (caustic, solvent-based and highly oxygenated)
- radiation (for example, high UV)
- water immersion and high humidity
- surface wear from rain, dust and wind.

Degradation is exacerbated when components are under constant or cyclic loads, and when the factors above act in combination, such as in offshore marine, sub-sea, low earth orbit, and high temperature propulsion environments.

As well as the performance of composites when exposed to repeated stimuli over long time periods, it is also important to understand the behaviour of composites and protect them when exposed to short-term, highly damaging events such as impact and fire.

### 7.3.1.1 Fibre durability

As the primary load-carrying element of a composite structure, composite fibres need to be durable. The choice of fibre used in the manufacture of a composite is a combination of factors, such as performance and cost, with other influences such as the sustainability of the source and durability. Table 6 summarises the durability of common fibre types against various factors including moisture and chemical attack.

Fibre type	Durability
<b>Carbon</b>	Stable in most environments except highly oxidising and sulphuric acid. Not effected by moisture
<b>Glass</b>	E-glass: aluminium boron silicate glass. Moisture sensitive due to leaching of alkali oxides from surface resulting in microcracking. Highly susceptible to damage by acids and alkali ECR-glass: contains boron trioxide and fluorine. Improved resistance to acids but not resistant to alkali C-glass: contains calcium borosilicate to provide structural equilibrium in corrosive environments AR-glass: contains alkaline zirconium silicates. Alkali resistant
<b>Natural</b>	High water absorption, poor microbial resistance, low thermal stability

Table 6: Durability of fibres commonly used in composites.

Carbon fibres are stable under most conditions and absorb very little moisture, so there is little change in maximum load strength with use. Glass fibres are very much affected by moisture and chemical environment due to ion leaching and attack by acidic and alkaline solutions. Table 6 shows several grades of glass fibre which have been formulated to better withstand a variety of chemical environments, but this often increases the cost.

Natural fibres are highly hydrophilic in nature and therefore absorb water well, which can negatively affect mechanical performance. They are also prone to biological attack. This is a useful property at end of life where a natural fibre composite could be composted but, in service, this could prove problematic.

### 7.3.1.2 Resin durability

The durability of thermoset and thermoplastic polymer materials is highly dependent on their chemical composition. Table 7 shows some generic differences between the two polymer classes.

Property	Thermoplastics	Thermosets
<b>Mechanical</b>	Flexible and elastic. High resistance to impact (10x more than thermosets). Strength comes from crystallinity	Inelastic and brittle. Strong and rigid. Strength comes from cross-linking
<b>Thermal</b>	Melting point lower than the degradation temperature	Melting point higher than the degradation temperature
<b>Moisture</b>	Generally resistant to moisture (except polyamides)	Can absorb moisture
<b>Chemical resistance and solubility</b>	Highly chemically resistant but can dissolve in organic solvents	Chemically resistant and insoluble in solvents
<b>Creep</b>	Can be susceptible to creep	Higher resistance to creep

Table 7: Durability properties of thermosets versus thermoplastics.

Table 8 provides a breakdown of the durability of common thermoset resins to weathering, chemical attack and thermomechanical effects.

Resin type	Weathering	Chemical resistance	Thermomechanical behaviour
<b>Polyurethanes (thermoset)</b>	Sensitive to light and hydrolysis and climates with strong sun and/or high moisture. White or clear grades turn yellow or brown and mechanical properties decrease	Limited resistance to moisture and hot water. Acids and bases accelerate hydrolysis. Resistance to organic chemicals is generally acceptable	Dynamic fatigue strength can be fair or good for certain grades. Continuous use temperature varies from 80–130 °C, low temperature behaviour can be acceptable down to -55 °C or less. Fire resistance is naturally weak
<b>Unsaturated polyesters (thermoset)</b>	Used in applications where long-time weathering is implied (e.g. automotive, shipbuilding, construction). Behaviour is improved using gelcoat, which maintains mechanical performance and reduces yellowing	Good resistance to moisture and hot water. Attacked by highly oxidising acids, aromatic hydrocarbons, chlorinated ketones, esters and solvents. Resistant to aliphatic hydrocarbons and alcohols	Continuous use temperatures in an unstressed state generally vary from 90 °C up to 140 °C. $T_g$ values range from 90–210 °C. Fire resistance is weak but can be enhanced with additives
<b>Phenolic resins (thermoset)</b>	UV light resistance is good with a slight risk of surface deterioration. Resistance to moisture is good	Chemical resistance is grade specific. Strong and oxidising acids decompose phenolic resins. Phenolics are resistant to aromatic, aliphatic, polar or non-polar common organic solvents, aqueous salt solutions, halogenated organics such as carbon tetrachloride or trichloroethane, and automotive fluids such as brake fluid, antifreeze and glycol	$T_g$ is high (170–200 °C), and modulus retention is good at high temperature. Continuous use temperatures range from 100–170 °C. Creep is very weak. Fire resistance is high, producing a relatively low amount of smoke at a relatively low level of toxicity. Phenolic resins have a high char yield
<b>Epoxy resins (thermoset)</b>	Not UV resistant and require additives for UV stability. Moisture absorption is moderate with time. Epoxies are susceptible to environmental stress cracking	Resistance to water is grade dependant and epoxies can absorb water. Can be attacked by strong acids and bases. Organic solvent resistance is generally good, with exceptions such as ketones and certain chlorinated solvents	Good dynamic fatigue behaviour. $T_g$ values are high due to the high cross-linking density of epoxies, with some systems having $T_g > 200$ °C. Fire behaviour is poor, and additives must be used to reach required standards
<b>Poly(propylene) (thermoplastic)</b>	Needs to be modified with UV stabilisers to withstand UV light exposure and heat. Low moisture absorption (0.01%–0.03%/24hrs)	Largely unreactive, chemically, and has high resistance to dilute and concentrated acids, alcohols, bases and mineral oils. Good resistance to aldehydes, ketones, esters, aliphatic hydrocarbons, vegetable oils. Limited resistance to aromatics and oxidising agents	Low $T_g$ of -20 °C and a minimum use temperature of 0 °C. It has a mid to high crystallinity of 50–85% and a relatively high melting point range of 160–170 °C. Needs to be modified with flame retardants to meet minimum FST standards, and this leads to some knockdown in mechanical performance
<b>Poly(amide) (thermoplastic)</b>	High abrasion and wear resistance. Hydroscopic with a water absorptivity of 0.1–1.5%/24hrs and it has poor hot water resistance. Poor UV light resistance, undergoing auto-oxidative degradation under UV, resulting in discolouration, chain scission and loss of mechanical properties	Good chemical resistance with no appreciable swelling due to aliphatic hydrocarbons, fuels, oils, esters, ketones, dilute and concentrated alkalis, fats, and oils. Aromatic and chlorinated hydrocarbons can be problematic to some grades. Attacked by concentrated mineral and organic acids, phenols, cresols, and oxidising agents	Relatively high $T_g$ and high melting temperatures from 175–275 °C. Mechanical properties decrease on heating. Unmodified polymers undergo molecular weight degradation on heating. Self-extinguishing in a fire with a limiting oxygen index (LOI) value of 28, the minimum for self-extinguishing behaviour
<b>Polyetherimide (thermoplastic)</b>	Good UV resistance and weatherability. Low moisture absorptivity and good hot water resistance	Resistant to most hydrocarbons, alcohols, fully halogenated solvents, mineral acids, and mild alkali. It is susceptible to aromatic and partially halogenated solvents	High $T_g$ of 215–217 °C and a softening point of 219 °C. Self-extinguishing, with an LOI of 47
<b>Polyether ether ketone (PEEK) (thermoplastic)</b>	Not resistant to UV light and requires UV stabilisers for outdoor applications. Low moisture absorptivity of about 0.06–0.12%/24h and good hot water stability	High chemical stability to a spectrum of compounds, but are susceptible to concentrated anhydrous and strong oxidising agents	Melting point of 334 °C and a $T_g$ of 150 °C. High thermal stability and an LOI of 35, so they are inherently flame retardant

Table 8: Durability of common thermoset and thermoplastic resins<sup>104, 105</sup>

## 7.3.2 Enhancing performance

Different resin and fibre systems in combination show variable performance under operational conditions. To increase their performance and long-term durability, a range of additives are routinely combined with the resins and fibres during formulation. These additives improve impact and crack resistance by resin toughening, improve UV resistance, strengthen the matrix-fibre interaction, and improve resistance to fire events.

### 7.3.2.1 Toughening

When producing an advanced thermosetting resin system for demanding environments, such as aerospace, formulators often add materials that help to toughen the inherently brittle matrix.<sup>106</sup> Epoxy resins, for example, have low impact resistance and low crack initiation energy because of their high cross-link density. Without the addition of toughening agents, the use of epoxy in many demanding applications would be limited if accumulated damage led to significant structural failure. Various toughening strategies are possible, including the addition of rubber compounds, thermoplastics, rigid particles, block copolymers and hyperbranched and dendritic molecules.<sup>107</sup>

- **Rubber compounds:** Toughened epoxies have become the norm in high percentage composite airframes, such as the Boeing 787 Dreamliner and the Airbus A350 XWB.<sup>108,109</sup> They are formulated by the addition of either functionalised acrylonitrile-butadiene rubbers or the addition of core-shell rubber (CSR) particles.<sup>110</sup>
- **Thermoplastic toughener:** Thermoplastics such as polyether ether ketone (PEEK), polyether sulphone (PES), polystyrene (PS) and poly (methyl methacrylate) (PMMA) are common tougheners for epoxy and are dissolved in the resin before cure to produce finely dispersed thermoplastic regions throughout the matrix.<sup>111</sup> They overcome some of the limitations of rubber tougheners due to their high T<sub>g</sub>, high modulus, rigidity and ductility.<sup>112</sup>
- **Block copolymers:** Polymers such as poly(ethylene oxide)-poly(propylene oxide)-poly(ethylene oxide), or PEO-PPO-PEO, have one block miscible in the matrix and one immiscible. These self-assemble to form micelle-like structures, which are then fixed during cure.<sup>113</sup>
- **Rigid particle toughening:** Inorganic nanoparticles such as silica, alumina, nanoclays, carbon black, carbon nanotubes and graphene are added into the resin.<sup>114-119</sup> These particles are very small and must be dispersed finely enough to impart toughening mechanisms such as plastic deformation and crack deflection.

Many of the toughening mechanisms described above are from fossil-derived chemicals. For a more sustainable solution tougheners derived from bio-derived sources would be preferable. Advances in this area include the use of epoxidised vegetable oils from sources such as soyabeans and linseed, the development of bio-derived block copolymers, and the use of plant-based nanofillers such as nanocrystalline and nanofibrous cellulose.<sup>120,121,122</sup>

### 7.3.2.2 Weathering protection

For polymer systems exposed to UV light during use, stabilisers are often added to prevent photocatalytic breakdown. For carbon fibre composites, UV degradation is less of a problem, as the carbon fibres absorb UV light. For glass fibre composites there are two main methods:

- **UV absorbers:** these are additive molecules which absorb UV radiation as it penetrates the polymer matrix. Many UV absorbers are based around hydroxybenzophenones and benzotriazole. Although not effective at protecting the surface of a structure, they are a good solution for the bulk polymer.
- **UV stabilisers:** these molecules interact with the chain scission mechanism and prevent the propagation of polymer degradation. They are known as free radical scavengers. A widely used class of UV stabilisers are the Hindered Amine Light Stabiliser (HALS) compounds.

Similarly to tougheners, these additives are generally from fossil-derived sources. However, they are added in low amounts (typically 0.3–0.5% w/w) and there is some work looking into sustainable chemistries for this application. Plant flavonoids have been investigated as sustainable UV stabilisers and have been shown to inhibit both oxidation and UV degradation in polymers.<sup>123</sup>

### 7.3.2.3 Sizing for fibre matrix improvements

‘Sizing’ is a coating applied to the surface of fibres during the manufacturing process to protect the filaments during handling and processing, and to improve the adhesion between the fibre and the matrix. This results in better mechanical properties, chemical or water resistance, and thermal stability. Sizing agents are applied by the fibre manufacturers, but the chemistry is specific for each type.

- **Glass fibre sizings:** these have a general structure  $[X-Si(OR)_3]$ . The silane functionality binds strongly with the glass surface and the chemistry of the X group allows the agent to become involved in the resin cross-linking reaction, leading to a very strongly bound interfacial region.
- **Carbon fibre sizings:** these are physisorbed to the carbon fibre surface and improve the wetting of the fibres by the resin and may also have reactive functionality that cross-links with thermosetting resins to improve the strength of the fibre-resin interface. This is especially important for thermoplastic composites as there is no cross-linking reaction and they have higher viscosities.

Natural fibres have very hydrophilic surfaces which absorb moisture readily and this can affect the strength of the resin-fibre interaction negatively. Techniques exist to improve the smoothness and homogeneity of the natural fibre surfaces, make them less hydrophilic, improve the wetting properties of the resin on the fibres and promote cross-linking with the matrix.<sup>124</sup> These include:

- physical methods – corona and plasma treatment, UV irradiation, fibre beating and heat treatment
- chemical modification – treatment with alkali, silanes, acetylation, benzoylation, peroxides, malleated coupling agents, sodium chlorite, addition of acrylic functionality and acrylonitrile grafting, isocyanate, stearic acid, permanganate, triazine, oleoyl chloride and fungal treatments).

### 7.3.3 Coatings for composites

Coatings are used in many applications to improve the durability of fibre-reinforced composite systems.

They improve chemical resistance, increase thermal protection and resistance to fire, increase electrical conductivity and indicate possible damage to the substructure after impact.<sup>125,126</sup>

The environmental resistance challenges mentioned in the previous section imply a critical need for the successful adoption of more sustainable underlying materials such as bio-derived resins or natural fibres. It is likely that current fossil-derived coating systems will enable qualification of more sustainable materials (fibres/resins/adhesives) in the near term but also suggests a future opportunity for the realisation of more sustainable coating systems.

Structures such as wind turbine blades can suffer from leading edge erosion, where the combined effects of wind, dust and the impact of water droplets can lead to significant damage to the composite surface.<sup>127</sup> The resulting surface roughness increases the drag of the blade through the air making it less efficient. The pitting and microcracking at the leading edge also result in moisture uptake and microcracking, which could eventually lead to significant blade failure. The use of protective coatings in such applications can lead to the reduction of the leading-edge erosion and can significantly improve the lifetime of the composite blades.

### 7.3.3.1 Intumescent coatings

Intumescent coatings are multicomponent systems, containing polymeric binders, a charring agent, an acid source, a blowing agent, inorganic fillers and adjuvants. When heated to elevated temperatures the intumescent coatings build a multicellular char, typically accompanied by a dramatic increase in volume that insulates the underlying substrate. The heat insulation either prevents the substrate from reaching the pyrolysis temperature or reduces the pyrolysis rate.

They have been used mainly in construction to prevent steelwork from exceeding the critical temperature of 500 °C in the case of fire.<sup>128</sup> They are a potentially good option for composites as they remove the need for fire retardants in the substrate which can lead to performance reduction.

### 7.3.3.2 Protection of less durable sustainable materials

For an application where the underlying composite structure can be manufactured sustainably from a combination, such as a bio resin and a natural fibre, the use of a coating of a few microns in thickness over the surface of the composite to greatly improve the performance and durability is likely to be beneficial.

Gel coating has been used to improve the mechanical performance of a jute-epoxy composite system when exposed to varied acidic media.<sup>129</sup> However, the downside to using a different material on the surface of the composite could impact end of life: this layer may have to be removed to allow the composite to be recycled effectively, or to break down naturally.

## 7.3.4 Conclusion

Many of the performance enhancing mechanisms outlined in this section rely on standard fossil fuel sourced chemicals. A challenge to chemists and formulators is to find sustainable sources for such additives from bio-derived or recycled sources. Even if these additives cannot be substituted by sustainably sourced alternatives, their influence on the durability of composites can be quite dramatic even when the levels required are very low. The resulting increase in composite lifetime could result in a reduction in the amount of repair and replacement required.

Closer collaboration between chemists, material scientists and composite engineers could help in the development of functional materials that allow for damage detection to be assessed when it happens. Such systems include coatings that ‘bruise’ when a damage event occurs.<sup>20</sup> Another example is including aligned nanotube strain-sensing layers in a composite that can determine effects such as creep or tensile failure due to changes in electrical resistance.<sup>130</sup>



## 7.4 Reuse and repair

This section outlines the opportunities to repair and reuse composite parts and materials to extend their lifetime. The waste hierarchy prioritises both options over recycling to maximise the value of these materials. While the opportunities for chemistry may be less apparent in composite reuse and repair, research and development could accelerate the development of solutions which are currently at a low TRL in these fields.

**Table 15** within the Appendix summarises the workshop discussions within this section.

### 7.4.1 Introduction

If damage is detected, repairing parts is a sustainable way of extending the lifetime of composite parts in accordance with the waste hierarchy.

Since the aerospace industry has pioneered the large-scale use of composites, aircraft dominate the literature surrounding composite repair.<sup>131,132,133,134</sup> However, considerable research has also been applied to marine structures and could be equally applicable to other large composite structures where part replacement is either too costly or impractical, for example, wind turbines.<sup>135</sup>

The heterogeneity and anisotropy of FRPs, means their damage or failure behaviour is complex: the fibres, matrix, interface and their combinations can be damaged in myriad ways at multiple length scales from any single event. These include:

- **impacts** (collisions, dropped tools, etc.), the most common initiation mechanism, which can result in a complex combination of damage types. Figure 11 depicts surface puncturing, matrix microcracking, delamination, internal voids and fibre breakage
- **barely visible impact damage** (BVID), where much of the damage is invisible and leads to significant challenges in terms of damage detection<sup>136,137</sup>
- **manufacturing defects** (for example, porosity, fibre misalignment and microcracking from machining or shrinkage)<sup>138</sup>
- **environmental exposure.**<sup>139</sup>

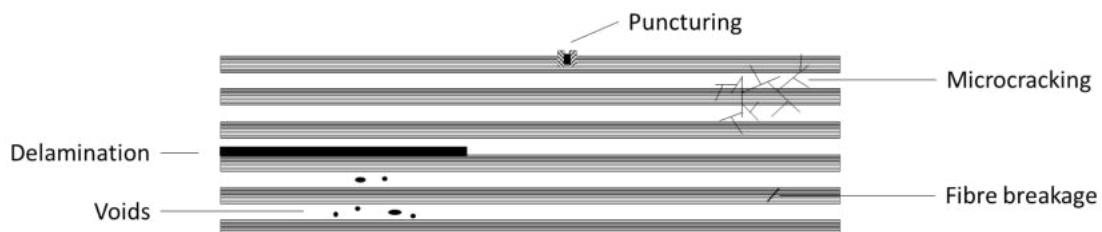


Figure 11: Common damage categories of FRPs<sup>140</sup>

## 7.4.2 Repair strategies

The objective of any structural repair is to restore the original mechanical performance and ideally restore any further functionality (such as aerodynamics).

### 7.4.2.1 Patches

Composite patches exist in a variety of forms. Scarf joints are often preferred for patch repair, since they result in a load distribution that is most true to the original structure. In addition, they also have the advantage that they tend to have a minimal effect on the aerodynamic profile.

Patching can be very effective in some cases fully restoring mechanical performance. Nevertheless, the most effective processes are expensive, particularly in terms of labour costs.<sup>132,135</sup>

### 7.4.2.2 Liquid resin injection

One of the most mature alternatives to patching is liquid resin injection.<sup>131,141,142</sup> This process involves injecting low viscosity resin into pre-drilled holes within a damaged area of composite and then curing it. Typically performed under vacuum, this facilitates both the closure of fracture surfaces and resin infiltration.

Although not entirely straightforward, resin injection is regarded to be simpler and cheaper than patching methods. It has most potential in the automotive sector where there is low energy impact and very little fibre is damaged.<sup>139</sup> In aerospace, there are strict certification protocols which currently preclude the widespread adoption of injection repairs.

### 7.4.2.3 Self-healing

Beyond resin injection, much of the modern research into alternative composite repair methods concerns ‘self-healing’ technology. Composites are ideal candidates for this concept because they are easily damaged, and their repair can be both complex and expensive. Table 9 highlights the main technologies that have been developed over the last two decades.

Classification	Extrinsic systems	Intrinsic systems
<b>Description</b>	The healing agent is typically sequestered from the main matrix, e.g. single or dual-microcapsule archetype. When broken, capsules release the healing agent into the damaged zone and self-heal by chemical reaction	A matrix additive (e.g. thermoplastic phase) or matrix dynamic chemistry (e.g. covalently adaptable network (CANs)/vitrimers)) allows the matrix itself to flow and repair cracks. Invariably, these systems require an external stimulus (usually heat) to initiate repair
<b>Examples</b>	A single microcapsule undergoes post-release and a catalyst, distributed throughout the matrix, initialises polymerisation. Ring-opening metathesis polymerisation (ROMP) of dicyclopentadiene with a Grubbs’ (Ru) catalyst is one of the leading technologies in this area since it is fast and efficient. Significant drawbacks to this approach include cost, toxicity and dispersion of the Ru catalyst, as well as the limited temperature tolerance of the system	Intrinsically healable polymers generally incorporate dynamic covalent chemistry (DCC) and are often defined as CANs, vitrimers (a subcategory of CANs) or dynamic covalent network polymers (DCNPs). The most common chemistries in this area are disulfides and the Diels-Alder (DA) reaction. Although a wide variety of functional chemistries exist, relatively few have been applied to make high-performance (healable) composites
	Dual microcapsule (MC) works by an appropriate hardener/catalyst entrained within separate capsules distributed alongside the monomer capsules throughout the matrix. These systems are usually based on epoxy/amine-hardener polymerisations or similar reactions and therefore tend to avoid the use of expensive metal catalysts. Encapsulation of these agents is often challenging, as is their disruption to fibre architecture and erosion of baseline mechanical performance <sup>143-147</sup>	Thermoplastics can melt, although this is more than 300 °C for engineering thermoplastics. Nonetheless, with adequate pressure, molten TPs can flow and therefore be repaired. However, the lack of cross-linking often makes TPs less stiff than thermosets, while also making them susceptible to solvents and prone to creep. In an attempt to infuse thermosets with self-healing characteristics, researchers have blended both miscible and immiscible thermoplastic/thermoset combinations

Table 9: Major classifications of self-healing technology

In most research it is implied that entire structures would be made of fully self-healing material. This is not necessarily the optimal approach since, by design, composite structures have known susceptible features that present an opportunity for more targeted application. Locations where matrix damage/delamination occurs are good targets, so self-healing material might be best applied to design features including section changes, ply drops, stringer run-outs, holes and joints.

Little self-healing research has been transitioned into real-world application. However, it remains an important strategy, alongside other repair approaches, in making composites more sustainable.

### 7.4.3 Reuse strategies

Reuse may be particularly valuable where composites are:

- continuous, with highly aligned fibres
- high value
- challenging to recycle efficiently.

However, the intrinsic material complexity of composites and the associated diversity of their applications means that composite reuse is fraught with challenges.

#### 7.4.3.1 Material identification

FRPs vary widely in terms of their constituents. Identifying polymers is already difficult but when combined with fibres, fillers, coatings and pigments in a complex waste stream, it can be extremely challenging. In most reuse applications it is unlikely that a mixture of unknown materials will give the desired properties. It is therefore crucial to be able to identify a composite efficiently.

With crosslinked (thermoset) polymers, which are common in composites, identification is particularly challenging, since insolubility precludes the use of many powerful chemical techniques (solution NMR spectroscopy, for example). Nevertheless, a range of techniques have been developed for such purposes, including FTIR spectroscopy and laser-induced breakdown spectroscopy.<sup>148</sup>

As design for end of life becomes increasingly important, it may be that composite manufacturers become better at digitally 'labelling' their parts. QR codes and RFID tags may not be the solution for engineering structures, but a similar digital identification method could be highly valuable for streamlining reuse as well as repair and recycling.

#### 7.4.3.2 Disassembly

Many reuse options involve using a part in a different application to its original purpose. Consequently, the disassembly of large, complex structures into the desired components is complicated by the range of bonding methodologies employed both at composite-composite and composite-metal joints.

To reduce machining burdens, designed disassembly may be beneficial when dealing with large composite structures at end of life. Modular structures comprising several smaller units attached together, either by reversible adhesives or mechanical joints that can be unfastened, gives engineers more flexibility when it comes to extending lifetime.<sup>149,150,151</sup>

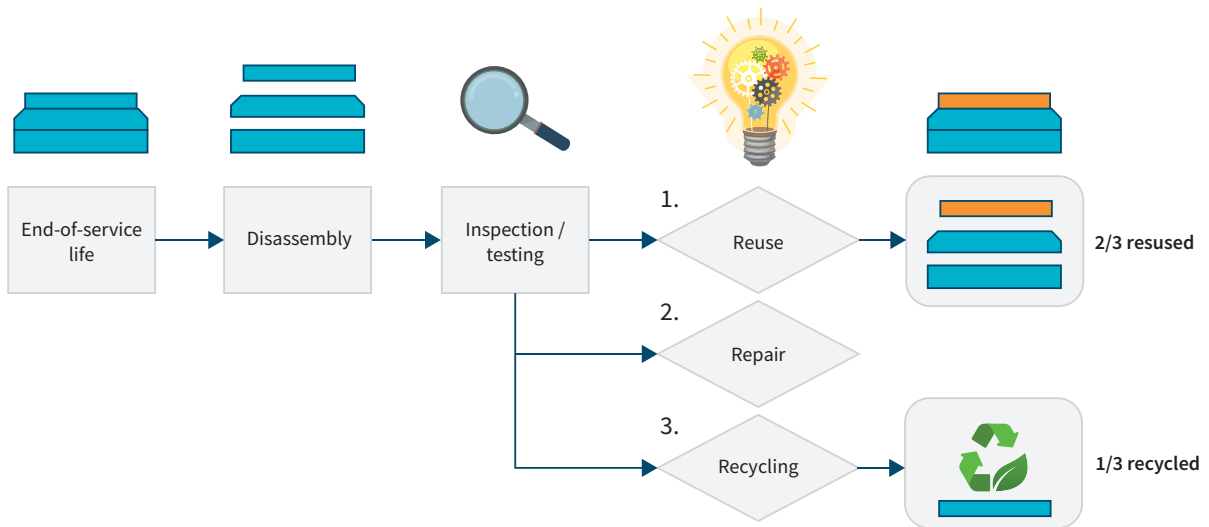


Figure 12: The repair, reuse and recycling of a modular composite structure. In this example, two subcomponents are viable for a second lifespan in the original application and one subcomponent is damaged beyond economical repair and is recycled.<sup>137</sup>

Figure 12 outlines an example of a large modular composite structure and its separation into its constituent subcomponents.

After its prescribed service life, each of these parts can be inspected and assessed for the most appropriate end-of-life treatment:

- components that remain in good condition can be reassembled into new iterations of the superstructure they were originally designed for
- damaged, defective, or otherwise worn parts can be assessed for repair viability or be fed into the most appropriate recycling process.

With appropriate requalification protocols, modular designs could facilitate direct structural reuse but there appears to be very few examples of this to date. As such, the use of modular design strategies could both extend composite service life and increase its circularity.

However, it should be noted that there are drawbacks to the use of modular composite structures such as the heterogeneity of FRPs, which makes the design and modelling of joints more complex and, crucially, fibre continuity; continuous fibre reinforcement usually gives the best mechanical performance (most effective load transfer).

### 7.4.3.3 Suitable application

The variety of different materials with different performance characteristics and volumes (both considering part sizes and number) means that a one-size-fits-all strategy is challenging to adopt. A bespoke, case-by-case basis is needed for reuse, which is possibly impractical outside of large-scale projects such as wind blade repurposing.

### 7.4.3.4 Qualification

Requalification relates to the testing and certification of repurposed or repaired structures. Many industries, notably aerospace, require strict certification of materials/structures prior to their application.

There is little, if any, literature concerning the recertification of reused or indeed recycled composite materials. With any significant change in material or change in application, some testing will be required to validate performance. As a minimum, composites intended for reuse in demanding loading conditions should be assessed by one or more NDT methods (ultrasonics, for example) to assess the presence of hidden damage.

To give manufacturers confidence in exploring reused composites, destructive testing of larger assembled components could be helpful. In the long term, extensive destructive testing of composites intended for reuse would clearly raise sustainability issues and so a significant amount of research is required to help validate end-of-life composite components.

## 7.4.4 Conclusion

Composite repair is dominated by patching techniques. Considerable research has been performed into exploring resin injection repair techniques, which can be effective. However, these techniques are only applied in limited circumstances due to certification. Self-healing has become a hot topic over the last 20 years but there are several significant challenges that are preventing wider adoption. These include:

- certification and validation
- localisation of treatment
- requirement for external stimuli
- erosion of baseline properties and performance
- cost.

All composite repair methods may benefit from modular design, which may make localised repairs more straightforward and more easily characterised. Structural health monitoring, outlined in [Section 7.7](#), could also benefit all composite repair methods by better informing engineers as to when and where repairs should be affected. Chemical knowledge, techniques and research applied to developing easily repairable engineering polymers, and creating new ‘self-healing’, will accelerate the development of solutions in this field.

Reuse represents an important strategy for reducing the environmental impact of fibre-reinforced polymer composites. From a lifecycle perspective, reuse is generally preferential to recycling. Identification and requalification of composites remain significant challenges and are currently the subject of very little research.

Methods to streamline composite identification, including using digital identification methods, could make end-of-life management of composites much easier. The testing and modelling of composite structures after their regular service life should be performed to give confidence to those who would reuse them in high-performance applications. These are outlined in [Section 7.7](#).

One of the major advantages of cutting down large composite structures, such as wind turbine blades for use in less demanding applications, is the reduced need for extensive (destructive) testing campaigns during their certification/requalification. Design for reuse by using reversible adhesives, modular design and other techniques may significantly increase the viability of composite reuse.

Composite reuse is a field in its infancy and would greatly benefit from more research and more businesses working to facilitate it. The relevance of chemistry to composite reuse is less obvious than recycling or repair. Nonetheless, there is a role for chemistry in enhancing methodologies surrounding polymer identification and developing/improving reversible adhesives.

## 7.5 Chemical recycling technologies

This section outlines chemical recycling techniques to enable the efficient recovery of materials from conventional composites. This includes composites that are already manufactured or will be manufactured soon. [Table 16](#) in the Appendix summarises the workshop discussions in this section.

### 7.5.1 Introduction

Composite materials present significant problems at end of life. As composites are made of at least two distinct materials, recycling techniques need to be capable of recovering multiple distinct materials. This makes their recycling more complex than conventional materials like plastic packaging and metals, leading to many composite parts ending in landfill. As the composite market grows so too does the problem of composite recycling. In the wind industry alone, it is estimated that, by 2050, 190,000 tonnes of carbon fibre-reinforced polymer (CFRP) waste will have been generated.<sup>152</sup>

Significant research has been carried out to assess and develop the capability to recycle composite materials.<sup>153-160</sup> This has largely been focused on the recovery of carbon fibre from FRPs, which is driven by economics. These economic drivers do not exist for the recovery of lower value fibres like glass or for the polymer matrix itself and therefore less progress has been made.

[Table 10](#) summarises the key processes used in composite recycling, which have been demonstrated, to some extent, at academic and commercial levels.



Recycling approach	Type	Material kept in supply chain?	Summary
<b>N/A</b>	Landfill/incineration	No	The majority of composites are currently placed in landfill due to the complexities of their recycling. This approach loses all the embedded energy and value of the material out of the supply chain
<b>Feedstock supply</b>	Cement kiln	No	Glass fibre composite waste may be used in cement kilns as both a fuel source to offset coal and a supply of raw material. This reduces the environmental impact of cement manufacturing if coal is offset, but material is still lost from the supply chain
<b>Mechanical</b>	Shredding/grinding	Polymer and fibre (downcycled)	A low energy technique widely used in other industries. Produces a downsized form of composite (typically shredded, granulated or powdered) for use as a filler or a low performance feedstock or aggregate. Both resin and fibre are downcycled and lose inherent value <sup>157</sup>
<b>Electrical</b>	High voltage fragmentation	Polymer and fibre (downcycled)	High voltage electrical pulses used to degrade the composite into fragments. As with mechanical recycling, the recyclate may be used in low value applications as a filler or aggregate
<b>Thermal</b>	Pyrolysis	Fibre only	Thermal decomposition of polymer at high temperatures (500–700 °C) ideally within an oxygen free atmosphere. Fibre may be reclaimed and (subject to post-processing to manage fibre surface contamination e.g. char, or oxidised material), reprocessed into a new composite. Some derivations of pyrolysis use the polymer as a source of fuel within the system
	Steam pyrolysis	Fibre only, potential for polymer	Polymer is removed by exposure to superheated steam under pressure. Optimisation of the process can be achieved through the addition of rapid compression and decompression cycles. The technology has the potential to produce reclaimed fibre with less char and surface damage than observed in pyrolysis. There is the potential, with future development, to capture the degraded polymer
	Fluidised bed pyrolysis	Fibre only	Composite material is fed into a bed of silica and hot air is blown over it. The sand abrades the resin which is then volatized and is removed in the gas stream. The technology has been optimised to reduce the amount of fibre damage and surface char when compared to standard pyrolysis
<b>Chemical</b>	Solvolytic	Fibre and polymer	Solvolytic uses a chemical solvent to degrade the resin and allow recovery of the fibre with minimal reduction in the mechanical performance of the fibre. By choosing the right conditions the resin can be reprocessed back into reusable chemicals <sup>157</sup>

Table 10: Summary of composite recycling techniques

## 7.5.2 Chemical recycling

It is widely acknowledged that a range of recycling approaches will be needed. However, this section focuses only on chemical recycling as part of the overall solution for end of life.

Chemical recycling processes, such as solvolysis and thermolysis, provide the opportunity to recover fibres with minimal performance drop as well as collect the resin for reuse. Solvolysis, in particular, gives an opportunity for the recovery of resin and its reuse in the supply chain. The process uses the solvating power of a liquid, often combined with elevated pressure and temperature, to degrade any resin present and expose the fibres for reclamation. The temperature required is lower than pyrolysis so fibres can be recovered with minimal mechanical performance loss and no char residue. The approaches can broadly be split into two categories:<sup>162</sup>

- **supercritical solvolysis** – this requires high temperature and pressure in the recycling chamber to hold the solvent as a supercritical fluid. Supercritical solvents have an increased solvation strength and a low viscosity so can be used to degrade chemically durable thermosets
- **subcritical solvolysis** – uses lower temperature and pressure but generally requires harsher chemicals to compensate for the lower energy system.

There is an inherent need for solvolysis to be specific to the type of waste being fed into the process. This is because conditions required to degrade a thermoplastic such as polypropylene will be different to those required to degrade a thermoset like an epoxy. Even between two thermosets different solvents and operating conditions will be needed due to the different chemical bonds present.

## 7.5.3 Key resin types

Unlike other techniques, solvolysis offers the possibility of recovering the resin into a usable chemical. Depending on the resin this could be depolymerisation back to its original monomer form or controlled degradation into a platform chemical to be fed into another chemical supply chain. For solvolysis to be successful the chemistry of the composite waste needs to be well known so optimal conditions can be selected.

The following section describes promising examples of solvolysis for key resin types and the limitations of current research.

### 7.5.3.1 Thermosets

Epoxy resins provide a challenge for solvolysis. There are few chemical bonds that are easy to target for degradation. Academic work has shown that the carbon-nitrogen bonds present in amine cured epoxy resins can be targeted to break the cross-linking formed during the cure process.<sup>163-165</sup> Both these examples would enable fibre recovery with minimal loss of performance but recovering any value from the solvated resin would be challenging because they produce a complex mix of aniline-based chemicals. Solvolysis has also been demonstrated for anhydride cured systems.<sup>166</sup>

Polyester resins provide a more obvious route for solvolysis through the readily hydrolysed ester linkage. This is a common chemical linker, which is present in other polymers such as polyethylene terephthalate (PET) and polylactic acid (PLA). As such, the chemical cleavage of polyester bonds has been widely studied.<sup>167-169</sup> Polyesters can be broken down through hydrolysis, methanolysis, glycolysis, aminolysis and ammonolysis, providing multiple strategies for their chemical recycling.<sup>29</sup>

Researchers have shown progress in this area using supercritical ethanol and 1-propanol followed by heated acetone to achieve 100% resin elimination. In this example, clean fibres were recovered and GC-MS identified that short chain esters were formed from the resin, rather than degradation into its monomers. This would prevent the recovered chemicals being fed directly back into the unsaturated polyester supply chain but could present a valuable route into other supply chains.<sup>170</sup>

Another approach demonstrated solvolysis of unsaturated polyester resins with an acetone/water mix.<sup>171</sup> Mass spectrometry identified solvolysis products as phthalic acid and dipropylene glycol monomers as well as a secondary reaction product, isophorone. This example also demonstrates the possibility of recovering value from the resin itself.

### 7.5.3.2 Thermoplastics

Thermoplastics can be treated differently to thermosets. This is because they have not formed irreversible bonds during their cure cycle, so they can usually be solvated with an appropriate solvent to enable separation of the original polymer and in some cases can be depolymerised back to the original monomer either thermally or with appropriate chemical treatment. Two examples of research in this area are:

- **polypropylene** – used in the packaging industry, polypropylene has seen considerable interest in its recycling. While not all learnings can be applied, it provides a knowledge base for the composites industry. Researchers have shown resin and fibre recovery using a xylene/acetone mix with no loss in mechanical behaviour over multiple recycling loops. They did see some evidence of matrix degradation through molecule weight analysis, but this did not affect performance<sup>172</sup>
- **polyamide** – there are many types of polyamide but the approach to their chemical recycling is largely universal as the amide bond common to them all is the best target for chemical attack. They can be degraded by hydrolysis, ammonolysis and glycolysis.<sup>173</sup>

### 7.5.4 Conclusion

Composites are an integral part of the global strategy to achieve net zero, especially through the implementation of green technologies like hydrogen and wind. Therefore, it is problematic if this enabling green technology has a global recycling rate of only 2%.<sup>2</sup> With the EU taking action to limit the import of foreign waste, the UK cannot guarantee that exporting waste is a viable option.<sup>174</sup> To increase the uptake of composite recycling it must become economically viable, which could be through increased penalties for non-recycling disposal strategies (i.e. legislation) or by ensuring the products recovered are of significant value.

The cost of carbon fibre manufacture is prohibitive to the success of the industry and investment is needed to develop new mechanical recycling methods which are more cost effective.<sup>2</sup>

Chemical recycling techniques are needed alongside mechanical processes to:

- minimise the damage of recovered fibres and the corresponding reduction in mechanical strength while retaining length and alignment
- efficiently and selectively process resins into reusable chemicals to be fed back into the supply chain.

Chemical recycling technologies show promise alongside other technologies to create a supply chain for the recycled material. However, there are several challenges to achieving this.

### **Resin recovery**

The composite industry uses a range of different resin types, each with different chemistries: an aerospace grade epoxy resin has a very different chemistry to a polypropylene composite. This presents a challenge. Either recycling techniques need to be developed for each resin chemistry or the recycling techniques need to be generic and able to handle multiple different resin types.

Standard analysis methods can be deployed to analyse the recovered resin to ensure it is at a suitable purity level for reintroduction to the supply chain. This is an important step to demonstrate that any reclaimed chemicals can match the value and performance of virgin materials.

### **Fibre recovery**

Most recycling techniques require a shredding stage so non-aligned short fibres are recovered. During the recycling process any chemical treatment that was applied to the surface of the fibres at manufacture will be removed. Without retreatment the fibres may not form a strong interface when used in further manufacturing. This topic has been explored to some degree, but further work is needed to develop standard methods for the resizing of fibres.<sup>175,176</sup>

### **Waste streams**

The range of combined materials used in a composite part complicates recycling processes. Waste streams either need to be stripped and sorted into clean waste streams or processes need to be capable of handling dirty waste streams. This is particularly challenging if pure feedstock chemicals are targeted from the recycling process.

Composites often have a coating applied to them that provides another layer of difficulty when recycling composites. Effective ways of removing coatings before recycling need to be developed.

For dirty waste streams, there is potential for material to be fed into a cracker process and simple platform chemicals produced. This is energy intensive and removes the inherent value built into the material so is the less desirable option but still viable within a circular economy.

## Material identification

Like the concepts outlined in [Section 7.4.3](#), a common problem preventing recycling is understanding the chemical makeup materials at the end of their life. Composites often have a long lifetime and the materials used in their manufacture may not have been accurately logged as it passed along the supply chain.

Without knowing the chemistry of the matrix, it is not possible for waste handlers to design a recycling strategy. Increased collaboration and information are needed along the supply chain to ensure that composites manufactured today can be easily identified.

For those composites already manufactured sorting methodologies and analysis techniques need to be developed to identify the chemistry of the materials at end of life. This would likely use established analytical methods like infrared spectroscopy (IR), Raman spectroscopy and gas chromatography-mass spectrometry (GCMS).

For composite recycling to become the norm it needs to be commercially competitive with the current practice of purchasing virgin material and disposing at end of life.

The cost of non-circular disposal of composite parts is likely to get more expensive as society is becoming increasingly aware of the importance of recycling. Landfill tax in the UK is currently £98.60 per tonne and is only likely to increase, creating a significant financial burden for the composite industry.

If recycling techniques can also be scaled up and reliable supply chains can be formed there is the potential to unlock large amounts of value from the raw materials embedded in composite waste.

A better understanding of which chemical recycling techniques to apply to which composite types could highlight the standard approach for each composite class, adding great value to the industry. Likewise, an overview of the chemicals that can be recovered from chemical recycling and their value to the wider supply chain would help define the direction in which the chemical recycling of composites should take.

## 7.6 Inherently recyclable materials (designed for recycling)

Chemical recycling is not always possible and for next-generation composites there is an opportunity to develop new materials which are inherently recyclable at end of life. This section discusses opportunities to develop new materials that match the performance of conventional composite materials but have a mechanism for materials recovery at end of life.

### 7.6.1 Triggered degradation thermosets

In an alternative approach to the vitrimers previously discussed, thermosets have been synthesised and studied where degradation of the network could be triggered by various means. Below, are some examples.

**Diels-Alder linkages:** Diels-Alder (DA) adduct is stable under ambient conditions, but the crosslinked network is depolymerised at high temperatures and restored upon cooling. Recyclable thermosets and thermoset composites have been reported using DA linkages, but extensive monomer and oligomer synthesis is required to prepare them.<sup>177,178</sup> For example, DA and furan (or maleimide) groups need to be introduced into the structure of the monomers and oligomers. Cross-linking is achieved through maleimide (or furan) derivatives with multifunctional groups.<sup>179-181</sup> Recyclable thermosets containing DA structures within polyurethane and epoxy resins have also been reported.<sup>182</sup> The reversibility of the DA chemistry under relatively mild conditions without catalyst or solvent has enabled the reprocessing and recovering of thermosets but their practical applications is concluded to be limited due to their extensive synthetic complexity and corresponding high cost.

**Imine bonds:** The imine bond has been used as a dynamic exchange bond in the preparation of thermosets.<sup>183</sup> The exchange reactions have been reported to occur under relatively mild conditions, but it is influenced by external stimuli such as solvent, pH and temperature changes. The physical properties of malleable and recyclable thermosets can be tuned by varying imine bonds, diamine monomers, degree of cross-linking, solvent and monomer concentration.<sup>184-190</sup>

Embedding imine bonds into epoxy crosslinked networks has been reported to enable good reprocessability with comparable properties to conventional high-performance thermosets.<sup>191</sup> By acid-aided hydrolysis of the imine linkages, reshaping and repairing thermosets has also been achieved but, so far, with unsatisfactory mechanical and thermal properties. In addition, the long-term hydrolytic stability of polyimines in environmental conditions could be a major concern that needs further review.

**Disulfide bonds:** Disulfide bonds are weak dynamic covalent bonds. Thiol/disulfide exchange reactions have been used for the preparation of recyclable thermosets.<sup>192</sup> Fully cured epoxy networks containing disulfide linkage could be ruptured by reduction and re-established by oxidation under mild conditions.<sup>193-195</sup>

**Bio-based epoxy vitrimers:** Conventional epoxy thermosets are commonly constructed by petroleum-based resources. Researchers have also investigated thermosets containing bio-based vitrimers derived from renewable resources such as furan, lignin, vanillin and vegetable oils. They have demonstrated their degradability in the presence of catalysts, acids or bases.<sup>179,194-223</sup>

A bio-based epoxy vitrimer with dynamic Schiff base groups was synthesised from epoxidised soybean oil, vanillin, and 4-aminophenol. When combined with carbon fibre, it was reported to exhibit composite with good mechanical strength. Researchers demonstrated recyclability by deconstruction of the network by acid induced dissociation of the Schiff base linkage.

### 7.6.2 Vitrimers

Vitrimer development is one approach that the composites industry could adopt for developing inherently recyclable materials. They are crosslinked networks containing dynamic covalent bonds, known as covalent adaptive networks (CANs). Such polymer networks have been shown to be processable or recyclable through exchange reaction of the dynamic covalent bonds.<sup>194,224-240</sup>

Other researchers have created vitrimers by introducing dynamic covalent bonds into a cross-linked polymer network to transform thermosets into recyclable material.<sup>223,227,241-247</sup> Dynamic bonds have been shown to exhibit the ability to break/reform and reshuffle either autonomously or upon a suitable stimulus. This enables composites with properties such as shape-memory, self-healing, recyclability, weldability, malleability, and (re) processability.<sup>232,248-251</sup>

Epoxy thermosets used to produce high-performance composites cannot generally be repaired or recycled. One example of a vitrimer-based alternative is a fully recyclable epoxy based CFRP comprising diglycidyl ether of bisphenol A (DGEBA), fatty acid linker and Zinc catalysts.<sup>252</sup> Their repair or recycling can be achieved by dissolving in ethylene glycol (EG) at elevated temperature. Bond exchange reactions within the CAN break the long polymer chains into small segments via transesterification reaction. The carbon fibres and epoxy matrix were repolymerised into a new composite, proving almost 100% recyclability. However, it should be noted that their method has only been tried on a small scale.

Another example of vitrimer chemistry is glass and carbon fibre-reinforced dynamic epoxy system prepared by diglycidyl ether of bisphenol A (DGEBA) and aminophenyl disulfide (AFD).<sup>223</sup> Short fibres were obtained from mechanical recycling which was more suited to non-structural applications. Some publications address the topic of recycling vitrimer FRP and report that it is possible on a small scale with minor losses in the mechanical properties.

<sup>241,253,254</sup>

### 7.6.3 Conclusion

Several viable routes to triggered degradation thermosets have been identified and could offer routes to more easily degraded polymer matrix structures at acceptable cost. Crucially, these chemistries will need to be designed with industrially viable chemical recycling technology in mind and the associated separation processes.

Vitrimers are another longer-term option which could offer benefits in allowing different options for reusing materials (reforming, for example), but current approaches look costly in materials makeup and face market adoption challenges associated with their unusual properties. For incorporation in chemical recycling, vitrimers typically require a mechanical process of abrasive grinding followed by compression moulding of the powdered binder above its vitrimeric transition temperature. In a fibre-reinforced composite, such a grinding action would result in complete reduction of fibre length, and therefore limit the materials' potential for reuse as cheap composite fillers, rather than a replacement for virgin fibres.<sup>16</sup> Therefore, it is important to improve the recycling efficiency of these high-performance epoxy vitrimer materials for industrial applications where high volume production is involved.<sup>250,255</sup>

## 7.7 Underpinning tools

Alongside the trends discussed in the previous sections there are several chemistry-based tools and approaches that will enable the progression towards more sustainable composites. Analytical techniques, accelerated and real-time tests, predictive modelling and digital tools outlined in this section underpin the concepts already discussed, in particular:

- new materials design and development for low carbon feedstocks and inherently recyclable materials
- material degradation detection and damage assessment for repair and reuse qualification
- verifying durability and performance prediction for enhancing composite lifetimes
- material identification for end-of-life processing.

### 7.7.1 Verifying durability

When designing and manufacturing composite systems, verifying their durability is key to predicting their performance over very long timeframes. However, FRPs have only been used for a few decades and long-time performance data is not available. Verifying durability underpins the concepts outlined in [Section 7.3](#), Increasing composite lifetime.

Currently, material durability assessments are done using a combination of real-time testing, accelerated testing and modelling. The National Physics Laboratory has published a comprehensive report into the current methods for testing and predicting durability of composites.<sup>256</sup> [Table 11](#) outlines several ISO and ASTM standards for the accelerated testing of polymers and composites that are readily used to predict durability under different environmental stimuli.



Source of degradation	Test method
<p>Liquid absorption: Characterisation of liquid absorption in polymers and composites</p> <p>Standard: ISO 62 or ASTM D570 or ASTM D5229</p>	<p>Immersion of coupons of standard dimensions in test liquids (aqueous and non-aqueous) at a constant temperature. The change in mass of the samples is determined over a set time period. The results can be plotted as an absorption curve from which the time to saturation can be determined. The conditioned coupons can then be tested thermally or mechanically to determine the knockdown effects on the material properties resulting from exposure to the liquids</p>
<p>Thermal stability: Evaluating the thermal endurance properties of plastics exposed to elevated temperature for long periods</p> <p>Standard: ISO 2578</p>	<p>Based solely on the change in certain properties resulting from a period of exposure to elevated temperature. The sample is returned to ambient temperature after conditioning before the property of interest (e.g. tensile strength) is determined</p>
<p>UV irradiation: UV radiation exposure to simulate the effect of exposure to sunlight</p> <p>Standard (natural exposure): ASTM D1435-20 ASTM G24-21 ASTM D4364</p> <p>(Accelerated exposure): ISO 4892: part 3 or ASTM D4329-21 ISO 4892: part 2 or ASTM D2565-16 ISO 4892: part 4 or ASTM D1499-13v ASTM D2990-17</p>	<p>Materials can be conditioned at sites where there is extended daylight hours and a high UV index (e.g. the Middle East or the southwestern states of the USA)</p> <p>Materials are conditioned in a controlled chamber environment under artificial light</p>
<p>Creep: The time dependent change in strain due to a constant applied stress over a set period. In composites, creep is a polymer matrix dominated phenomenon. Thermoplastics generally exhibit more creep behaviour than thermosets due to their reduced cross-linking</p> <p>Standard: ISO 899-1:2017</p>	<p>Measured under specified environmental conditions, primarily temperature and humidity</p> <p>A method for determining tensile and flexural creep under specified conditions. The method is suitable for use with rigid and semi-rigid, non-reinforced, filled and fibre-reinforced plastics</p>
<p>Biological attack: Resistance to bacterial and fungal attack</p> <p>Standard: ISO 846</p>	<p>This method assesses the resistance of plastics to bacterial and fungal attack under controlled environmental conditions</p>
<p>Environmental stress cracking (ESC): Complex phenomenon involving mechanisms such as liquid diffusion, crack development and craze formation. Thermosets are more susceptible to ESC than thermoplastics. Once a liquid diffuses into a polymer, it promotes cracking and crazing at sites of stress concentrations</p>	<p>Moderate applied stresses can accelerate the effect, and many of the tests for ESC involve putting samples under an applied stress, either as a constant deformation or a constant load. The chemical resistance of the polymer to the diffusing liquid is of vital importance, as are the environmental conditions to which the system is exposed</p>

**Table 11: Overview of standards used for accelerated testing of polymers and composites**

Models can be used to describe the effect of stimuli on the breakdown of polymeric materials. Data from the tests described in [Table 11](#) have been used to predict the service lifetime of many composite systems when exposed to temperatures, moisture, applied loads and UV weathering. These models are not without their difficulties, and often multiple factors combine to produce effects that cannot easily be predicted.

Further development in this field by the chemistry community is important to the concepts outlined in [Section 7.3](#). Improving accelerated testing methods and predictive models would ensure better prediction of composite performance and service life.

### 7.7.2 Detecting damage and material degradation

Assessing the in-service material degradation of composite systems is important for understanding the evolving structural health of the composite and the lifetime of the application. This is key for making decisions about repair and reuse and requalifying composite parts in secondary applications, outlined in [Section 7.4](#). There are many established techniques for assessing damage and degradation in composites, which include:

- thermomechanical testing of aged coupons to look at knockdown in strength and thermal performance
- microscopy (both optical and electron) to look at microcracking and void development
- X-ray CT scanning to look at defects through a whole structure and spectroscopic methods (FTIR, NIR, MALDI-TOF mass spec) to look at chemical changes in the material.

These methods require samples to be taken and tested to failure in a laboratory, or specimens to be aged alongside the component in-service. A range of non-destructive test methods can also be employed to assess the nature of the composite including ultrasonic testing, Eddy current testing, acoustic emission testing, thermography, shearography and visual inspection.

**Structural health monitoring involves the observation and analysis of a system over time using periodically sampled measurements that report the integrity of a structure. It can be used to monitor changes in material and geometric properties of engineering structures and has been applied across numerous sectors including aerospace, energy, defence, and civil infrastructure. Methods are being developed to monitor large structures (for example, bridges, buildings, aircraft) in service without removing them from service.**

These methods use techniques such as acoustic emission testing and strain gauging to do this. However, there are many challenges involved in structural health monitoring and it is a complex field of investigation. Developing chemistry approaches alongside reuse and repair strategies could considerably extend the lifetime of composites.

### 7.7.3 Digital tools

Established digital and data science techniques combined with the high-throughput synthesis of molecules and formulations, analysis and characterisation, and process monitoring, are becoming increasingly important to the chemistry-using industries which directly impacts innovation in the composites sector.

The chemical industry has highlighted the importance of these digital technologies in a Chemical Industries Association report from 2021.<sup>257</sup> Applications span open-architecture IT platforms employing artificial intelligence (AI) to drive drug discovery and catalyst development, as well as data-driven process modelling, improvements and cost reductions in polymer processing.

Wider advances in applying digital technologies to chemistry will positively impact all aspects of the development and commercialisation of more sustainable composite materials. Specific priorities for the chemicals sector include supply chain digitisation (for example, the implementation of blockchain), prototype materials and formulation databases, the use of big data, digital design tools and workforce upskilling.

These have direct relevance to the Industry 4.0 challenges identified by the composites sector and beyond, to Industry 5.0: the formation of a sustainable, human-centric and resilient European industry. Some tools are already being implemented in national industry programmes.<sup>258</sup> These tools include the accelerated development of:

- formulated resins through advanced robotics and digital design
- multiscale modelling and digital twins to enable predictive models to de-risk and optimise the scale up of new formulations
- new approaches to LCA on chemicals and processes.

Such state-of-the-art modelling techniques are being applied to the coatings industry. They are also enabling data driven investigations into the properties of materials. This is crucial in identifying alternatives to improve sustainability, supply and safety issues in the chemical industry.

#### 7.7.4 Environmental impact data

As net zero and decarbonisation have taken over as the key drivers for industry, global warming potential or CO<sub>2</sub>eq (carbon dioxide equivalent) has become a key metric by which products and designs are selected and developed. There is an absence of training, tools and underpinning data for existing materials, preventing their entry into new markets.

This presents a significant opportunity for the chemistry community to ensure that the relevant underpinning data is quantified and developed alongside any new material systems. This would increase their competitiveness and acceptance in new markets and ensure their environmental impact is measured and transparent from the very beginning.<sup>259</sup>

To increase the uptake or consideration of new sustainable chemistries in the supply chain, the composites sector should:

- ensure comparability with existing systems: to allow for systems to be treated as drop-in replacements with reduced levels of qualification and redesign
- demonstrate significant advantages in the material (for example, performance or functionally based), that warrant the cost of qualification
- share data on the material systems, particularly life cycle assessment and durability data, which is seeing increasing priority by designers when selecting a material and is typically not available or is hidden, even for traditional and established composite materials
- use digital predictive methods to reduce the amount of physical testing and cost associated with adopting new materials, as already noted above.

# 8 Opportunities

**Chemistry as a discipline underpins several elements of a composite. It therefore offers the composites supply chain many opportunities to move towards more sustainable practices in the production, use, and end-of-life strategies of composites.**

We have identified six themes for the chemistry and composites community to consider to improve the sustainability of composites. **Section 11** also contains case studies to highlight solutions that are already being developed within the supply chain.





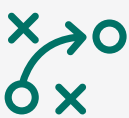
### Integrating with the bioeconomy

The transition away from petrochemicals towards bio-derived sources of carbon presents opportunities for the composite industry. Drop-in bio-derived replacements could be developed that match the performance of resins, fibres and other constituents derived from petrochemical feedstocks. The industry could also adopt new chemistries made available from bio-derived sources to enhance performance.



### Adopting waste and circular economy approaches

As supply chains develop strategies to decarbonise, the composites industry can adopt waste and circular economy approaches to produce sustainable composite materials. This includes maturing chemical recycling techniques for composites and other polymeric materials and using chemistry to lower the carbon content of synthetic routes to common composite materials.



### Designing end-of-life strategies

As new composites come onto the market, chemistry can contribute to the design of end-of-life strategies involving improved chemical recycling techniques linked with materials design concepts (for example, triggered degradation and vitrimers). It can also be applied in repair and reuse technologies. In particular, chemical and materials science has a significant role to play in matching materials sets for recycling with appropriate processing conditions to ensure energy efficiency, high yield and minimal damage in recovered materials.



### Improving the energy efficiency of composites manufacture

As reducing energy consumption becomes more important in manufacturing, chemistry can, for example, be used to develop lower temperature cure systems and systems based on non-thermally activated mechanisms.



### Adopting digital and computational chemistry approaches

By harnessing the power of digital and computational chemistry approaches, the composites industry can better design new materials, predict performance, and more rapidly bring new solutions to market.



### Government policy agenda for sustainable materials

All the opportunities explored require broad support from government agencies through a UK advanced materials strategy and funding for chemistry related research for the composites industry.




We have combined the insights from industrial and academic workshops, desk research and sector knowledge to identify 19 chemistry focused opportunities that could enable the development of sustainable solutions that benefit the composites sector as a whole. [Table 12](#) provides details of collaborative activities that could be adopted to enable the development and implementation of sustainable solutions across the supply chain.

Theme	Opportunity	Driver and barriers	Actors	Approach and impact
	Exploiting the growth of platform chemicals produced from bio-derived carbon in the wider supply chain	<p><b>Driver:</b> Market demand for sustainable materials with reduced embodied carbon</p> <p><b>Barrier:</b> Cost of change moving to a more sustainable materials supply chain</p>	<p>Biomass industrial groups</p> <p>Material formulators</p> <p>Chemical producers</p>	A clearer understanding of the key bio-based platform chemicals required for composite formulation would enable better integration with UK bioeconomy investments and links with the wider chemicals supply chain. Further efforts in this area would ultimately enable formulators to select bio-based chemicals over petrochemicals reliably, which would in turn grow the UK supply chain and increase supply chain security
	Exploiting bio-based materials to achieve superior performance, e.g. bio-based benzoxazines with superior properties to petrochemical	<p><b>Driver:</b> Bio-based materials reduce embodied carbon and their ability to offer superior performance</p> <p><b>Barrier:</b> Cost versus the need for change. Generally lower performance compared to petrochemically sourced materials</p>	<p>Academic researchers</p> <p>Material formulators</p> <p>OEMs</p>	Identifying composite relevant chemistries for bio-based materials would enable the development of promising novel bio-derived resins and fibre candidates for scale up and process optimisation. Parallel life cycle assessment would ensure that candidates offer superior sustainability benefits over petrochemical feedstocks. Further demonstration of sector relevance would ensure that materials are developed with high enough TRL for commercialisation alongside accessible and credible environmental data. This could result in novel bio-materials reaching the market, enabling key sectors to reduce the embodied carbon of composite products
	Establishing bio-based polyacrylonitrile (PAN) for the production of carbon fibre	<p><b>Driver:</b> Increasing demand and market growth for carbon fibre driven by technical requirements of hydrogen and wind industries</p> <p><b>Barrier:</b> Low maturity of bio-based PAN production options</p>	<p>Hydrogen and wind industries</p> <p>Carbon fibre manufacturers</p>	Development is needed to demonstrate the scale up potential of various non-PAN bio-based production options. In parallel, performance and life cycle assessment of different options would provide accessible and credible environmental data. These would provide a robust starting point for developing a business case for the scale up of bio-based PAN that will meet carbon fibre demand in the UK. Accessible and credible environmental data would also allow qualification and performance benchmarking that would de-risk industry adoption of alternative lower GWP PAN for carbon fibre production. Ultimately, reduction in embodied carbon of products needed for net zero

Table 12: Summary of chemistry-specific opportunities within six key themes





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Table 12: continued

	<p>Polyfurfuryl alcohol resins with their chemistry modified to improve processability and enable wider adoption of the technology</p>	<p><b>Driver:</b> Low embodied carbon replacements needed for phenolic resins with similar FST properties</p> <p><b>Barrier:</b> Water release during reaction currently limits the material to high cost processing routes</p>	<p>Academic researchers</p> <p>Material formulators</p>	<p>Developing a range of techniques to manage PFA cure is needed to address this challenge. A proven manufacture technique for PFA resins that is FST performance verified would enable the replacement of phenolic resins with a bio alternative, significantly reducing the embodied carbon of products required for fire retardancy. Further development to produce parts relevant to key industries (C&amp;I, aero) would demonstrate scalability and enable FST testing</p>
	<p>Composites applications for bio-based polymers developed for other applications e.g. PLAs being produced for packaging which match the performance of polypropylene</p>	<p><b>Driver:</b> Market demand for sustainable materials with reduced embodied emissions</p> <p><b>Barrier:</b> Materials developed in other sectors such as packaging have lower performance requirements</p>	<p>Plastics industry bodies</p> <p>Academic researchers (polymers)</p>	<p>Identifying relevant candidates from composites applications for bio-based polymers in other applications could enable the development of screening projects to test promising materials. Developing a database of candidate materials including the test data could ultimately develop new links with material suppliers and facilitate more awareness of bio-based polymers to composite designers. This could stimulate engagement from new companies in the composites supply chain and develop commercially available bio-based materials used in manufacturing</p>
	<p>Sizing development for natural fibres to improve performance and reduce variability in processing and performance</p>	<p><b>Driver:</b> Cost and low embodied carbon of natural fibres can contribute to decarbonisation and growth of the composites sector</p>	<p>Fibre suppliers</p> <p>Agricultural experts</p> <p>Academic researchers</p>	<p>Research into natural fibre sizing to remove inherent barriers of natural fibres and scale up of promising solutions would enable natural fibre composite manufacture. Producing demonstrator manufactured parts and conducting testing would enable the development of sizing chemistry for natural fibres and further development at a commercial level. De-risking natural fibre for the industry would ultimately reduce the use of fibre with high embodied energy for the entire sector</p>

continued &gt;





Table 12: continued

	<p>Use of waste materials as feedstock for the manufacture of the chemicals needed by the composites industry e.g. chemical transformations of waste materials to building blocks for resins for composites</p>	<p><b>Driver:</b> Market demand for materials with reduced embodied emissions</p> <p><b>Barrier:</b> Competition for feedstocks with other markets and the availability of materials at scale</p>	<p>Academic researchers</p> <p>Industry OEM T1 manufacturers</p> <p>High CO<sub>2</sub> producing sectors (e.g. glass, steel, cement)</p>	<p>Work is needed across sectors and industries to create demand for key feedstocks. Further links with chemical search engines and trade bodies would raise awareness of the potential use of waste materials as feedstocks for manufacturing chemicals for the composites industry</p> <p>When demand is created a business case would be developed to establish low carbon feedstocks to create key materials for the composites industry. Ultimately, a low carbon supply chain would be established</p>
	<p>Identification of valuable products from chemical recycling and the opportunities raised</p>	<p><b>Driver:</b> Market demand for materials with reduced embodied emissions</p>	<p>Chemical manufacturers</p> <p>Academic researchers</p>	<p>A study is required to determine the market volumes of composites and the wider chemical sector to identify value from chemical recycling outputs. When demand is created a business case would be developed to establish valuable products from the chemical recycling of composites. Ultimately, a low carbon supply chain would be established</p>
	<p>Low carbon route to bisphenol A (BisA) and/or low carbon replacement for BisA based materials</p>	<p><b>Driver:</b> BisA is a key raw material for high-performance composites with no current cost-effective route to decarbonisation</p> <p><b>Barrier:</b> Alternates to Bis A do not offer cost/performance equivalence</p>	<p>Academic researchers</p> <p>Manufacturers</p>	<p>Increased research into alternative drop-in replacements for BisA would enable further development and scale up of low carbon routes. This would ultimately deliver cost-effective solutions for lowering the carbon content of epoxy based composites without sacrificing performance, further fuelling a low carbon supply chain</p>
	<p>Chemical recycling improvements to recover matrix into usable form</p>	<p><b>Driver:</b> reduction needed in the quantity of composite waste at EOL</p>	<p>Plastics and packaging industry</p>	<p>Conducting a technoeconomic study to show promising approaches for chemical recycling would scale up the development of solutions. Developing processes to recover chemicals from recycling processes would accelerate the demonstration of material recovery and best practice for different composite materials. This would ultimately lead to increased recycled feedstock for use in the supply chain and reduction in non-recoverable composite waste at end of life</p>

continued >







Table 12: continued

	Fibres recovered with minimal mechanical performance loss through chemical recycling	<b>Driver:</b> Fibre recovery main driver of recycling due to inherent value. Minimising performance loss retains value	Recycling companies	<p>Improved chemical characterisation of reclaimed fibre (e.g. fibre surface as well as mechanical properties) would increase understanding of reclaimed fibre properties. Manufacturing with reclaimed fibre would also provide better understanding of processing needs.</p> <p>Conducting LCA of reclaimed fibre would produce reliable environmental data, ultimately de-risking its adoption and reducing the embodied carbon of products, as needed for net zero</p>
	Developing next-generation vitrimers	<b>Driver:</b> Recyclable FRP production <b>Barrier:</b> Low TRL, unproven. Availability of commercial materials	Academic researchers (polymers)  Material formulators  Recycling companies	<p>Reviewing solutions to identify the most industrially relevant vitrimer candidates would stimulate academic research towards the most viable candidates. Further development of demonstrator parts as well as showing fibre/matrix recovery would enable the development of candidates for scale up and commercialisation and appropriate recycling techniques. This would lead to the development of commercially available resins with easier recovery at end of life, further reducing the reduction of composite waste and lower GWP impact from recycling</p>
	Novel cure mechanisms for thermoset composites, e.g. technologies for wider adoption of UV triggered curing, technologies from adhesives	<b>Driver:</b> Energy required for curing is high for many resin systems  <b>Barrier:</b> Some solutions would require high CAPEX costs	Academic researchers (polymers, catalysis)  Material formulators  Manufacturers	<p>Research investigating novel cure mechanisms would identify new curing solutions that could be scaled up to a degree that manufacturing could be attempted. Developing a technological case for new curing mechanisms would enable industry to explore the transition to lower impact curing techniques</p>
	Additives/catalysts for low temperature curing	<b>Driver:</b> Low cure temperature reduces the energy consumption during manufacture  <b>Barrier:</b> Low cure systems currently produce resins with low $T_g$ and have challenges during processing (short pot life)	Academic researchers (polymers, catalysis)  Material formulators  Manufacturers	<p>Investigate the opportunities that known technologies/ approaches in related industries may provide for low temperature curing. Developing materials with lower temperature cure profiles and environmental data to show impact would enable the manufacture of composite parts with lower energy input. This would, ultimately reduce energy use during manufacture, lower GWP and cost</p>





continued &gt;

Table 12: continued

	<p>Chemical technologies to enable additive manufacture with composites and integration with other additive manufacturing processes</p>	<p><b>Driver:</b> More efficient processing especially for more complex parts</p>	<p>Manufacturers Thermoplastic suppliers</p>	<p>Review chemical technologies to establish a roadmap for developing materials for composite additive manufacture. This would drive further academic and industrial research, ultimately reducing the barriers to adopting low energy intensive manufacture techniques</p>
	<p>Accelerated chemical materials design and development using computational modelling and robotics</p>	<p><b>Driver:</b> Reduced cost and increased speed in developing material sets <b>Barrier:</b> Availability of suitable infrastructure</p>	<p>Academics Material formulators Other sectors (e.g. pharmaceuticals)</p>	<p>Consultation with wider chemicals industry to understand the opportunity to develop computational modelling and robotics for accelerated materials design. This could be used to develop guidance to academia and industry on the best route forward, ultimately leading to the reduced material development cost and timescales</p>
	<p>Application of digital twinning to accelerate the development and scale up of formulations and products</p>	<p><b>Driver:</b> Reduced cost and increased speed for iteration development <b>Barrier:</b> Cost of initial model development</p>	<p>Academics Material formulators Other sectors (e.g. pharmaceuticals)</p>	<p>Consultation with chemical modelling and composite experts to identify targets for digital twinning. Development of models would enable comparison with real-life data and validation. Further demonstration of chemical modelling for composite products would enable wider adoption in formulation and design, ultimately resulting in reduced material development cost and timescales</p>
	<p>Improve modelling of composite durability; structural health monitoring</p>	<p><b>Driver:</b> Reduced cost; increased product lifetime (repair/replace only when required)</p>	<p>Academics Material formulators OEMs</p>	<p>Defining the environmental conditions relevant to each sector is needed initially. Correlating accelerated aging, real-life data and chemical modelling would further build understanding. Developing chemical modelling to better understand composite degradation can then be applied to material development to improve composite durability. Ultimately, the lifetime of composite parts will be increased, reducing manufacturing and associated embodied carbon. A reduction in over-engineering due to increased confidence in material will also be achieved</p>

continued &gt;

Table 12: continued

	A reliable, verifiable tool to enable searching for materials, suppliers and associated metrics such as bio content and embodied CO <sub>2</sub> as well as performance data	<p><b>Driver:</b> Challenging for composite material users to make an informed choice</p> <p><b>Barrier:</b> Need wide industrial buy-in to make it work. A third-party body would be needed to oversee it</p>	Industry and sustainability groups	A greater understanding of sustainability activities being developed within the composites sector would enable better links with chemical search engines. Creating accessible tools for promoting low carbon materials would enable broader awareness of the carbon content of materials across the composites industry
	Carbon taxation strategy to drive economics favourably towards sustainable solutions to materials challenges	<p><b>Driver:</b> Make sustainable materials financially favourable</p> <p><b>Barrier:</b> Supply chains are international with unequal taxes for Scope 1 and 2 emissions</p>	Government	Two mutually supporting approaches are required: 1) consistency across frameworks to ensure credible accounting of carbon impacts at the business-to-international level, improving the quantification and clarity for Scope 3 emissions; 2) the development of a carbon taxation strategy to incentivise the transition to sustainable materials in supply chains
	UK strategy for advanced materials needed to drive priorities for sustainable materials	<p><b>Driver:</b> improve the UK Government's ability to support materials supply chain innovation in a complex area</p> <p><b>Barrier:</b> complexity and overlapping responsibilities in Government; significant UK supply chain gaps</p>	Key stakeholders to clarify sector needs and economic impacts	Collaboration is required across all convening and strategic bodies to create a credible UK advanced materials strategy. In parallel, translation of composite industry requirements to the wider chemistry programmes is needed to realise industry economic pull and demonstratable routes to impact
	Funding for investment in chemistry related research to support the composites sector: will be applicable across most topics above	<p><b>Driver:</b> maintain the longer-term health of the UK composites industry</p> <p><b>Barrier:</b> connection with fragmented/multinational base for composites research</p>	UKRI (IUK/ EPSRC/ BBSRC), HVMC Industry	An advanced materials strategy needs to be backed up by funding investment. Funding programmes need to be put in place to address the composite challenges chemistry can help solve. This will drive investment in the UK supply chain and help grow the value of the UK composites industry

While these opportunities are focused on UK collaboration, we recognise that supply chains and science do not follow borders and so many of these will be applicable to other geographies.

Where challenges overlap with other industries such as plastics, packaging and other foundation industries, partnerships need to be formed at a strategic level to enable collaborative action. Wider knowledge sharing between scientific communities operating in different areas of chemistry, composites, materials, industrial biotechnology and sustainability is also needed to stimulate the development and implementation of new ideas and solutions for the benefit of the composites sector.

# 9 Conclusion

**Composites are crucial to delivering the UK's net zero targets and contribute, more widely, to the UK economy. They continue to be used across industry in sectors such as aerospace and defence, marine, automotive, and construction and infrastructure. The use of composites has also enabled the continuing transition towards renewable energy. They form the basis of wind turbine blades and are predicted to be heavily used in storage and transportation within the hydrogen economy.**

The composite market will continue to grow as dictated by the delivery towards net zero but there are two major barriers casting a shadow over their use. The increasing demand for composite materials, particularly carbon fibre-reinforced, is not being met by an increase in or generation of UK production. This is creating the potential for insecurity within the supply chain and risks the net zero delivery. The second barrier is the environmental impact of the composite supply chain, specifically the high GHG emissions associated with raw materials extraction and processing, and the processes currently used in their manufacture. This report has explored the underpinning chemistry of composite materials and the opportunities to move towards a more sustainable future.



The complete lifecycle of a composite was investigated in this report: from raw materials to formulation and manufacture, through to waste management at end of life. Two workshops were held to understand the views of academic and industry stakeholders along the composite supply chain. The outputs from these workshops were used to inform the sustainability trends that are discussed in the report. These are: low carbon feedstocks; manufacturing efficiency; increasing composite lifetime; repair and reuse; chemical recycling technologies for legacy materials; inherently recyclable composite materials and underpinning tools.

The investigation identified 19 chemistry-focused opportunities to enable the development of sustainable composites solutions under the following six themes.

- Integrating with the bioeconomy
- Adopting waste and circular economy approaches
- Designing end-of-life strategies
- Improving the energy efficiency of manufacturing
- Adopting digital and computational chemistry approaches
- Government policy agenda for sustainable materials.

The urgency of change in moving towards a more sustainable economy has never been clearer and chemistry will play a significant enabling role. To realise each of these opportunities, five key steps are required which mandate action from multiple stakeholders within industry, government and academia.

1. **A new generation of composite materials must be developed** which can be readily recycled at end of life.
2. **Chemical recycling techniques must be implemented** to move the composites industry from a linear model to a circular one.
3. **Bio-derived chemicals need to be incorporated into the composites supply chain** in place of petrochemicals.
4. **Collaborative partnerships** between academia, the composite supply chain, and the chemical industry are needed to develop and scale solutions.
5. **Broad support is needed from government agencies** through a UK advanced materials strategy. This needs to include funding for the chemical sector to coordinate activity, ensure targets are achieved, and stimulate chemistry research for adoption into the composites industry.

The UK is a world leader in composite manufacture. It has the capability to be a world leader in composite sustainability too. The priority to tackle sustainability challenges from both companies and individuals was clear throughout the writing of this report. With the right focus, strategy and funding this aspiration can be realised along with the significant opportunities it brings.

# 10 What's next?

**Chemistry has a vital role in helping the composites sector transition towards more sustainable practices and deliver on net zero targets. As you will see in the case studies (Section 11), there are promising developments already in progress. However, chemistry's contribution to sustainable composites will be slow to realise unless much greater collaboration happens.**

The Royal Society of Chemistry is well placed to empower chemical scientists to contribute their knowledge, skills and experience to tackling sustainability in the composites sector. This will complement the actions taken in creating de-risking interventions, collaborative projects and thought leadership by the National Composites Centre and CPI through Sustainable Composites.

Through its dedicated action plan, the Royal Society of Chemistry, NCC and CPI will raise awareness of the issues raised in this report with all those who have the influence to make change happen.

## An action plan from the Royal Society of Chemistry:



### 1. Championing new research

Research is crucial to developing sustainable solutions for the composites industry. This could include developing new bio-derived chemicals for composite applications and improving chemical recycling techniques to help move the industry towards a circular economy. However, without an extensive and visible pipeline of chemistry research across all aspects of the composites life cycle, future solutions will struggle for visibility and be limited in their impact. The Royal Society of Chemistry will encourage greater awareness of the needs of the composites sector by encouraging individuals from this community to 'step into' the chemistry research domain. As examples, this greater awareness and visibility may be achieved through multidisciplinary journal collections, featuring international research invited by industrial and academic guest editors.



### 2. Promoting skills development

Engaging the chemical science community is important for developing new sustainable composite solutions. The Royal Society of Chemistry will, therefore, incorporate composites into its CPD initiatives to support the upskilling of chemical scientists. Those skills will also be acknowledged as part of professional recognition schemes such as Chartered Chemist and Registered Scientist. The Royal Society of Chemistry will also inform chemical scientists of pathways and opportunities within the composites sector at all stages of their careers.

## An action plan from the NCC and CPI:



### 3. Encouraging collaborations

Greater collaboration is needed at all levels to develop and scale solutions. Whether that is interdisciplinary collaboration between engineers and chemical scientists, academia-industry partnerships to progress the most promising solutions, or supply chain cooperation to adopt them: without opportunities for researchers and businesses to work together to develop chemistry solutions, progress will be slow. The National Composites Centre and CPI will create project teams, consortia, working groups and capabilities to de-risk and support industry in the delivery of sustainable composite products and their supply chains. And bring together the composites industry to build and communicate the market demand for sustainable technologies and chemistry solutions.

# 11 Case studies



## Increasing the energy efficiency and lifespan of wind turbines

Swiss company Gurit has developed RENUVO™, a glass fibre-reinforced polymer resin system that is designed to repair damaged wind turbine blades to extend their lifespan.

This technology allows more efficient energy generation by shortening repair times, which would otherwise cause lengthy operational downtime. It also requires no two-part mixing or heat to cure, cutting overall ancillary use, hazardous waste and cost – repairs can also be carried out in harsh environments, such as offshore wind farms. Through repairing rather than replacement, the lifespan of a turbine can be significantly increased, reducing the environmental impact of end-of-life concerns such as landfill.

RENUVO™ uses UV-activated polymer chemistry to form a structurally robust material. This allows the easy

application and forming of wind blade repairs which can be hardened on demand to achieve the required strength and stiffness properties. The technology differs to traditional acrylate or methacrylate-based polymer systems in that it is free of solvents and monomers such as styrene. This lowers toxicity, improving the safety for users.

Gurit is a system partner for wind energy customers globally with a focus on wind turbine blades and hopes to enable the wider adoption of renewable energy to support the global decarbonisation goals.

[www.gurit.com](http://www.gurit.com)







## Recyclability: working towards a new standard in the composite industry

**Thermoplastic resin Elium® enables composites to be recycled in two different ways, making it very different to most current thermoset resin-based composites.**

The starting monomer can be recovered through chemical recycling and is able to be reused in recycled resin production for the manufacture of new composite parts. And through mechanical recycling, it is possible to create a new object altogether.

This contrasts with most thermoset resin-based composites, which often are either sent to landfill or incinerated.

The resin is used in wind turbine blades, composite reinforcement bars for concrete (rebars) in the civil engineering sector, in hydrogen tanks and in sailboats. The three main benefits of these advances come in relation to mechanical performance, improved productivity in using the resin, and recyclability.

As an example of its practical uses, one of Arkema's subsidiaries, Bostik, already has developed a structural adhesive for Elium® composite. During chemical recycling, the adhesive was found to boost, rather than hamper, the recovery of the monomer.

[www.arkema.com](http://www.arkema.com)





## Working to make computational chemistry more accessible to materials scientists

**Simulations are used to help pharmaceuticals companies discover new drugs – and now they could be used to develop better polymer materials.**

Molydyn's Atlas platform makes molecular dynamics simulation easier than ever before. Through the use of artificial intelligence and decision making, Atlas allows all chemists to run simulations with inputs and outputs that they inherently understand. It enables chemists without modelling experience to benefit from simulations.

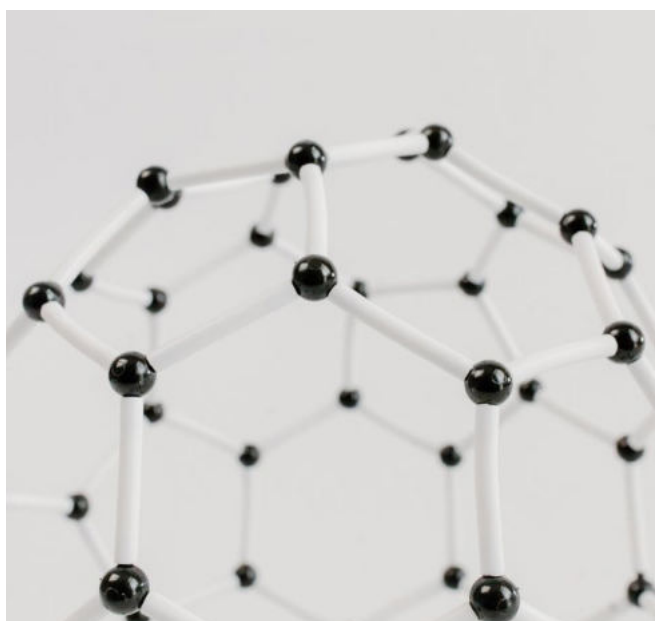
The initial focus for Atlas is to help academics teach the next generation of computationally-guided chemists and conduct more cost-effective innovative research. Chemistry students can now quickly access powerful tools and gain hands-on experience into how effective they can be.

Simulation tools can also allow institutions with limited lab access to conduct cutting-edge research while keeping costs low, and it can help SMEs and universities compete with better funded research.

Molydyn is working to simultaneously make materials research more sustainable and develop materials that enable key green technologies, such as hydrogen storage. The drive to help scientists adopt computational chemistry approaches is the obvious opportunity.

Atlas can even simulate molecules that are hard to acquire or have never been synthesised. The platform can help companies design for end of life by simulating a multitude of polymers made with chemistries that are known to be easy to reprocess.

[www.molydyn.com](http://www.molydyn.com)





and



## Championing the manufacture and use of more sustainable acrylonitrile

Acrylonitrile is found in all sorts of products we use in daily life, such as fleece clothing, tear-free shampoos, medical gloves and toy bricks. It is also a crucial precursor in the production of carbon fibre for the composite sector. Around six million tonnes of acrylonitrile – worth in the region of \$14 billion – are produced and sold every year, from a predominantly petroleum-based supply chain.

Trillium is developing a technology called bio-ACN™ with the intention to build, own and operate the world's first renewable acrylonitrile plant. The bio-ACN™ process uses proven chemical processing techniques to economically produce acrylonitrile at scale from plant-based feedstocks.

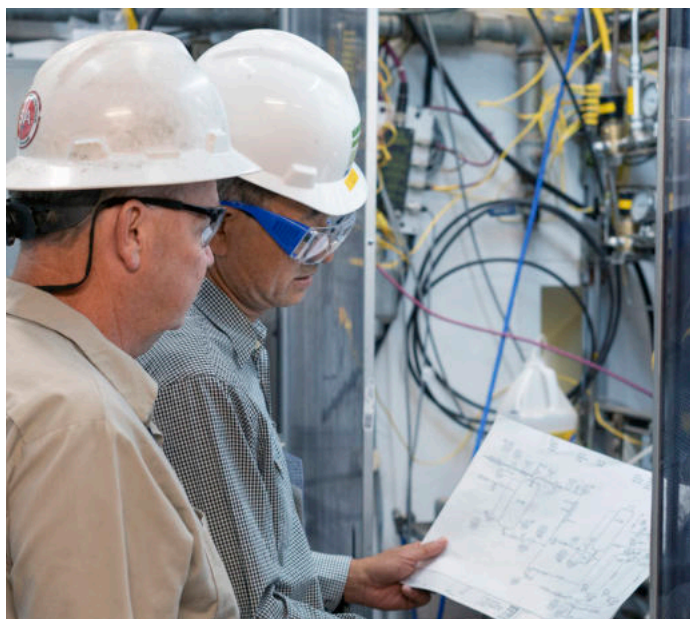
This method minimises water and energy usage and reduces waste, while the carbon footprint of acrylonitrile drops by roughly 70% compared to the conventional petrochemical process.

Materials, chemicals and solutions experts at Solvay recently agreed to collaborate with Trillium to evaluate the use of bio-ACN™ for carbon fibre applications. Solvay's carbon fibre-reinforced composite technologies already offer opportunities to cut weight and fuel consumption, and they can also reduce assembly costs by replacing metal parts frequently used in advanced applications, such as in transport and infrastructure.

In working together to understand and demonstrate bio-ACN™ in the carbon fibre supply chain, Solvay and Trillium are working to deliver a lighter, cleaner and greener future.

[www.solvay.com](http://www.solvay.com)

[www.trilliumchemicals.com](http://www.trilliumchemicals.com)



# 12 Appendix

## 12.1 Workshop tables

Category	Challenge/opportunity
<b>Awareness</b>	Database of low carbon feedstocks needed to raise awareness in the wider community
<b>Carbon capture</b>	Carbon capture could be used to feed into the chemical market in the future
<b>Economics</b>	Low carbon solutions not yet at scale so come at a cost premium
	Link in with wider chemical industry so there is scale
	Disruption in traditional supply chains
<b>Feedstock</b>	Need for low carbon aromatics to feed into composite supply chain
	Greater supply of bio-derived epichlorohydrin
<b>LCA</b>	Robust environmental impact needed to show the benefit of moving to lower carbon feedstocks
<b>Mass balance</b>	The mass balance approach could be used to ease the transition to low carbon feedstocks
<b>Cost</b>	Costly to introduce new materials due to new manufacturing infrastructure and qualification of new materials
	Direct drop-in replacements for low carbon feedstocks would minimise the cost of transition

Table 13: Challenges and opportunities for low carbon feedstocks

Category	Challenge/opportunity
<b>Curing</b>	High temperatures currently needed to achieve high cure conversion
	Opportunity to explore non-thermal curing
	Faster-curing resins (without exotherm risk) would reduce energy input to thermal curing
	Better understanding of kinetics to minimise energy input needed (process monitoring)
<b>Out-life</b>	Longer out-life – microwave curing?
	Ambient storage prepreg
<b>Process enablers</b>	Materials for out-of-autoclave
	Materials for additive manufacture (ALM)
	Materials for AFP/ATL?
<b>Consumables</b>	Reusable consumables, e.g. silicon consumables, biodegradable, recyclable?
	Reusable consumables at higher temperature
	Release agents, peel plies etc.
	Recyclable consumables
<b>Waste</b>	Large amount of scrap produced
	Over-engineer

Table 14: Challenges and opportunities for energy and material efficient manufacturing

Category	Challenge/opportunity
<b>Durability</b>	The chemical degradation of composites needs to be better understood in order to predict degradation
	Better chemical modelling of durability is required to increase confidence in composite lifetime
	Introduction of sustainable materials must not reduce the durability and lifetime of composite parts
	Natural fibres need improved coatings to increase their long-term durability
	Coatings for composites are needed for weathering protection and fire resistance
	Damage can be hard to detect in composite materials; functional materials need to be developed to detect damage in situ
<b>Reuse and repair</b>	In order to effectively reuse/repair, the materials used in a composite need to be identified using chemical analysis
	Composite parts must be designed for disassembly to enable ease of reuse/repair
	Reversible adhesives are needed to enable design for disassembly
	Repaired parts need to have a pathway to requalification and lifetime extension
	Self-healing composites need to be developed to reduce the burden of repair

Table 15: Challenges and opportunities for durability, reuse and repair

Category	Challenge/opportunity
<b>Maximising recyclate value</b>	Resin degraded and lost out of supply chain during fibre recovery
	Reuse lifespan of recyclate needs to be established
	Recovered fibres do not match performance of virgin fibres
	Recovered fibres need to be resized
<b>Waste streams</b>	Recycling techniques need to be able to deal with mixed feedstock waste streams
	Coatings and other additives need to be removed to clean waste streams as much as possible
<b>Material identification</b>	Current waste at end of life is unlabelled and was manufactured some time ago
	Composition of waste often not shared along the supply chain
	Robust identification methods needed
<b>Economics</b>	Cost of recovery needs to be less than landfill
	Recycled material needs to be cost competitive with virgin material
	Long composite lifetime, needs to be valuable at end of life
<b>LCA</b>	Some recycling techniques are highly energy intensive/use harsh chemicals
	No clear environmental impact framework to assess recycling approach
	Recycling down to platform chemicals is energy intensive
<b>Strategy</b>	Energy production from waste plants may consume waste streams
	Technoeconomic study is needed to highlight the best recycling approaches
	Need to identify valuable chemicals to target from recyclate
	Need a standardised approach on how to treat each class of composite waste

Table 16: Challenges and opportunities for composite recycling

## 12.2 Examples

In addition to the examples referred to throughout the report, Table 17 provides an additional list of examples from the literature review.

Example	Section
Huntsman has delivered an 80% reduction in GHG emissions since 2019, with a concomitant reduction in weight per weight (w/w) CO <sub>2</sub> emissions per kilogram product of 40% <sup>15</sup>	7.1
BASF has a commitment to net zero by 2050 including circular economy solutions <sup>16</sup>	7.1
INEOS recently announced large investments in carbon sequestration and storage (CSS) at its Grangemouth site which produces olefins and polymers, including polypropylene <sup>17</sup>	7.1
Anhydrides: <ul style="list-style-type: none"> <li>• Maleic anhydride from sugar derived levulinic acid or renewable furfural<sup>41,42,43</sup></li> <li>• Phthalic anhydride from one-pot synthesis of bio-sourced materials</li> </ul>	7.1
Benzoxazine resins synthesised from vanillin <sup>61,262</sup>	7.1
Sicomins low temperature epoxy system <sup>263</sup>	7.2
3D printing of continuous fibre parts pre-impregnated with epoxy resin <sup>264</sup>	7.2
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