

THE SUSTAINABILITY OF FIBRE- REINFORCED POLYMER COMPOSITES

A Good Practice Guide

Composites 
Trade Association

 NATIONAL
COMPOSITES
CENTRE

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FOREWORD

In modern industry, sustainability is the cornerstone of everything we do. We live in a world where the purchasing demographic is more socially aware than ever before and to thrive in the 4th industrial revolution means migrating to the 5th industrial revolution – where sustainable, circular materials and products are considered standard.

Sustainability is everyone's responsibility. If you want to know who is responsible for sustainable innovation, simply look in a mirror.

Dr Alan Banks, UK Innovations Manager, Ford Motor Company Limited and Chairman, Composites UK

The principles of sustainability are based upon the interdependence of environmental, social and economic systems and the promotion of their health through strategic innovative development. Low carbon societies will be wholly reliant on the benefits that only composites can deliver such as lightweight transportation, renewable power generation & distribution, and flexibility in design for infrastructure projects. This guide is both a comprehensive summary of what has come before and a call to arms of what must follow to help close the loop on the composite value chain and secure composites as the go to materials for sustainable design.

Dr Steven Brown, Group Sustainable Technology Manager, Scott Bader Company Limited and Sustainability Director, Composites UK

Reaching net zero emissions and delivering sustainable economies is a global priority. Composites play an important role in driving decarbonisation through: light-weighting to improve fuel economy and reduce emissions; manufacturing higher performance products and increasing product lifespans by decades through corrosion resistance and durability. But there is more we need to do. There are limited options for recycling, with processes that often degrade the materials' performance. This means only 15% of the 110,000 tonnes of composites produced in the UK each year will be reused or recycled at their end-of-life. Whilst more than 95% of composites are made from raw materials and resins that are unsustainable. We need to act now to develop sustainable composite materials for the next-generation of lightweight, super-efficient transportation and energy products from airplanes to turbine blades, hydrogen storage to electric vehicles.

Dr Tim Young, Head of Sustainable Technologies, National Composites Centre

PREFACE

In 2019, the UK was the first major economy to pass a net zero emissions law¹, now followed by more than a dozen others, with pledges from many more. During the recent coronavirus pandemic numerous articles were published calling for a “reset”, to start back on track to a more sustainable future², alongside political rhetoric calling for society to “build back better”. The voices of many scientists, and of environmental activists such as David Attenborough, Ellen MacArthur and Greta Thunberg have made it clear in recent years that there is a direct threat to our welfare from climate change, pollution, resource depletion and ecosystem disruption. Increasing numbers and severity of floods, droughts, heatwaves and wildfires are focussing our attention on the need to act now while we still have time. It is becoming increasingly clear that “Human wealth depends on nature’s health”.³

The composites industry is both part of the solution and part of the challenge on this journey to a better future. Composite materials are key enablers of decarbonisation and net zero cannot be achieved without them. However, composite materials also have their own environmental impacts and these will need to be steadily reduced for humanity to have a sustainable future. Each business involved with composite materials therefore has a clear responsibility to play their full part in addressing these twin challenges of net zero and circularity, understanding the full impact of all their supply chains from raw materials, through manufacturing, in use, at end of life and into the next life.

Given the scale of these challenges, it can be difficult to know where to start to make a difference. It is our sincere hope as authors that this Good Practice Guide will help all composites businesses take many more practical steps quickly on the road towards true long-term sustainability. We wish all our readers well with this great endeavour.

Malcolm Forsyth, Sustainability Manager, Composites UK

Stella Job, Grazebrook Innovation (Sustainability Manager at Composites UK 2013 to 2021)

¹ ‘UK becomes first major economy to pass net zero emissions law’, BEIS, 2019. <https://www.gov.uk/government/news/uk-becomes-first-major-economy-to-pass-net-zero-emissions-law>

² E.g. ‘How the great COVID-19 reset can help firms build a sustainable future’, World Economic Forum, 15th May 2020. <https://www.weforum.org/agenda/2020/05/the-covid-19-reset-sustainability/>

³ Dasgupta, Andersen, ‘Coronavirus shows we must change our economy to recognise that human wealth depends on nature’s health’, Independent, 5/6/20 <https://www.independent.co.uk/news/business/analysis-and-features/biodiversity-economy-coronavirus-covid-19-dasgupta-review-a9550156.html>

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EXECUTIVE SUMMARY

The composites industry is developing and growing. The purpose of this document is to provide guidance at an introductory level as to how the composites industry can develop sustainably going forwards. The famously quoted Bruntland Report⁴, back in 1987, said:

“Humanity has the ability to make development sustainable to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs”.

It goes on to say:

“The concept of sustainable development does imply limits - not absolute limits but limitations imposed by the present state of technology and social organization on environmental resources and by the ability of the biosphere to absorb the effects of human activities”.

We in the composites industry need to define and understand those limitations. We must be aware of the effects of our activities from raw material supply, through manufacturing processes, in-service impacts and to end-of-life, or preferably start-of-new-life. If we cannot be fully sustainable now, we must still do all we can now while working towards an increasingly sustainable future.

In 2019 Composites UK developed a ‘Vision and Roadmap for Sustainable Composites’, looking ahead to 2040.⁵ This roadmap is now being progressed apace through various activities by Composites UK and its members, including the High Value Manufacturing Catapult (HVMC) centres. That Vision is good, but it does not yet go far enough. The industry needs to consider 2140, and even 3040, when there will be no fossil-derived materials in use unless they have achieved full circularity, and our energy use and emissions to land, air and water will need to be in balance with our planet, or our planet will have become uninhabitable.

To help the composites industry progress towards this goal, this guide aims to cover all the key aspects that need to be considered when formulating and implementing the sustainability plans that will be needed.

Chapter 1 introduces the topic of sustainability to ensure there is a good foundation of understanding about what is meant by sustainability and circularity and why they matter. In the following chapters, some of the key aspects that any composites actor needs to consider are explored, including design for sustainability, the use of life cycle assessment tools for determining impacts, the potential use of recycled and bio-based materials and where & how they can best be incorporated and the ways in which resources can be processed more efficiently with lower environmental impacts. The guide then reviews the ever-increasing range of targets and metrics that organisations need to consider or comply with, the increasing range of options for recycling composite waste materials (especially at end of life) and the growing influence of policy and legislation on composites markets, all of which composites organisations need to be aware of. The guide is completed with a closing summary of the key next steps that organisations now need to be undertaking and a series of helpful glossaries and appendices to help readers navigate a large number of acronyms and definitions.

No guide of this kind can ever be completely comprehensive but the contents of this guide will enable all composites organisations to progress in a well-informed and robust way on their journey towards future, long-term sustainability.

⁴ ‘Our Common Future’, World Commission on Environment and Development. Published by Oxford University Press on behalf of the United Nations, ISBN: 978-0-19-282080-8. Text download at <https://sustainabledevelopment.un.org/index.php?menu=1375&year=1987>

⁵ ‘Vision and Roadmap for Sustainable Composites’, Composites UK 2019. <https://compositesuk.co.uk/industry-support/environmental/sustainable-composites-roadmap/>

1. INTRODUCTION TO SUSTAINABILITY

Author: Malcolm Forsyth

There is little doubt now that the 2020s will be dominated by the need to successfully address the challenges to humanity posed by a changing climate. A steady flow of scientific data is highlighting ever more clearly the impact that human activity is having on the natural systems our planet depends on, and there is a rapidly growing focus on the changes needed for human activity on planet Earth to become “sustainable” for the long-term health and prosperity of the human population. But what do we mean by “sustainability”? And can we quantify “sustainability” and therefore measure our progress towards it? This good practice guide seeks to give its readers both a clear understanding of what “sustainability” is, and how, as players in the composites supply chain in the UK & beyond, individual companies can play a part in successfully addressing this vital global challenge.

1.1 Scope

This guide addresses sustainability good practice for all players in the value chains of composite parts, from the suppliers of raw materials used, to the manufacturers and assemblers of consumer or industrial products incorporating composite materials. While mentioning economic and societal aspects of sustainability, the main focus of the guide is practical information on pathways available now to support progress towards a more environmentally sustainable composites industry.

A composite material is one which is composed of at least two materials, which combine to give properties superior to those of the individual components. This good practice guide refers primarily to fibre reinforced polymer (FRP) composites, usually involving carbon, glass, aramid, basalt, polymer or natural fibres embedded in a polymer or resin matrix, which may be thermoplastic or thermoset.

Readers new to the subject may find ‘Appendix 1: Glossary & Terminology’ a useful reference.

1.2 What do we mean by “sustainability”?

The Brundtland Commission for the United Nations, in the 1987 “Our Common Future”⁶ report, helpfully defined “sustainable development” as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs”.⁷

The essence of all the many definitions for “sustainable development” and “sustainability” developed since then is that of working in balance with natural systems so that there is not a systematic degradation of these systems which are essential to the continuation of all life on Earth. Some definitions have also introduced the concept of balance and fairness in human society as being essential to a sustainable future for humanity, and this is well illustrated in the concept of human business activity operating within nested circles (see Figure 1.1).⁸ This figure makes it clear that a healthy human business (or economy) needs a healthy human society around it for the business/economy to flourish, and in turn, a healthy human society needs a healthy natural environment around it, for the society to flourish. In other words, if the Earth’s natural environment is not

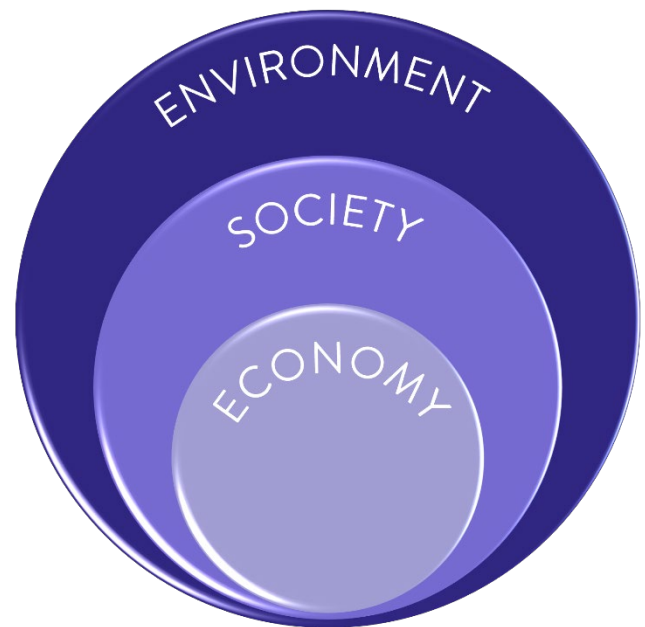


Figure 1.1: Nested circles of economy, society and environment

⁶ ‘Our Common Future’, World Commission on Environment and Development. Published by Oxford University Press on behalf of the United Nations. Text download <https://sustainabledevelopment.un.org/index.php?menu=1375&year=1987>

⁷ <https://www.iisd.org/topic/sustainable-development>

⁸ Diagram adapted from <https://sustainabilityadvantage.com/2010/07/20/3-sustainability-models/>

“healthy”, it will be impossible for human society to flourish, or for any human business activity or economy to flourish. Human economic activity and human society are, in reality, wholly-owned subsidiaries of the global environment and this provides the best context in which to consider “sustainability”.

The inter-linking nature of business/economy, society and environment is well-captured in the updated 17 United Nations Sustainable Development Goals (SDGs) shown in Figure 1.2.⁹ These goals provide a comprehensive summary of all the aspects of a sustainable society that humanity must address, for true sustainability in the future. They also provide a very helpful framework to map any individual organisation’s activities against, enabling measurement of progress towards long-term goals, and ensuring a holistic view is taken.



Figure 1.2: United Nations Sustainable Development Goals (SDGs). Used with permission ¹⁰

All these goals are important for society as a whole, but the use of composites has a significant, positive contribution to make to some of these goals (such as goals 6, 7, 8, 9, 11, 13). Goal 12: ‘Responsible Consumption and Production’ presents significant challenges to the composites industry, and this guide is predominantly focussed on addressing environmental impacts in that context, and proposing possible solutions to these impacts, while not detracting from positive in-service impacts elsewhere.

1.3 Why does sustainability matter?

Individuals and companies could have many different motivations and drivers for addressing the challenges of sustainable development, such as personal and emotional connection to nature, fear for the future for their children, and concern about the future viability of their current business profit streams. As we enter the 2020s, it is now becoming clear for all business organisations and companies that firstly the current way of operating of most, if not all, organisations is far from being truly sustainable, and that secondly this current “unsustainability” is becoming a major business survival risk going forward.

1.3.1 Financial sustainability

All companies rely on investment funds and positive cash flow to be able to maintain their current business activity, and grow their activity going forward, and financial providers (such as banks and investment companies) are now clearly

⁹ <https://www.un.org/sustainabledevelopment/sustainable-development-goals/>

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considering “climate change risk” as being an investment risk when assessing potential investments.¹¹ Ratings which measure a company's exposure to long-term environmental, social, and governance (ESG) risks are increasingly scrutinised, and several major financial organisations have stopped investments in fossil fuel extraction and power plants, supporting renewable energy investments instead.¹² Transport sectors are also now investing massively in electric drivetrains, battery technologies and hydrogen propulsion systems, in line with government commitments to move away from fossil fuel use.

There is no doubt that this change in financial funding will have a profound impact on all market sectors, including the composites value chains. As a result, there will also be clear winners and losers – many well-known companies and brands are undoubtedly now facing the need to change the nature of their operations significantly or they will disappear in the coming years.

1.3.2 Availability and appropriateness of petroleum-based feedstocks

For decades, human society and business activity has been based on the widespread and low-cost availability of fossil fuels, which has led to the supply of a very diverse range of carbon-based products from which to construct the materials which shape our everyday lives. The composites industry is a prime example of this with the development of polymer resins from petroleum-based feedstocks, enabling the production of an amazing array of composite products which bring benefits such as high strength to weight ratio, chemical and temperature resistance and great design flexibility. However, the combustion of fossil fuels is the major contributor¹³ towards atmospheric levels of carbon dioxide (CO₂) reaching historically-unprecedented levels (see Figure 1.3). In turn, this CO₂, along with other greenhouse gases, is causing rapid and unpredictable changes in the earth's climate systems. It is now clear that human society must move away from a dependence on fossil fuels if it is to re-establish a stable global climate environment, and enable a sustainable future.¹⁴

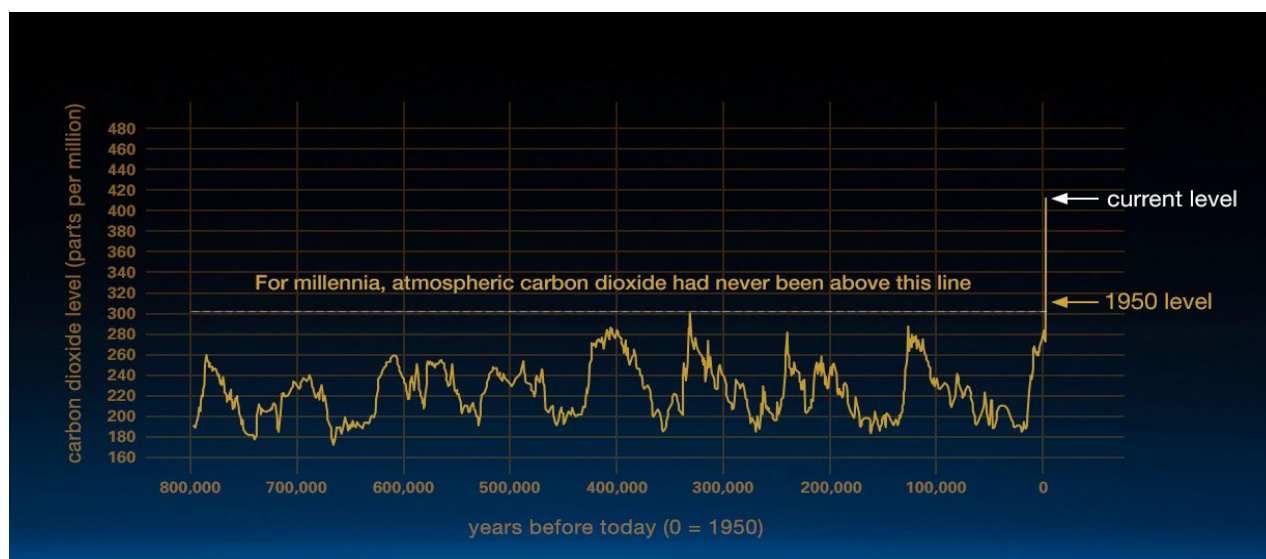


Figure 1.3: This graph, based on the comparison of atmospheric samples contained in ice cores and more recent direct measurements, provides evidence that atmospheric CO₂ has increased since the Industrial Revolution. NASA¹⁵

This inevitable move away from fossil fuels for energy may also impact the ongoing use of petroleum-based feedstocks for the production of chemicals in the medium to longer-term. Therefore, industries like the composites industry, currently

¹¹ “Climate risk is investment risk: BlackRock exiting thermal coal investments”, S&P Global, Jan 2020. <https://www.spglobal.com/marketintelligence/en/news-insights/trending/ielAyMF1ZEZZHhP1MVhWBQ2>

¹² ‘European Investment Bank commits to ending the financing of fossil fuel projects’, Climate Action, Nov 2019. <http://www.climateaction.org/news/european-investment-bank-commits-to-ending-finance-of-fossil-fuel-projects>; and ‘Sharp rise in number of investors dumping fossil fuel stocks’, Financial Times, Sept 2019 <https://www.ft.com/content/4dec2ce0-d0fc-11e9-99a4-b5ded7a7fe3f>

¹³ Approximately two-thirds of increase in atmospheric CO₂ is due to fossil fuels, and most of the remainder is due to loss of soil organic carbon due to land use change. See ‘Soil Carbon Storage’, natureEDUCATION Knowledge Project <https://www.nature.com/scitable/knowledge/library/soil-carbon-storage-84223790/>

¹⁴ See ‘Climate Change 2013: The Physical Science Basis’, IPCC 2013 <https://www.ipcc.ch/report/ar5/wg1/>

¹⁵ Data from Luthi, D., et al. 2008; Etheridge, D.M., et al. 2010; Vostok ice core data/J.R. Petit et al.; NOAA Mauna Loa CO₂ record. <https://climate.nasa.gov/evidence/>

almost completely dependent on petroleum-based feedstocks for its raw materials, will need to seriously look at changing to alternative feedstocks, derived from more sustainable annually-renewable sources, to maintain an ability to supply composite products to its customers.

Uncertainty over the medium to longer-term availability of petroleum-based feedstocks, and the resulting price volatility and/or increase which accompany reducing availability, as well as an increasingly negative public/consumer perception of their use, are strong drivers for companies to seriously investigate the use of bio-based resins for composites parts. Another important driver for doing so in the short-term is that most of the commercially realistic end-of-life (EOL) processes for recovering value from composites parts, involve burning the resin to enable fibre recovery, and in this scenario of resin combustion, a bio-sourced resin is better for greenhouse gas emissions than a petroleum-sourced resin.

1.3.3 Changing consumer attitudes

In addition to a changing financial investment culture and questions over the long-term availability of current raw materials, all companies must also now recognise that consumers are better-informed and more willing to exert pressure through their spending choices than ever before, helped in part by the ability of social media to rapidly spread information (both true and false) and to motivate people to take action. The recent protests led by Extinction Rebellion, and school climate strikes led by Greta Thunberg, have shown clearly the significant public concern over climate change and environmental damage, and this public pressure is likely to grow further in the future. This changing consumer mind-set therefore creates opportunities for companies able to positively engage and convince consumers of the improved sustainability of their products, but undoubtedly also poses threats to companies unwilling to recognise the growing consumer demands for fast changes and improvements from a sustainability perspective.



Photographs of Extinction Rebellion protests in London and Birmingham in 2019, courtesy of [Stefan Muller \(CC by 2.0\)](#) and [Callum Shaw \(unsplash\)](#)

1.3.4 Conclusions & key messages

In conclusion, sustainability matters to all companies and organisations because it will, inevitably and rapidly, become a major focus for risk management going forward, and a major driving force behind financial investment support (or not), the availability of raw materials (or not) and consumer buying decisions (or not). All organisations will need to be able to show how they are positively contributing to sustainability, to maintain the support, and hence a right to operate, from all their key societal stakeholders – immediate customers, end consumers, employees, financial investors and wider society.

These are the key reasons why sustainability really does matter to the composites industry and why all composites players, wherever they are in the value chain, must consider their plans for sustainability as a very high priority.

1.4 What do we mean by the 'Circular Economy'?

The concept of the 'circular economy' is one which has been increasingly publicised in recent years, often in connection with the growing problem of what to do with the volumes of waste produced by modern societies across the world. Most value chains today operate in a very linear fashion with raw materials extracted from the earth's crust, and then refined and processed into useful articles, which are then buried in landfill sites or incinerated when they reach the end of their useful life. The composites industry largely operates in this manner today. However, as the earth's resources become depleted, and societies run out of space to dump their waste, this linear way of operating is increasingly being challenged and so people and

organisations are all now seeking a more ‘circular economy’ going forward. Figure 1.4 shows this necessary transition from a ‘linear economy’ to a ‘circular economy’.

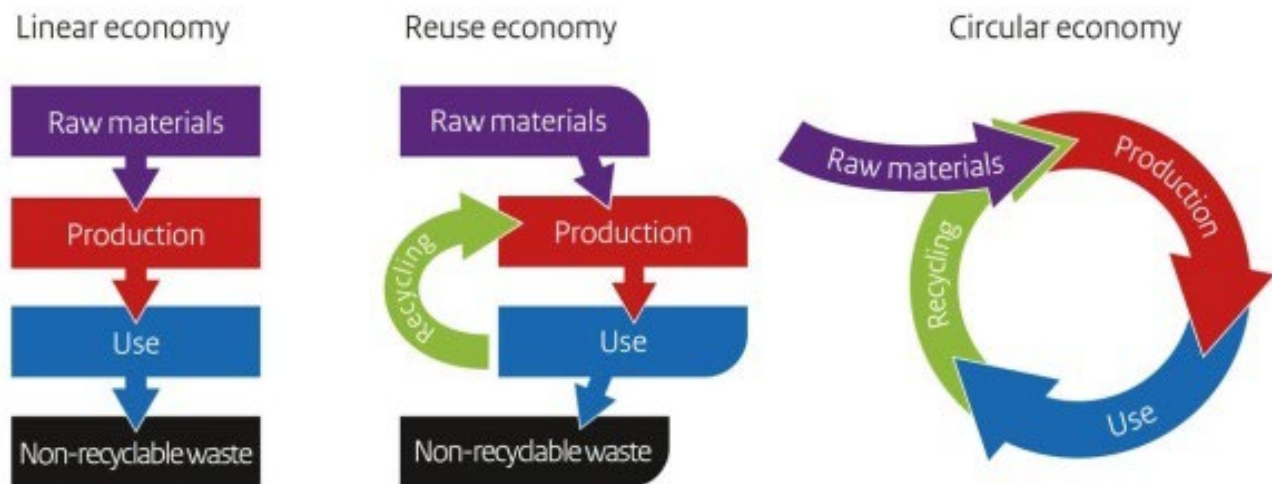


Figure 1.4: Moving from a linear economy to a circular economy

A circular economy can be defined as:

“An economic system aimed at eliminating waste and the continual use of resources”¹⁶

or

“An alternative to a traditional linear economy (make, use, dispose) in which we keep resources in use for as long as possible, extract the maximum value for them while in use, then recover and regenerate products and materials at the end of each service life”.¹⁷

The Ellen MacArthur Foundation describes the circular economy as based on three principles, driven by design:

1. Eliminate waste and pollution
2. Circulate products and materials (at their highest value)
3. Regenerate nature

It is underpinned by a transition to renewable energy and materials and decouples economic activity from the consumption of finite resources.¹⁸ Circularity within one industry does not occur in isolation. Many opportunities can be realised by cross-industry circularity where waste from one industry can contribute valuable feedstocks to another. For example, where agricultural waste from food crops is used to make resins (see chapter 5).

¹⁶ https://en.wikipedia.org/wiki/Circular_economy

¹⁷ <http://www.wrap.org.uk/about-us/about/wrap-and-circular-economy>

¹⁸ 'What is a circular economy?' Ellen MacArthur Foundation <https://ellenmacarthurfoundation.org/topics/circular-economy-introduction/overview>

An illustrative example of a “circular economy” can be seen in Figure 1.5 below.

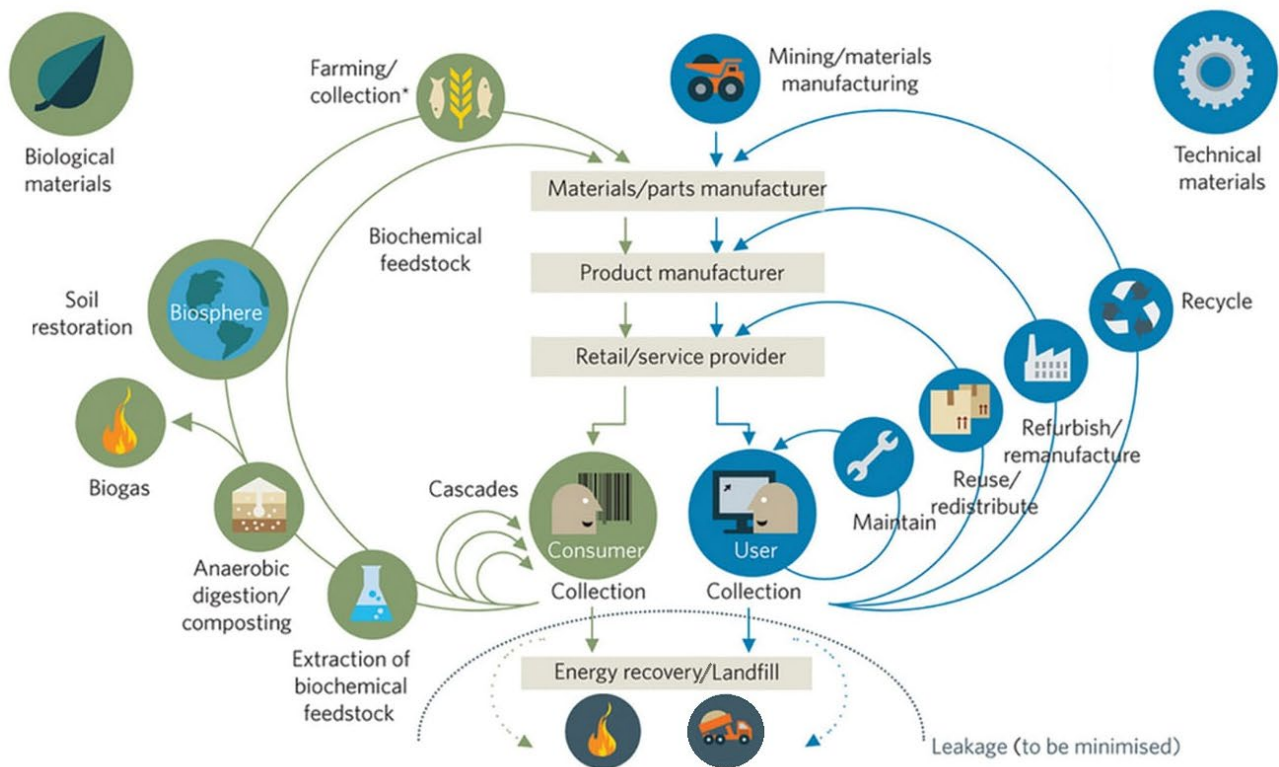


Figure 1.5: How a circular economy could operate. Adapted from the Cradle-to-Cradle Design Protocol by Braungart & McDonough

1.5 How do composites contribute to sustainability today?

Composites have a major role to play in helping a wide variety of industries move towards a sustainable future. They enable the longest, most efficient wind turbine blades, bringing us cheap renewable energy. Their excellent specific strength and stiffness enables lighter products, which reduce fuel use, and increase range in transport, and allow for easier, faster installation and reduce the need for supporting structures or foundations in construction. Composites don't rust, so the need for maintenance and painting is reduced or eliminated, especially in marine and chemical environments. This durability, combined with excellent fatigue resistance and repairability, means that composites can increase product lifespan by several times in many applications compared to the materials they may replace. Composites are therefore a key part of the solution to the climate change challenges that we face and the composites industry should therefore be well-placed to flourish in the future.

However, the stiffness, strength and durability that make composites environmentally excellent in use, also make them a challenge to recycle. Recycling solutions are improving, but the infrastructure for collection, separation and sorting still need to be developed and work still needs to be done to create markets for recyclate. Higher value, more circular recycling routes are also still needed. As a result, today's composites industry value chains are mostly linear rather than circular and this remains one of the industry's biggest sustainability challenges.

1.6 What needs to be addressed now?

For composites to have a secure place in a future aligned with the circular economy, the composites industry now needs to demonstrate or address the following key issues and needs:

- **Continue to positively market the benefits of composites** for low cost, lightweight structures and parts but at the same time, recognise the urgency with which solutions to the climate change crisis and resulting business risks are needed, and that the composites industry must change and adapt both to provide solutions and to address its own shortcomings.
- Actively pursue a range of options to **move the composites value chain to be much more circular**.

- **Design composites parts for greater or complete circularity** through careful material selection, appropriate joining techniques and enabling easy disassembly and material recovery at end of life (see chapter 2)
- Develop capability in **whole life cycle impact assessment** of products, to intelligently understand sensitivities and priorities in design and through-life management (see chapter 3)
- **Increase the recycled content of composite parts**, using the recycled material available now, and develop higher value recycling and recovery processes and supply chains, to move composites closer to 100% recycled material use in the medium/long term (see chapter 4)
- **Increase the usage of bio-based materials** in composite parts now where appropriate and value-adding, and support the development of supply chains to enable usage of higher quantities in the medium/long term (see chapter 5)
- **Increase resource efficiency at all stages of the composites value chain** through process optimisation, minimising and managing in-house waste, training, quality and good procedures (see chapter 6)
- **Use energy efficiently** and follow good practice in measuring and reporting energy and carbon impacts (see chapter 7)
- Understand **end-of-life processes**, as they exist now and as they are likely to be in the future, and work with waste management companies to develop supply chains which will optimise the value of waste (see chapter 8)
- Follow and influence the changing **policy and legislation** landscape, understanding the impact in different sectors and keeping composites at the forefront of the opportunities it raises to enable positive change (see chapter 9)
- **Keep looking to the future**, short, medium and long term, and work with universities, research organisations, supply chains and government to develop what is needed for an increasingly sustainable future (see chapter 10).

If these actions are successfully pursued, the composites industry can and will play an increasingly important role in the future, enabling sustainable composites businesses to succeed and flourish by providing composite parts of significant value to a sustainable society living in balance with its environment for the long-term.

The rest of this good practice guide is intended to provide the guidance and direction needed to help organisations get started (or continue) in addressing the impact of their own activities in the short-term and point them towards opportunities for collaboration with others to address the whole value chain challenges that will need to be overcome in the medium/long term.

2. DESIGN FOR CIRCULARITY

Author: Malcolm Forsyth

2.1 Introduction

Now that the future need for a more “circular economy” with the use of composites materials is clear, the key challenge for everyone in the composites industry is to work out how, in practice, to move towards a more circular use of composite materials. This is likely to require increased recycling of composite parts at end of life and greater use of recycled materials in the short-term, and greater use of bio-based materials in the medium/long term. These changes present quite complex challenges and can be approached in a number of ways as is summarised below, but will require everyone in the value chain rethinking how products are designed and which materials are used.

Currently, composite parts are typically designed for maximum durability, and in some cases with future repair in mind, but rarely with end-of-life dismantling and material recovery in mind. This design focus will now need to change going forwards. Whilst maintaining durability and service life of parts will remain very important considerations, a better balance between in-service aspects and end of life aspects will need to be found, if greater circularity with composite parts is going to be achieved. It is also important to recognise that changing nothing in the current design and material selection of parts, will undoubtedly lead to the future use of composites being increasingly challenged and, in some cases, substituted, in many current applications, as downstream fabricators and end consumers increasingly demand the use of more visibly circular and responsible materials, with clear independent validation of this status.

2.2 Key considerations for future design

When designing a part in any material, a designer needs to keep the following aspects fully in mind:

- What is the desired service life of the part?
- What is the requirement for access and repair during that service life?
- What are the conditions in which this part must operate which could compromise its performance?
- What allowance (if any) is there for material property change or degradation over its service life?
- How will the part be assembled or joined to other adjacent parts?

In addition, the designer needs to be aware of material selection preferences the end-user may have, and any manufacturing or assembly conditions which could favour one type of material over another.

Composite materials have been increasingly used in many markets because of the many performance benefits they can bring (compared with other materials) such as light-weight strength, chemical resistance (and hence corrosion resistance) and durability/stability of performance. These all bring clear benefits for end-users, particularly in recent times where light-weighting (for example in transport applications), has become a key design focus. In addition, designers may need to allow for extreme load conditions on their part, which may never arise in practice but can significantly extend the service life of the part when operating under more normal conditions only.

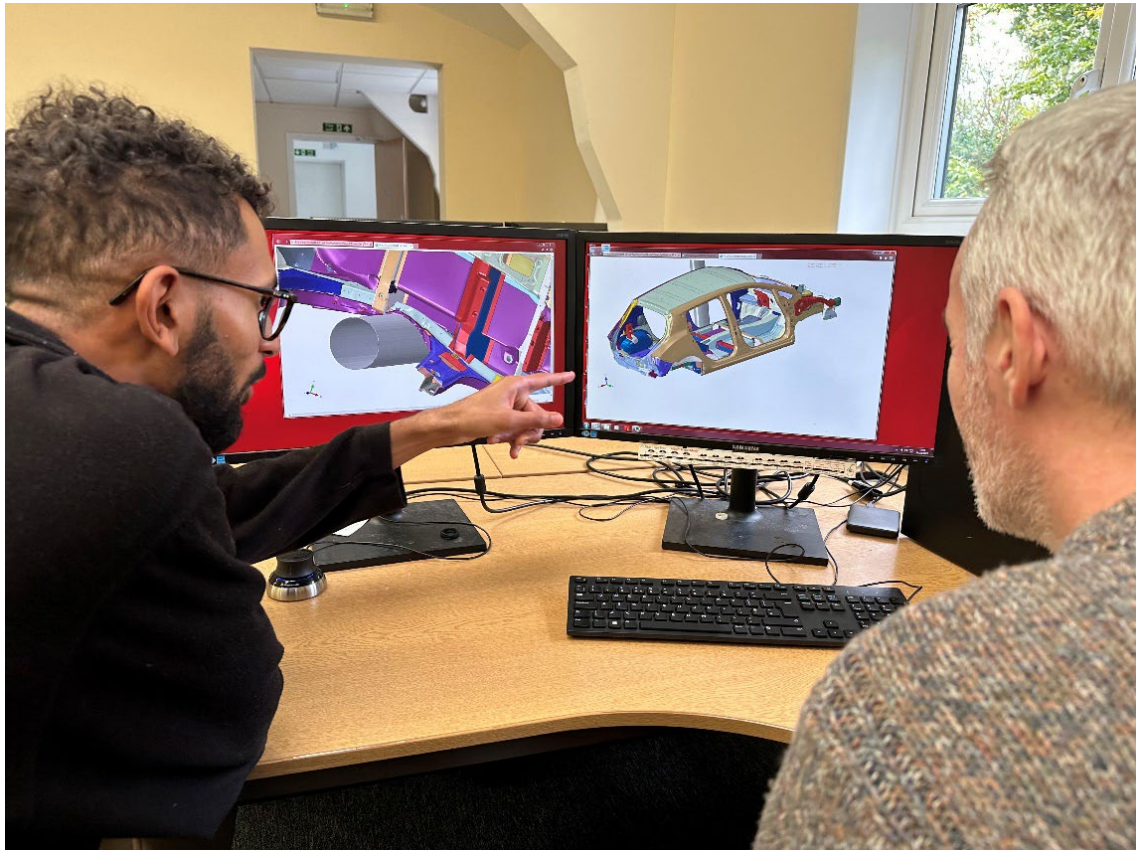


Photo courtesy of Engenuity Limited

As a result, the inherent performance aspects of composite parts (especially their durability), and the extra design margin included, can mean that the actual life of the composite part exceeds the required in-service life of the final assembled item. When this final assembled item reaches the end of its planned service life and requires recovery or disposal, the composite part itself remains in good condition but may not be readily recovered or recycled. The advantageous material features of composites during service life clearly now bring some new challenges when repair needs and end of life disassembly aspects need to be considered, and with greater circularity now required going forward, a different approach will need to be taken by part designers if real progress with circularity of composite parts is to be achieved.

Reuse or refurbishment not only minimises waste but also retains the embodied energy used in manufacture, including the derivation of the chemicals and fibres, transport through the supply chain, and the curing or heat processing of the composite part. By reusing the already manufactured composite part the energy required to create the new product is significantly reduced.

Designers of parts and whole assembled units will need to consider the following aspects in greater detail and develop different designs to take account of the changing needs and wishes of their customers:

- Can recycled materials or bio-based materials be used for the composite part instead of virgin polymer or fibres and to what extent?
- Can the design and material selection of the composite part be adjusted so that the service life of the composite part better reflects the expected actual usage of the whole assembled item (rather than exceeding it)? Or could it be refurbished /re-used? Monitoring of in-service loading may support re-use potential.
- Can the composite part and whole assembled item be designed to allow for disassembly:
 - For easy access for repair (if and when needed)?
 - So that different materials can be easily separated and cleaned to allow for effective material recycling?
 - Where joining processes allow for easy reversibility where required?
 - With materials which allow fibres and resin matrix to be separated and recovered for future use?
- Are there choices to be made where different sustainability factors conflict and how do we quantify that to enable decision making?
- What will be the economic impact of making a more sustainable product, both up-front and through life, and will consumers be willing to pay a premium for this if needed?

These questions are challenging ones to find answers to but are now key considerations that all designers need to have fully in mind, to ensure their parts or assembled items are both capable of fully meeting customer needs and are also fully fit for a future world where much greater circularity with materials will be expected.

A checklist of issues to consider in design, with a methodology suitable for early-stage design which can be modified as appropriate is found in Appendix 3: D4S methodology & Checklist.

2.3 Hazardous chemicals and recycling in a tightening regulatory environment

In addition to these design considerations, part designers will also need to be more fully aware of a changing regulatory landscape with regard to available materials and the likely future phasing out of materials considered to be unacceptably toxic or harmful to humans and/or the natural environment.

2.3.1 REACH

The ‘Registration, Evaluation, Authorisation and Restriction of Chemicals’ (REACH, including UK REACH since Brexit) regulations are increasingly focussed on the substitution and elimination of harmful chemicals to protect human health and the environment which has an impact on the range of materials available for designers of composite parts. This may soon be expanded to include polymers, which will have impact on the matrix materials used in the composites value chain. More details at 9.4.1.



2.3.2 SCIP



An imminent aspect of this tightening regulatory environment in the EU is the requirement to submit information to SCIP, the database for information on Substances of Concern In articles as such or in complex objects (Products) established under the Waste Framework Directive (WFD). The SCIP database ensures that the information on articles containing Candidate List substances is available throughout the whole lifecycle of products and materials, including at the waste stage (which may include production waste as well as end-of-life waste). The information in the database is then made available to waste operators and consumers. More details at 9.4.2.

The intention of SCIP is to reduce hazardous chemicals in waste, to promote substitution with safer alternatives and to help identify hazardous chemicals in waste and so enable more effective recycling. It highlights the need to limit use, not only of banned chemicals, but of chemicals which may become banned or may limit recycling at the end of life. As a result of these tightening regulatory controls, and others likely to come in the future, greater thought will be needed going forward by composite part designers about material selection and circularity aspects.

2.3.3 Halogenated fire retardants

Halogenated fire retardant (HFR) materials have been widely used for many years to greatly enhance a composite part's ability to withstand the effects of exposure to direct flames, and to reduce the rate at which flame will spread across or through a composite part, and in that respect, they have undoubtedly contributed significantly to the safety of passengers in trains and other mass transit vehicles. However, there is now clear evidence that these halogenated compounds are harmful to both human health and the environment, and a number of these compounds have been identified as SVHCs under the REACH regulations in Europe, and so are now being restricted or banned from use in Europe.

As well as these human health and environmental impact concerns, the presence of these halogenated materials in composite parts raises problems within the main end of life recycling process for composites parts commercially available today – co-incineration in a cement kiln. In that process, these halogenated materials result in products which are corrosive to the steel reinforcements used in concrete, and therefore composite parts containing halogenated fire-retardant additives may be banned completely or will need to be heavily diluted by other streams which may not be possible or welcomed by plant operators. They also limit applications for mechanically recycled composites. These products clearly now present a growing list of issues to downstream users and waste processors, and this will require part designers to increasingly look for other ways to achieve the fire retardancy required in specific parts.

Further details on the options available to designers for fire retardant composite parts can be found in ‘Fire Performance of Fibre-reinforced Polymer Composites – a Good Practice Guide’, published by Composites UK.¹⁹

2.4 Joining and disassembly

A critical consideration for all part designers is how their final part will itself be assembled, and how it will then be connected to other parts or structures in a larger assembly. Traditionally, metal fasteners or fixings (such as screws or rivets) were the norm but these have been increasingly replaced with chemical adhesives which offer a fast and effective means of joining materials, with the capability of being robotised to further enhance production times and lower costs. However, the use of chemical adhesives, which usually involve an irreversible chemical reaction to achieve the desired adhesive strength and temperature resistance properties, does now present a problem if the part or assembly is to be readily disassembled for maintenance or to enable material recovery at the end of its working life.



Photo courtesy of Scott Bader Company Limited

The use of chemical adhesives will continue to bring many benefits in terms of in-service part performance but increasingly a different balance may need to be struck between adhesive bond strength and ease of part disassembly. This may be achieved through the development of ‘disbonding’ adhesives with a reversible bonding reaction, or if not, then alternative methods of joining (including a return to mechanical fastenings of some sort or thermoplastic welding) may need to be considered, which provide both the bond & part strength needed during in-service life, and also an easy disassembly when the assembly and its constituent parts reach the end of their working life and enter a recycling process.

Further information on joining technologies can be found in ‘Joining of Fibre-reinforced Polymer Composites – a Good Practice Guide’.²⁰ The following points, drawn from the chapter on disassembly (chapter 10 on page 59) highlight some of the key points to be considered:

- Mechanical fastenings are the easiest joining technique to disassemble, and are well suited to applications where frequent disassembly for inspection, maintenance or repair will be needed.
- The use of thermally-expandable particles in debonding adhesives is another promising process for disassembling composite parts, although the requirement for high temperature, and increased cost and complexity, may limit applications.
- Other potential debonding adhesive technologies are still largely unproven in composite applications, and may involve greater cost and complexity.
- Disassembling welded thermoplastic joints has potential, depending on the welding process. Resistive implants can be incorporated to facilitate this.

¹⁹ ‘Fire Performance of Fibre-reinforced Polymer Composites – a Good Practice Guide’, Composites UK, 2019
<https://compositesuk.co.uk/wp-content/uploads/2021/12/Good-Practice-Guide-to-Composites-Fire-1.pdf>

²⁰ ‘Joining of Fibre-reinforced Polymer Composites – a Good Practice Guide’, Composites UK, 2020
<https://compositesuk.co.uk/wp-content/uploads/2021/12/Joining-Good-Practice-Guide-FINAL.pdf>

Designers must make sure that they keep the whole life impact of both joining and disassembly in view when making their decisions.

2.5 Use of multi-materials

Composites are by nature multi-materials, combining the properties of a fibrous material with a resin matrix, to achieve specific end-product characteristics, but the use of multi-materials in parts can go far beyond purely the use of a composite material, with any one assembly often including multiple resin and fibre types in the composite elements, as well as other, different materials such as coatings, core materials, thermoplastics, metals and wood. Historically, designers have sought to use whatever materials could bring the desired physical performance properties in the part in its service environment, at the lowest possible cost, and have not given particular consideration to the potential issues faced at end of life when a multi-material assembly might need to be disposed of. However, in some cases multi-material solutions can provide significant efficiency improvements or enable multi-functional solutions. Now however, with the increased focus on circularity and recovery of materials at end of life, the use of fewer materials in a part or assembly may increasingly be favoured going forward since this will make end of life disassembly and recovery significantly easier.

In future, all part designers will need to consider more carefully whether the performance benefits gained from the use of multi-materials outweigh the problems at end-of-life disposal, from the perspective of both cost and environmental impact. An example of this challenge can be seen in the increasing use of glass/carbon fibre hybrids, where carbon fibre is used to add strength to composite parts, but the co-mingled presence of glass and carbon fibres together in one part is likely to make it more difficult to gain value from the fibres in existing recycling processes.

2.6 Software, data and computer aided engineering (CAE)

With the exponential increase in the power and capability of computers and digital systems, and the availability of data, there are huge opportunities for part designers using computer-aided engineering techniques, to make real improvements in the sustainability and circularity of their parts. There is increasing coverage of the opportunities available via “Industry 4.0” technology, and clear expectations that this technology will drive the next big wave of manufacturing improvements.

Benefits cited for the greater use of CAE include virtual prototyping (speeding up development cycles and reducing material needs), right first-time customization of products (again reducing material waste) and more accurate design for recyclability, enabling better material recovery at end of life. Although there will be a minimum scale of production to be reached for these benefits to be realised, it is likely that many composite parts, especially those for high volume industries like automotive, will meet or exceed this scale, and therefore there will be benefits, potentially significant ones, to be gained from investment in CAE. Further details can be found in a white paper on this subject available on the Composites UK website.²¹

CAE can play a key role in reducing material usage, which helps sustainability in manufacture and at end of life, along with light-weighting benefits reducing in-service emissions. Together with a robust approach to material characterisation, CAE can be used to accurately predict and optimise composites and joining technologies for a variety of desirable characteristics such as strength (e.g., resistance to abuse loading), stiffness (e.g., vehicle handling and ‘feel’), lifetime (durability) and passenger safety.

Far-UK uses a set of techniques collectively described as ‘Analysis-Led Design’. These techniques consider multiple performance parameters and produce several possible design solutions that achieve the specified requirements. Far-UK is using this approach to assess the possible environmental impact of a product through the development of a Pareto front tool. This tool enables them to meet requirements specified by a customer, considering different material options to find an optimal solution focused on minimising emissions through sustainable design, considering environmental impact as a first step, prior to manufacturing. See Figure 2.1. This Pareto front tool will continue to evolve over the coming year as Far-UK continues to advance its environmental analysis work.

²¹ https://compositesuk.co.uk/wp-content/uploads/2021/12/Hexagon_MI_MSC_WhitePaper-Sustainability_A4_pt.pdf

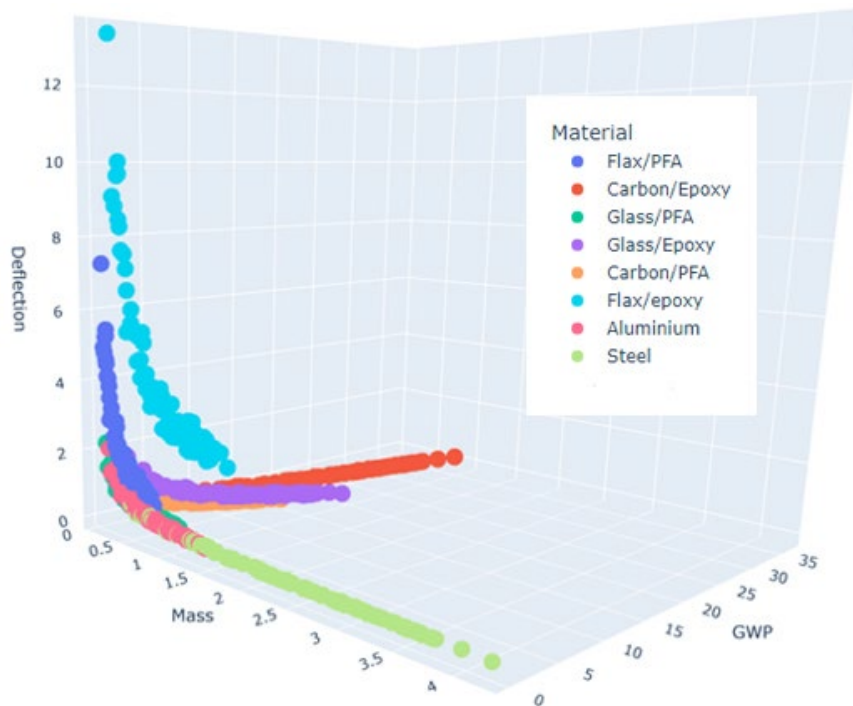


Figure 2.1: Far-UK is using a Pareto front tool to optimise solutions focused on minimising emissions through sustainable design. Image courtesy of Far-UK

2.6.1 Designing with recycled and bio-based materials

One way in which part designers can increase the circularity of their designs is to include recycled or bio-based material content whether fibres, resins or core materials. This is explored in more detail in chapters 4 ‘Using recycled materials’ and 5 ‘Using bio-based materials’ where available sources of material and manufacturing challenges are discussed.

The mechanical properties of recycled or bio-based materials can be more variable than virgin materials. This is generally less relevant with resins and more with fibres. In addition, recycled and natural fibres almost always come as discontinuous, short fibres. Many designers have only worked with long fibres, and current engineering analysis software does not handle either the discontinuous nature of the fibres or the variability well. This can lead to simply applying an unnecessarily high safety factor in design.

While the recyclers may work on developing intermediates with more consistent properties, designers can adopt novel approaches for designing with uncertainty. Characterisation of new materials is vital, and mean values of performance metrics for recylcate are important, but to use them confidently, there needs to be an understanding of variance and its impact on design and process robustness. Process design should have ability to adjust to / tolerate the measured batch variance and still create compliant parts.



Recycled carbon fibre nonwoven fabric. Photo courtesy of Gen 2 Carbon.

Stochastic modelling for design with recycled materials considers material property variation with probability-based analysis techniques and is a novel approach being used with recycled materials, including in a project with [FAR-UK](#) and [Impact Recycling](#) on mixed plastic waste.²²

As well as intelligent characterisation capability, design engineering company [Engenuity](#) has a unique capability to provide true predictive analysis of short fibre composites, having developed capability to design effectively with SMC/BMC materials for automotive. This can be applied to short fibre fabrics, as well as fibre-reinforced additive manufacturing materials.

2.6.2 Material environmental impact data

Chapter 3 'LCA - Understanding impact' covers life cycle assessment, which should increasingly be a core part of design in the same way that cost, safety and manufacturability are considered. There are some software packages available which allow for intelligent materials selection using interactive charting and comparison tools, where you can apply constraints on key properties and trade-off competing performance requirements. [Ansys Granta Selector](#) allows you to compare technical (e.g. mechanical, thermal, electrical, optical, durability, etc.), cost and environmental impact (embodied energy and/or carbon footprint, water, waste, recycling, restricted substances, critical materials, etc.) in this way, which is very powerful as a materials selection tool.²³ Similar capability is available through [Dassault Systèmes 3ds](#).²⁴

2.6.3 Product marking, RFID tagging and virtual twins

Marking of products would enable better options for reuse and recovery at EOL, particularly due to the wide variety of material compositions that are possible with composites. Product lifecycle management (PLM) software can be integrated at design stage, and continue into the use phase, through to EOL, potentially integrating data into digital or virtual twins. This could hold data such as:

- Material provenance
- Manufacturing information (batches, operators, machinery)
- Joining methods and disassembly instructions
- Usage, e.g. loading cycles
- Maintenance and repair
- EOL treatment, for validation of recycling

At present little data relevant to end of life (EOL) is recorded but understanding materials and joining techniques used could significantly improve the potential for recycling, and diagnostic and loading data could provide information as to the validity of a part for reuse or refurbishment. Intellectual property value means that for some sectors this would need strong encryption, perhaps using blockchain. It would also require standardisation of data storage such as has been developed in BIM for the construction sector and may need either regulation or a coordination between primes to incentivise compliance and consistency.

Marking is required under the end-of-life vehicle directive for plastic (including composite) automotive products over 100g (see 9.3.4). Standards exist in relation to product marking as follows:

- For automotive plastics, but relevant to filled and reinforced, thermoplastic or thermoset materials in any sector:
 - ISO 11469 'Plastics – Generic identification and marking of plastics products'
 - ISO 1043 'Plastics – Symbols and abbreviated terms'. Parts 1 to 4 cover basic polymers, fillers and reinforcing materials, plasticizers, flame retardants
 - BS EN 15343 on recycling traceability is relevant if there is recycled content.
- Construction products:

²² 'Plastic Recycling in Stochastic Modelling – PRISM', Innovate UK funded project <https://gtr.ukri.org/projects?ref=10004474>

²³ Ansys Granta Selector <https://www.ansys.com/en-gb/products/materials/granta-selector>

²⁴ Dassault Systèmes 3DS <https://www.3ds.com/sustainability/sustainable-production/reformulate-alternative-materials>

- BIM provides a framework for a “virtual twin” as part of collaborative working for buildings and civil engineering works, with BS EN ISO 19650 defining organization and digitization of information through the lifecycle (replaces parts of PAS 1192 and BS 1192).²⁵
- This may be used with Construction Operations Building Information Exchange (COBie) defined in BS 1192-4²⁶, which may soon be replaced with BS EN ISO 19650-4.
(More on BIM in context of LCA at 3.5.2)

The forthcoming ‘Ecodesign for Sustainable Products Regulation’ will develop requirements for ‘Digital Product Passports’ for almost all physical goods placed on the EU market. See section 9.5.3.

Some high value products in aerospace and automotive, and some construction products such as bridges, now have radio frequency identification (RFID) tags inserted in them for the purpose of tracking PLM and securing provenance and traceability. RFID is a low-cost way to uniquely identify parts and can be integrated into composite parts even where production and operating environments are challenging, as in the case study below.



Carbon ThreeSixty composite wheel containing a Trovan RFID tag. Photo courtesy of Carbon ThreeSixty.

²⁵ ‘What is ISO 19650?’ BSI <https://www.bsigroup.com/en-GB/iso-19650-BIM/>

²⁶ ‘What is COBie?’ NBS <https://www.thenbs.com/knowledge/what-is-cobie>

Case study: RFID in composite components

Will Battrick, Carbon ThreeSixty

Carbon ThreeSixty was seeking a simple, low-cost technology to secure the provenance and traceability of our structural composite products. The solution needed to be unobtrusive, seamlessly integrate with our existing process and provide a globally unique ID. The RFID transponder or ‘tag’ needed to meet the following requirements:

1. Lifespan proven minimum of 30 years in similar applications
2. Globally unique ID Code
3. ID Code structure not subject to alteration or deletion (electronically coded transponders can have their ID Code altered or deleted)
4. Associate all relevant asset information to the tag ID number in a secure database/look up table
5. Survive temperatures in excess of 180°C for the duration of matrix curing processes
6. Survive in the chemicals used in composite component manufacturing such as epoxies, bismaleimide, polyimide and phenol-formaldehyde resins.
7. Survive direct or indirect UV for the life of the transponder
8. Small form factor and simple to incorporate in the composite laminate
9. Capable of being read when embedded several millimetres or centimetres sub-surface
10. The tag (and readers) had to be cost effective

Our research into a suitable partner resulted in contacting Trovan, a global player in industrial RFID. Trovan has been a ‘pioneer’ in the design and production of low frequency RFID since 1988 and had more than 20 years’ experience in the composite component sector. Their tags met and exceeded all of the criteria we required. The tags are manufactured in Germany and tag reading equipment in Holland. Trovan is at the forefront of R&D into RFID technology and holds a number of patents relating to transponder design and manufacture.

Trovan provided us with sample tags and readers for testing. Our results were 100% reads at the temperatures and pressures we subjected the tags to. We are now installing Trovan RFID transponders in all our products.

2.7 General guidance and standards

With increased awareness of the challenges posed by climate change and the need to change patterns of material use and consumption, there have been several valuable guides issued in recent years which can be a helpful reference for part designers considering their material selection choices and the full life cycle of the part, including end of life disposal and potential material recovery.

A range of BS and ISO standards cover sustainable design. These are listed in Appendix 2: Standards. The most relevant are:

- The various parts of BS 8887 on ‘Design for Manufacture, Assembly, Disassembly and End-of-life processing’, which is summarised in a short BSI article²⁷
- BS 8001 on ‘Circular Economy’

²⁷ ‘Design MADE simple: Shedding light on the BS 8887 series of standards and their influence on sustainable design in the UK and beyond’ BSI <https://www.bsigroup.com/Documents/standards/case-studies/BSI-maximizing-performance-BS-8887-design-for-manufacture-assembly-disassembly-and-end-of-life-processing-case-study-UK-EN.pdf>

- ISO 14009, 'Environmental management systems — Guidelines for incorporating material circulation in design and development'

A set of case studies on the circular economy from AFNOR (French Standards Body) includes one on Tarkett Flooring which gives some useful learning & pointers for composites parts manufacturers.²⁸

Other more general guides which may be informative/useful include:

- Guidance on Circular Design from the Ellen MacArthur Foundation²⁹
- European Environment Agency report 'Circular by Design' gives an overview of the drivers for designing for the circular economy and some of the considerations required³⁰

The Composites UK website section entitled 'Design for Environment and LCA' also has a number of useful links.³¹

2.8 Conclusions

The challenges of achieving much greater sustainability with composite parts in future mean that the design for all composite parts will need to be carefully rethought, potentially significantly, and much greater emphasis given to both the use of recycled or bio-based materials in place of virgin materials, and also the ease of recovery and recycling at end of the working life of the part. As with all disruptive changes, this is both a challenge and an opportunity for part designers but is one which will require systematic attention and action, if composite parts are to continue to play a major role in industrial assemblies, combining their clear benefits of light-weight strength and durability with responsible raw material sourcing and end of life management, enabling much greater circularity than today.

²⁸ '6 organizations recount their experience!' AFNOR, Mar 2019 https://www.afnor.org/en/wp-content/uploads/sites/2/2019/04/testimonies_circular_economy2.pdf

²⁹ 'Circular Design', Ellen MacArthur Foundation, <https://archive.ellenmacarthurfoundation.org/explore/circular-design>

³⁰ 'Circular by Design', European Environment Agency, 2017 https://circulareconomy.europa.eu/platform/sites/default/files/circular_by_design_-_products_in_the_circular_economy.pdf

³¹ 'Design for Environment and LCA', Composites UK <https://compositesuk.co.uk/industry-support/environmental/design-environment-and-lca>

3. LCA - UNDERSTANDING IMPACT

Authors: Annabel Fitzgerald, Sophie Parsons

3.1 Introduction

Environmental impact can be defined as a change to the environment as a result of natural or human induced activities. In the context of engineering and technology, environmental impacts may be positive or negative and produced primarily through business activities, products, or services. With critical consequences such as depletion of finite resources and climate change becoming global issues, there is an urgent need to improve understanding of the current environmental impact of products and services. It is through this understanding of current state that problems can be identified, and improvements made. These problems must be viewed by taking a systems perspective, understanding the full life cycle of products and processes. The application of life cycle thinking is crucial to avoid shifting environmental burdens from one stage in a product's life to another. There are several different methods that can be used to quantify life cycle environmental impact, which will be discussed in more detail in the following sections.

Due to their complex nature, new challenges arise when investigating environmental impact of composite materials. The broad range of material combinations available, which are uniquely brought together to satisfy bespoke engineering requirements, often adds an additional level of intricacy to their assessment. While life cycle assessment (LCA) has been widespread amongst environmental engineers and scientists, the increasing societal demand, environmental imperative and shift in government policies to deliver Net Zero have forced a rethink across engineering to adopt LCA as a priority means of quantifying and promoting their businesses. As the demand for LCA studies has been increasing over the last few years, the opportunities for utilising LCA as a methodology not just for post-rationalisation quantification, but for process improvement, design optimisation and other business benefits has been developed across a multitude of research technology centres, academic establishments and by industrial experts.

3.2 Life cycle assessment

3.2.1 Background

LCA is a methodology that can be used to quantify the environmental impact of a product or process through all, or selected stages of its life cycle. The key stages of a lifecycle that are typically considered within this analysis are provided in Figure 3.1.

Because of the breadth and depth of assessment that is possible with LCA, it is becoming a widely used tool in order to assess environmental impact through enabling:

- Benchmarking current environmental impact of product or process
- Identification of environmental hotspots to enable improvements to be made
- Investigation into how long it takes for environmental savings to exceed environmental costs
- Comparison of materials and processes to select the least impactful
- Assessment of the comparison of environmental cost vs. economic cost
- Support for the design of new products/services
- Support for marketing and compliance to public policies



Figure 3.1: Key stages of a life cycle

When conducting an LCA it is important to think about which stages of the lifecycle need to be captured. This is known as defining the system boundaries. The typical systems boundaries that are used include:

- Gate to gate: The manufacturing stage of a product alone
- Cradle to gate: Raw materials extraction through to manufacturing of the product
- Cradle to grave: Raw materials extraction through to product disposal
- Cradle to cradle: Raw materials extraction, full circle back to raw materials

Once the stages of interest have been identified, the environmental inputs and outputs at each stage (or sub-process unit) are captured. Examples of environmental inputs may be materials, energy or water use, and example outputs may be emissions to air, emissions to water, and emissions to soil (Figure 3.2). These are also referred to as elementary flows (material or energy flows entering or leaving the system). These elementary flows at each stage are quantified and grouped together into categories depending on their effect on the environment. These categories are known as impact categories. There are many different impact categories, and LCA allows you to examine multiple impact categories for the same process, to ensure by reducing impact in one area that the impact isn't unknowingly shifted to another impact category. This is known as 'burden shift' and should be avoided where possible.

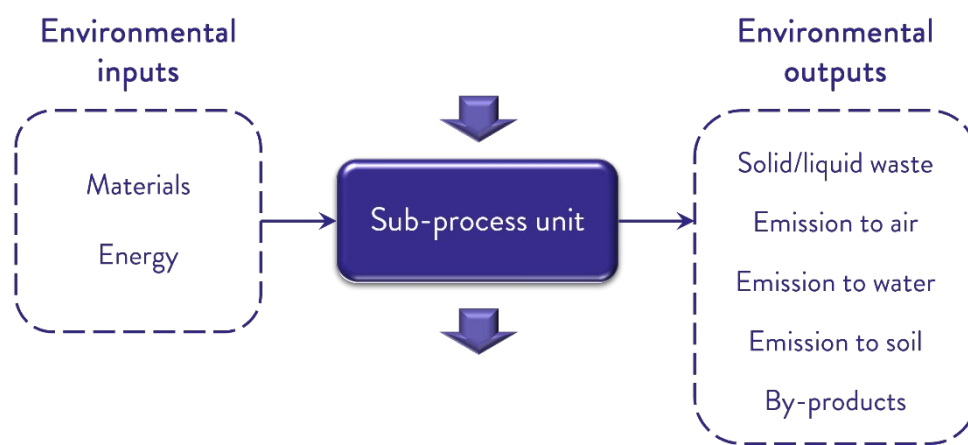


Figure 3.2: Examples of environmental inputs and outputs (elementary flows)

3.2.2 LCA Standards and Framework

The key standards to follow when conducting an LCA include:

- ISO 14040: 2006 – Environmental management. LCA Principles and frameworks
- ISO 14044: 2006 – Environmental management. LCA Requirements and guidelines

These standards provide a framework of the key stages to follow when conducting an LCA. This framework is illustrated in Figure 3.3.³²

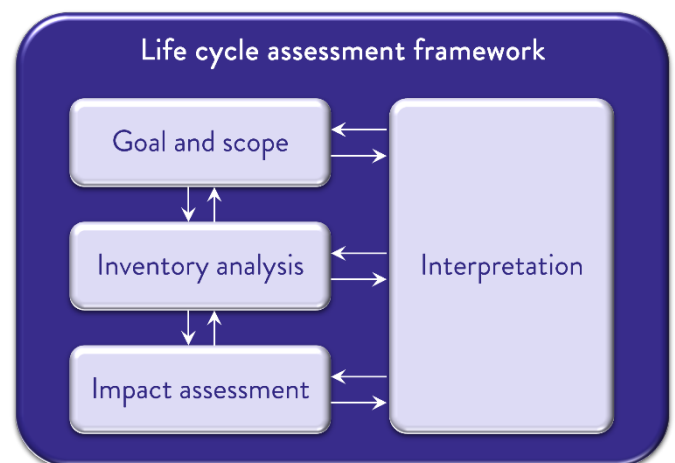


Figure 3.3: The ISO 14040 framework for conducting LCA

Goal and scope

The goal and scope definition occurs at the beginning of the study and is where the intention of the study is set. The goal states the reason for carrying out the study (e.g. marketing, product development, design support, comparison of products, etc), the aims and objectives, the intended audience (internal or external), and who has commissioned the work. Scoping activities identify stakeholders of the study, define the system boundaries (life cycle stages of interest) and impact categories that will be analysed. It also identifies the function of the product and its functional unit. The functional unit is a

³² ISO 14040:2006(en) Environmental Management – Life cycle assessment – Principles and framework

quantifiable performance characteristic of a product system related to its function. It must describe the system, in line with defined goals and objectives, and must be set to allow different products to be compared to fulfil the same function if necessary. The lifetime of the product must also be considered. For example, the functional unit for a pod-based espresso machine could be ‘the use of a coffee pod-based espresso machine making 20 coffees per day for five years’.

At this stage a decision should be made on whether the modelling is attributional or consequential. The basis for this is the aim or goal of the assessment. Attributional LCA looks at understanding what the allocated share of environmental burdens is associated with production, use, and end-of-life of a particular product system. This is the typical form for a product LCA. Consequential LCA, which is often used in policy-orientated settings, aims to understand the full share of environmental burdens that are expected to change when producing, using and disposing of that product. This type of LCA might be used to try and understand total environmental impact of implementing a new technology for example.

Inventory analysis

Inventory analysis is the data collection stage and is considered to be the most time-consuming step for an LCA. The first stage is to identify the process units for which the data is needed (based on the system boundaries defined in goal and scope definition). Following this, a list of all inputs and outputs relating to those process units needs to be collated. This is known as a life cycle inventory (LCI). The LCI is used in the analysis stage to calculate the environmental impacts. A process flow diagram can also be created to visualise all the process stages to be included in the analysis. Figure 3.4 provides a basic example of a multi-disciplinary training process flow diagram, detailing the key process stages involved in making a cup of tea. This process flow diagram provides a visual indication of what will be considered within the LCA study, and therefore which input and output flows (elementary flows) must be captured at each stage. The benefit of creating a process flow map is that it is a quick and easy way of seeing if all of the necessary elementary flows have been captured for each process unit.

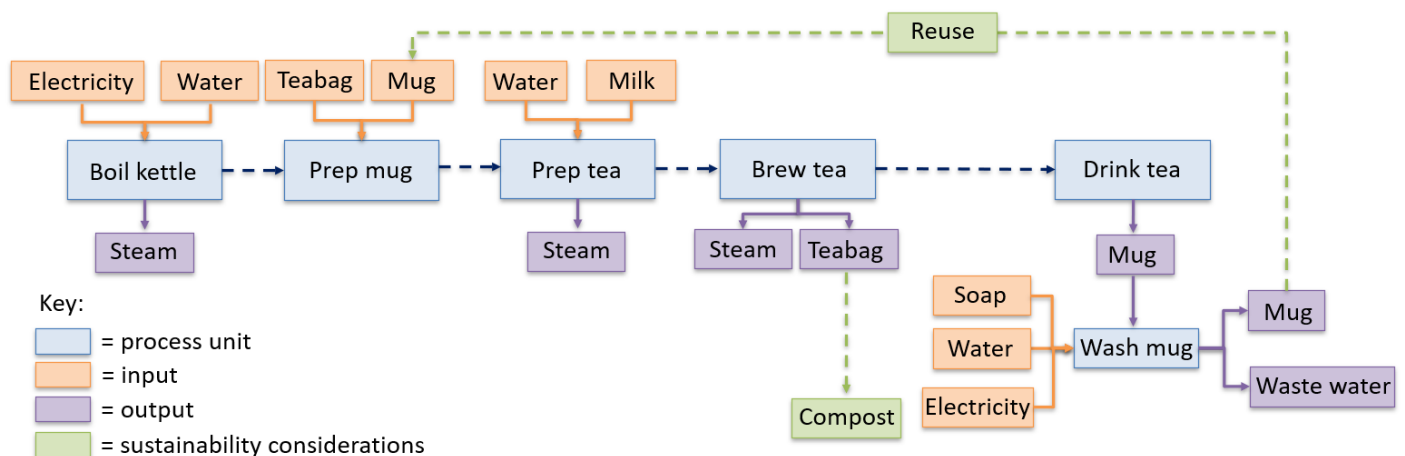


Figure 3.4: Example process flow diagram for making a cup of tea

Data used in the assessment can either be referred to as primary data or secondary data. Primary data has been measured directly from the source and is therefore a more accurate representation of the specific process to be analysed. Secondary data can also be used when it is not possible to measure primary data. This is data recorded within scientific literature, or LCA databases. As using secondary data will not exactly replicate the process under analysis, it is important to use data that is as similar to the process as possible, to ensure the results reflect the real scenario as closely as possible. Any assumptions made or known deviances from the original process parameters must be recorded for transparency. Whilst utilising secondary data is faster for the analysis than directly measuring data, the results will not be as accurate. Any data sources used within an LCA analysis must be recorded in the LCA report.

As well as ensuring the data reflects the processes under investigation as closely as possible, it is crucial to ensure any data that is captured is of the highest quality in order to achieve the best results. As a result, data should be analysed and validated. If data is not of a high enough quality, the collection process should be repeated. To ensure data quality is achieved, the following data quality requirements must be documented:

- Time related factors
- Geographical factors
- Technological factors
- Accuracy, completeness, and representativeness of data
- Consistency and reproducibility of data collection methods
- Data sources and representativeness
- Information uncertainty

Consistency and completeness of data are also important factors to check at this stage. It is important to check that the data gathered is sufficient to proceed, if it is consistent with the goal and scope, and that the methodology and other rules have been accurately and consistently applied for the whole product system.

Impact assessment

This stage is referred to as the Life Cycle Impact Assessment (LCIA). This stage is achieved through using available software packages, where the elementary flows that were captured in the LCI stage are grouped together into their respective impact categories. Examples of elementary flows and their groupings into impact categories are provided in Table 3.1. Impact categories can be further grouped into overall environmental consequences, termed macro-categories.

Table 3.1: Examples of elementary flows, impact categories and macro-categories created based upon GaBi database³³

Example elementary flows	Impact categories	Macro-categories
CO ₂ , CH ₄ , N ₂ O, CFC, HFCs, CH ₃ Br	Greenhouse effect	Ecosystems deterioration
SO _x , NO _x , HCl, HF, NH ₄	Acidification	
PO ₄ , NO, NO ₂ , Nitrates, NH ₄	Eutrophication	
Pesticides, PCB, Pb, Cd, Hg	Ecotoxicity	
Pesticides, PCB, Pb, Cd, Hg	Human toxicity	Human health
HCFCs, CFCs, CH ₃ Br, CH ₃ Cl	Stratospheric Ozone layer reduction	
CO ₂ , NO ₂ , CH ₄ , CFCs, HCFCs, CH ₃ Br	Photochemical smog	
NMHC (C _x H _y) NO _x	Winter smog	
Minerals, fossil fuels, uranium	Reduction of non-renewable resources	Resource reduction
Wood, wind or hydroelectric power	Reduction of renewable resources	

It is important when defining an LCA study to define which impact categories are of interest. This happens within the goal and scope definition phase. The environmental effects for each of the chosen impact categories are quantified in the assessment and can either be reported as separate stand-alone values, or they can be further grouped to give an overall impact for the macro-category or further still, a total environmental impact across all macro-categories to create a single score. Whilst this single score approach allows for a quick comparison of different products or scenarios, the drawback of this approach is that the granularity of the study is lost, and therefore hotspots and burden shift are not as easy to identify.

The characterisation stage assigns some magnitude to the impacts identified. This is done because all of the emissions that contribute to one impact category will not necessarily have the same contribution to the impact. Therefore, the elementary

³³ GaBi database (Sphera) 2021 s.w. 10.5

flows for each impact category are multiplied by a characterisation factor (weighting) to calculate its contribution relative to other elementary flows. This converts each elementary flow into category indicators, which are expressed as ‘equivalents.’ For global warming potential (GWP), LCI data is converted into CO₂ equivalents, while acidification potential converts LCI data to SO₂ equivalents. Environmental impact data is widely reported in this way. Examples of other category indicators and their units are provided in Table 3.2.

Table 3.2: Conversion from LCI data into category indicators for different impact categories using the CML method ³⁴

Impact category	LCI data	Category indicator	Following characterisation	Units
Global warming	CO ₂ , NO ₂ , CH ₄ , CFCs, HCFCs, CH ₃ Br	Global warming potential	Converts LCI data to CO ₂ equivalents	kg CO ₂ -eq (or kg CO ₂ e)
Stratospheric ozone depletion	CO ₂ , NO ₂ , CH ₄ , CFCs, HCFCs, CH ₃ Br	Ozone depletion potential	Converts LCI data to CFC-11 equivalents	kg R11-eq
Acidification	SO _x , NO _x , HCl, HF, NH ₄	Acidification potential	Converts LCI data to SO ₂ equivalents	kg SO ₂ -eq
Eutrophication	PO ₄ , NO, NO ₂ , Nitrates, NH ₄	Eutrophication potential	Converts LCI data to phosphate equivalents	kg Phosphate-eq
Photochemical smog	Non-methane hydrocarbon	Photochemical ozone creation potential	Converts LCI data to ethane equivalents	kg Ethene-eq

There are different LCIA methodologies that can be applied to the inventory data to generate the final LCA results. The most relevant methodology for the analysis depends on the impact categories of interest in the study. This can be discussed with the LCA practitioner at the beginning of the study to ensure the most relevant methodology is used.

There are some additional optional stages that can be conducted following characterisation of LCI data. These include normalisation, grouping and weighting. Normalising the data involves division of LCIA results to a reference value. This can equate to the total use of resources or emissions in a restricted area, or overall use of resources/total emissions in a particular country or region. Grouping is where the impact indicators are grouped to provide a value for the overall macro-category (Impact to ecosystem, impact on human health, impact on resources). Weighting is conversion of the LCIA environmental profile into a single score.

Interpretation

Interpretation is where results that have been generated are analysed to reveal the environmental impact. It is also where the quality of results is assessed, and recommendations are made based upon findings. Results are written up into a report which is subject to a final evaluation to guarantee the reliability of the study through the following checks:

- Completeness check – analysis of any missing or incomplete information.
- Sensitivity check – analysis to understand how the final results are influenced by data uncertainty, assumption, calculation procedures etc.
- Coherence check – assessment of how well the study meets the objectives.

It is important to note that LCA is an iterative process and therefore previous stages may need to be revisited to ensure that the results obtained are relevant to the initial goal and scope, and that the quality of results is acceptable for the study.

³⁴ GaBi Education. Handbook for Life cycle Assessment (LCA). Using the GaBi Education Software Package

Critical reviews should take place throughout the process to check that the study is still relevant to goal and scope, quality of data is acceptable, or if there are any new assumptions. Details about the results, data, methods and assumptions and limitations must be recorded in detail for transparency, so the reader can see exactly how the study was conducted.

Peer review

If the results of the study are to be published in the public domain (e.g. for marketing purposes), then the LCA must be peer reviewed (e.g. through academic publication or via credible and qualified practitioners) to ensure that the methodology is sound, the results are a fair representation and of a good quality. The report must therefore contain the information of the client, the LCA expert, the critical reviewer and other information necessary to make the report completely understandable. Critical reviews are undertaken to ensure that:

- The methods used to perform LCA are consistent with scientifically and technically valid standards.
- The data used is appropriate and reasonable in relation to the goal of the study.
- The interpretations reflect the goal of the study.
- The limitations of the study are identified.
- The report is transparent and consistent, and the type and format are addressed to the recipients of the study.

3.2.3 Commercial software for LCA

There are several LCA packages available to conduct LCA's depending on the level of detail that is required for the study. Some examples of software packages suitable for detailed LCA are provided in Table 3.3. These are typically used by trained LCA practitioners and a strong understanding of LCA methodology is needed to use them effectively. It is important to note that the cost of the software depends on the datasets that are required. While some packages are free to download, datasets need to be purchased for the analysis. Other software packages have a baseline level of datasets included in the standard price, but if additional datasets are needed, this will incur additional costs.

Table 3.3: Examples of LCA software packages

Tool Name	Supplier	Main Database	Free?	Free trial
GaBi	Sphera Solutions, Inc.	GaBi (covering range of sectors), ecoinvent, US datasets, EU Environmental Footprint	No	Yes
SimaPro	Pre Consultants B.V.	Multiple, largest being ecoinvent	No	Yes
OpenLCA	GreenDeltaTC GmbH	Software only. Free (e.g. EU Environmental Footprint) and paid for (e.g. ecoinvent) databases available as add ins	Yes	N/A

Numerous simplified LCA tools have been developed and many are available for free online, some of which provide a selection of carbon footprint and/or embodied energy, and others provide a range of impact categories. These are variable in their methodology and sources of data, and care should be taken when using them. A range of LCA software options is listed in Appendix 4: LCA software packages. Different software packages currently have differing levels of composites related data sets. It is therefore important to understand the availability and statistical nature of data sets that are provided within the software to understand whether it will meet the project requirements.

The European Composites Industry Association (EuCIA) has developed the free Eco Impact Calculator tool, often referred to as EcoCalculator, specifically for composites covering a range of impact categories. This uses data from manufacturers and materials suppliers across Europe, as well as databases such as ecoinvent.

3.3 Life cycle costing (LCC) and social life cycle assessment (S-LCA)

Environmental considerations are just one of the three pillars of sustainability. The other two are social and economic (Figure 3.5). There is growing interest in social life cycle assessment (S-LCA) as organisations look to quantify social impacts. Social considerations determine the effects on the people involved including workers, local communities, society and consumers, and investigate aspects such as human rights, working conditions and health and safety. Economic sustainability, evaluated through life cycle costing (LCC) refers to long term economic growth without negatively impacting social and environmental aspects. Combining these approaches is often referred to as life cycle sustainability assessment (LCSA).

LCSA is often represented as the following:

$$\text{LCSA} = \text{LCA} + \text{LCC} + \text{S-LCA}$$

For conventional LCC there are several industry standards, ISO 15686 (buildings and constructed assets), ISO 15663 (petroleum and natural gas industries). Cost over the lifetime of a product or system can be expressed in a number of ways, including whole-life costing, through-life costing, and total cost of ownership. Conventional LCC deals only with direct monetary cost, however it is possible to consider environmental or social costs as part of LCC. This type of LCC follows the ISO 14040/14044 LCA standards.

Compared with environmental LCA and its established frameworks and standards, S-LCA is a relatively new assessment method, with literature typically presenting a very broad range of approaches. Types of impact categories covered by S-LCA are: worker related issues like child labour, forced labour, working conditions and access to training; society related issues like corruption, and support and investment in local communities; and product-user related issues like consumer health and safety, and transparency of product information. Challenges with S-LCA include establishment of causality between processes and impact. This depends on multiple factors that can be difficult to quantify such as company culture or conduct. They also include the ability to draw comparison between the presence of a product or system and the absence of that product or system. This adds uncertainty and makes drawing comparisons difficult.

One important method for S-LCA developed by the United Nations Environment Programme (UNEP), is described in 'Guidelines for Social Life Cycle Assessment of Products'.³⁵ A free to download social impact audit tool in Excel, based on the UNEP guidelines has been developed by Ansys.³⁶

As with S-LCA, LCSA is far less mature as an assessment method when compared with LCA and comes with additional decision-making challenges in terms of how each of the three pillars of sustainability are viewed. Notwithstanding this, as organisations look to align themselves with approaches like the Sustainable Development Goals (SDGs) interest in LCSA in one form or another is likely to grow.

3.4 Tailoring LCA for decision making

LCA capability is undertaken by LCA practitioners to meet customer requirements. It is important when planning an LCA study to understand the overall purpose of the LCA, the level of detail that is required, and the target audience for the findings. These are typically captured and recorded in the goal and scope of the study.



Figure 3.5: Three pillars of sustainability

³⁵ 'Guidelines for Social Life Cycle Assessment of Products' UNEP/SETAC, 2009 <https://www.unep.org/resources/report/guidelines-social-life-cycle-assessment-products>

³⁶ 'Paper: Social Life-Cycle Assessment and Social Impact Audit Tool' Ansys 2021 <https://www.ansys.com/academic/educators/education-resources/paper-social-lifecycle-assessment-and-social-impact-audit-tool>

There are different types of approach that can be taken depending on the purpose of the study. For example:

- Benchmarking LCA – Assesses current state with regards to environmental impact.
- Costing LCA – Assesses economical cost against environmental cost at relevant stages of product lifecycle.
- Comparison LCA – Compares one product against another in different scenarios, i.e. material choice.
- Payback LCA – Assessing how long it takes for environmental benefits to overtake the environmental costs of producing the product.
- Targeted LCA – Highlights which parts of the product are the most impactful, enabling recommendations to be made to improve environmental impact.

The National Composites Centre notes that whilst all levels of complexity can be achieved, the key factor that needs to be established at the beginning of the work is the level of granularity required. This can be from rapid/screening assessment methods, to in depth peer reviewed LCAs using available software packages. This will influence what will be examined as part of the study, the tool required to make the calculations, the likely timescales required and the depth of expertise from LCA practitioners required.

All methods ensure compliance with the ISO 14040 framework but work to different timescales. Rapid LCA assessments are often utilised early in the design stage to make quick decisions. They are typically used by internal teams for materials selection and product development purposes. They may only consider one impact category and often only cover a limited portion of the product lifecycle. Whereas more complex LCA studies often include a larger array of impact categories within the study as well as covering a larger portion of the product lifecycle. These studies take longer to run but provide more detailed findings, and a more well-rounded view of the environmental impact. When the findings of an LCA require publication into the public domain, they also need to undergo a peer review from independent LCA specialists. Therefore, additional time needs to be factored into the study to enable the peer review to take place.

An example of the application of these approaches is provided in an LCA case study conducted by the National Composites Centre, comparing jute to carbon fibre: 'Cost and performance vs environmental impact: Using natural fibres in composite car panels'.³⁷ This was created for the purpose of demonstrating how LCA can be applied to composites to answer some key sustainability questions to real world problems.

3.5 Standards for application of LCA at product or project level

3.5.1 EPDs and PCRs

An Environmental Product Declaration (EPD) is a short document that describes how a product impacts the environment, and thus can be used as proof of a products' environmental credentials. It is based upon the findings from a LCA and is translatable across different countries. This is known as a Type III Environmental Declaration as defined in ISO 14025³⁸ and can be registered in programmes operated by the Building Research Establishment (BRE)³⁹ and the EPD International AB⁴⁰.

Product Category Rules (PCRs) provide guidance for categories of products, to enable equitable comparison across EPDs. PCRs describe the product category, the goal of the LCA, functional units, system boundaries, cut-off criteria, allocation rules, impact categories, information on the use phase, units, calculation procedures, requirements for data quality, and other information. Core PCRs for EPDs for construction products are defined in EN 15804.⁴¹ ISO 14025 establishes the peer-reviewed procedure for developing PCRs different categories.

³⁷ 'Cost and performance vs environmental impact: Using natural fibres in composite car panels', NCC
<https://www.nccuk.com/news/project-salsa/>

³⁸ ISO 14025:2006 'Environmental labels and declarations – Type III environmental declarations – Principles and procedures'

³⁹ <https://www.greenbooklive.com/search/scheme.jsp?id=260>

⁴⁰ Environdec <https://www.environdec.com/>

⁴¹ BS EN 15804:2012+A2:2019 'Sustainability of construction works. Environmental product declarations. Core rules for the product category of construction products'

EPDs are primarily used in construction, but increasingly PCRs have been developed for other areas such as food and vehicles.



Cubis Systems carry out EPDs for many of their products, including this GFRP RapidSTACK™ chamber. Photo courtesy of Cubis Systems.

3.5.2 BIM, BREEAM and CEEQUAL

BREEAM is the Building Research Establishment (BRE) Environmental Assessment Method.⁴² It sets best practice standards for the environmental performance of buildings through design, specification, construction and operation. CEEQUAL (Civil Engineering Environmental Quality Assessment)⁴³ assesses sustainability performance in civil engineering and infrastructure projects and was acquired by BRE in 2015 to operate alongside BREEAM. BREEAM assessments involve scoring according to environmental criteria, with weighting to achieve an overall score.

Building Information Modelling (BIM) has now been adopted in many countries and tracks information for buildings and infrastructure assets from design stage, through construction management and facility operation. It has been mandated at level 2 for public sector projects (in England and Wales) since 2016⁴⁴, and some local authorities may require it through planning conditions.

- Level 2 involves developing building information in a collaborative 3D environment with data attached but created in separate discipline models.
- Level 3 will include a single, collaborative, online, project model including construction sequencing, cost and lifecycle management information.

Using BIM data generated during design and build over the whole project lifecycle should enable faster, safer, less wasteful construction and more cost-effective, sustainable operation, maintenance and eventual decommissioning.⁴⁵ The real value

⁴² BREEAM <https://www.breeam.com/>

⁴³ CEEQUAL <https://www.ceequal.com/>

⁴⁴ HM Government. Industrial strategy: government and industry in partnership. Building Information modelling

⁴⁵ Shennan, 'BIM advances sustainability' 2014 Mott MacDonald <https://www.mottmac.com/views/bim-advances-sustainability>

of BIM will only truly come into play when BIM level 3 is adopted. A suite of standards has been published covering the format for storing data, mainly BS EN ISO 19650 parts 1, 2 and 5.⁴⁶

BREEAM and CEEQUAL can integrate with BIM, so the development of BIM to level 3 will enable more effective environmental impact throughout the lifecycle of built assets. Leadership in Energy and Environmental Design (LEED) by the US Green Building Council is a similar scheme.⁴⁷

3.5.3 European Commission's Product Environmental Footprint Category Rules

An important aspect of the European Commission's Circular Economy Action Plan is development of a harmonised methodology for the calculation of the environmental footprint of all products and organisations, called the 'Single Market for Green Products Initiative'.⁴⁸ A methodology was developed between 2011 and 2013, which has now been trialled in several product areas and developed further to create Product Environmental Footprint Category Rules (PEFCRs) for products as diverse as apparel, cut flowers and marine fish. It has also been developed for organisations as the Organisation Environmental Footprint Category Rules (OEFCRs). This is intended to increase reproducibility and consistency in product environmental footprint studies to enable a policy framework that will make sustainable products, services and business models the norm.⁴⁹

PEFCRs provide detailed technical guidance to complement general methodological guidance for environmental footprint for specific product types. PEFCRs follow the 'Product Environmental Footprint Category Rules Guidance', not ISO 14025, on the basis that "existing life cycle-based standards do not provide sufficient specificity... to support comparability of environmental claims".⁵⁰ So PEFCRs may not be compatible with EPD PCRs.

3.6 Carbon footprinting

A product carbon footprint exclusively measures greenhouse gas (GHG) emissions produced throughout a products life cycle. These can be reported separately as carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O) etc. or as kgCO₂-equivalents which includes all GHGs taking into account their GWP relative to CO₂. A carbon footprint calculates GWP (usually considering climate impact over 100 years, i.e. GWP₁₀₀) pertaining to emissions of suppliers, customers and distributors that are related to the manufacture and use of the product. It also registers any impacts associated with waste or recycling.⁵¹

For corporate reporting, the Greenhouse Gas Protocol standards distinguish emissions as being either direct (Scope 1) or indirect (Scope 2 & 3).⁵² Scope 1 emissions relate to everything produced directly by the company such as fuel combustion or process emissions. Scope 2 relates to emissions from electricity production. Scope 3 is anything upstream or downstream the company does not have direct control over.

Carbon footprinting can be certified through a range of different channels. These are internationally recognised and can be a way of effectively communicating the impact of the product.

- Publicly Available Specification (PAS) 2050⁵³
- ISO 14067 – Greenhouse gases – carbon footprint of products – requirements and guidelines for quantification⁵⁴

⁴⁶ BS EN ISO 19650-1/2/5 Series Kit 'Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM). Information management using building information modelling'

⁴⁷ LEED <https://www.usgbc.org/leed>

⁴⁸ 'Single Market for Green Products Initiative', European Commission, <https://ec.europa.eu/environment/eussd/smgp/index.htm>

⁴⁹ https://ec.europa.eu/environment/eussd/smgp/dev_methods.htm

⁵⁰ 'Product Environmental Footprint Category Rules Guidance' Version 6.3, p.23, May 2018, https://ec.europa.eu/environment/eussd/smgp/pdf/PEFCR_guidance_v6.3.pdf

⁵¹ 'Carbon footprinting guide', Carbon Trust, 2018. <https://www.carbontrust.com/resources/carbon-footprinting-guide>

⁵² Greenhouse Gas Protocol <https://ghgprotocol.org/>

⁵³ BSI PAS 2050 <https://www.bsigroup.com/en-GB/about-bsi/media-centre/press-releases/2011/9/NEWLY-REVISED-PAS-2050-POISED-TO-BOOST-INTERNATIONAL-EFFORTS-TO-CARBON-FOOTPRINT-PRODUCTS/>

⁵⁴ ISO 14067:2018 Greenhouse gases – Carbon footprint of products – requirements and guidelines for quantification

■ GHG Protocol Product Lifecycle Accounting and Reporting Standard⁵⁵

For organisations looking to make claims around carbon neutrality or being zero carbon, measurement of GHG emissions through carbon footprinting enables carbon offsetting to be considered. This is where carbon emissions created through a certain activity (like driving) can be compensated for by undertaking an activity to remove the same amount of carbon from the atmosphere (such as tree planting). The carbon removing activity must be completely separate from the carbon creating system for it to work. See also section 7.5 ‘Carbon neutral, net zero and carbon markets’.

3.7 Concluding remarks

LCA and other environmental impact calculation methodologies are becoming increasingly important in the pursuit of net zero and preservation of the environment. Using these methods to benchmark current environmental impact is a crucial step for any product or organisation in understanding where improvements can be made. There are many methodologies available depending on project requirements and timescales, which can be discussed with specialists at the beginning of the study. As well as considering environmental sustainability, to ensure a truly sustainable system, the social and economic pillars must also be considered.

⁵⁵ ‘Greenhouse Gas Protocol. Product Life Cycle Accounting and Reporting standard’
https://ghgprotocol.org/sites/default/files/standards/Product-Life-Cycle-Accounting-Reporting-Standard_041613.pdf

4. USING RECYCLED MATERIALS

Author: Nigel Keen

This chapter will focus on commercially available recycled materials formats, where they find the most appropriate uses in new composite products, and the allowances and benefits that make this viable. Available materials with recycled content supplied by Composites UK members are listed at '[Materials with Bio/Recycled Content](https://compositesuk.co.uk/industry-support/environmental/materials-with-bio-recycled-content/)'.⁵⁶ End-of-life (EOL) and recycling processes are described in chapter 8.

4.1 Introduction: Why should we use recycled materials?

4.1.1 Environmental and corporate responsibility

Many of the component materials in composites products are high in embodied energy. They come from oil extraction, mining or agriculture, and through industrial processes, all of which have environmental impacts related to energy and water use, generation of pollutant wastes, or damage to habitat and natural environments. When these materials are recovered, re-purposed, or in some cases simply sequestered for an extended period beyond first use, this mitigates these impacts.

In life cycle assessment (LCA) much depends on the assumptions made, but if one assumes the environmental impacts of virgin materials are 'written off' during their first product cycle, then the impacts of secondary materials in the life cycle inventory for subsequent re-use applications can validly be presented as those arising solely from the collection, recovery and recycling, and remanufacturing processes, especially if the envisaged end of life is further recycling. This means that if recovered or 'secondary' materials can partially substitute or replace completely virgin materials, it will make a significant contribution to reducing the environmental impact and improving the LCA case for a product or process.

Recycled carbon fibre (rCF) can have significantly less environmental impact than virgin material, having around 20% of the global warming potential (GWP) when incorporated as a random fibre into a composite, though this is very dependent on the fibre volume fraction (FVF), fibre alignment and design criteria.⁵⁷

Where weight is a factor, recycled carbon compares favourably with virgin GFRP, especially in stiffness driven applications. Where weight is not an issue, steel is actually a good material from a purely environmental perspective. Final material selection will always involve factors such as cost, production rate capability, environmental performance and other physical and mechanical properties.

4.1.2 Cost savings and profit margin

The other reason to recycle is economic. Environmental audits that look closely at manufacturing site waste streams and energy usage can be an extremely rewarding exercise. Secondary materials are often significantly cheaper than virgin materials. It may also be possible to self-source by repurposing in-process waste, out-of-life, end of line, and returned and unwanted products, and thereby reduce waste disposal costs too. To do this, behaviours may need to be changed on the factory floor to more rigorously segregate waste streams. Recycled materials may be deployed differently within a company's products compared to virgin materials to achieve a cost/benefit win. Savings on waste disposal and reduced virgin materials spend will be offset by the site footprint, labour and energy use for any recovery and recycling equipment, or additional production equipment, as well as any required modification additives, and so these other factors need to be carefully considered.



Carbon fibre recycling.
Photo courtesy of Gen 2 Carbon

⁵⁶ 'Materials with Bio/Recycled Content', Composites UK <https://compositesuk.co.uk/industry-support/environmental/materials-with-bio-recycled-content/>

⁵⁷ Meng F, McKechnie J, Turner T, Wong KH, Pickering SJ, 'Environmental aspects of use of recycled carbon fibre composites in automotive applications', Environ Sci Technol. 2017;51(21):12727–36

4.1.3 Supply security

Carbon fibre in particular has a projected shortfall in supply, as increased demand for lightweight materials, including hydrogen pressure vessels, comes on stream and the existing supply chain, which primarily caters to aerospace and motorsport and increasingly wind energy markets, is stretched. rCF can fill some of those gaps, by keeping virgin materials for aligned long fibre formats, substituting rCF into hybrid and discontinuous formats for intermediate performance products, and completely replacing the use of virgin materials in many short and milled fibre products. With high value materials in particular, the more times fibres can be reused, the better it is for both the environment and the economy.

4.1.4 National GDP impacts

The UK is a net importer of raw materials and semi-finished goods for use in composites manufacturing and also has one of the worst records amongst developed nations for effective recycling, particularly of plastics. Because of the UK's poor segregation and recovery, and the limited market for secondary materials here, the publicly quoted recycling rates often mask routine shipment overseas to developing nations where, rather than being recycled, they cause major environmental, social and economic damage to cultures and populations that are not equipped to deal with their own waste let alone ours too.

The true value of materials needs to be recognised. Recycling often focuses on repeated use in single-use short-lifespan products, but by contrast, composites can provide a route to re-use in high value products, or if not high value, then a route to sequestering them in durable long-lifetime products that can themselves be recycled much later.

Apart from positive environmental and reputational benefits, this could also have significant positive impact on UK national GDP. Effective recycling and materials circularity reduces imports, creates new value-adding jobs in collection, recycling processes and new secondary materials markets, encourages 're-shoring' and a stronger UK manufacturing base making products with higher UK-sourced materials content, and creating UK-developed intellectual property (IP), products and technologies that then can be exported in turn.

4.2 Overview of available secondary and recycled content materials

The first step for many manufacturers and 'green' product developers is to know what their palette of materials options looks like if they are determined to maximise or include recycled content in their product or components. The schematic below shows the correlation between the number of recycling steps and processes, and the increased value and performance of the secondary materials created moving left to right

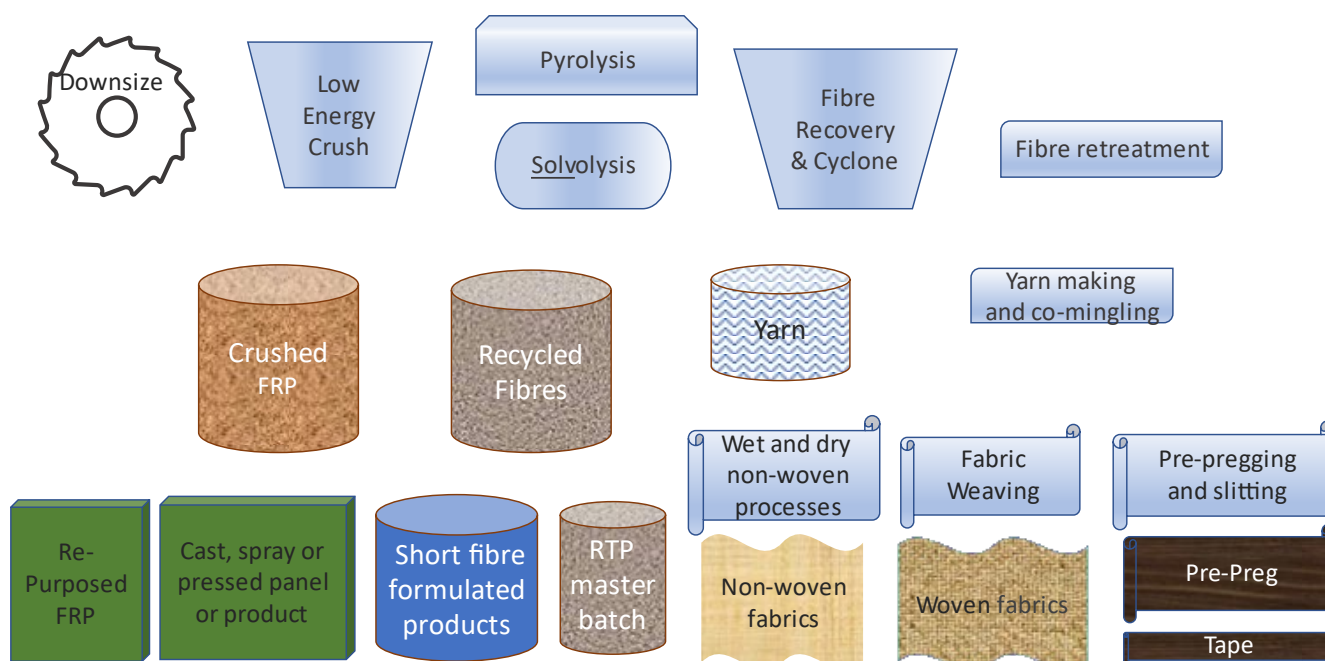


Figure 4.1: Overview of composite recycling processes and resulting materials

4.3 Materials from recycled carbon fibre reinforced polymer (CFRP) composites

Carbon fibre (CF) has both a high intrinsic cost and high carbon footprint. Recycling CF therefore offers both the highest potential economic value and biggest environmental impact, and so has been the main focus of composites recycling R&D and commercial efforts to date. High-performance applications where CFRP is the preferred material often require best possible mechanical and structural properties, requiring long fibres in unidirectional prepregs, woven fabrics or continuous tapes, tows or yarn formats. Finding room in a CFRP product design to incorporate recycled materials with lower performance characteristics can therefore be a challenge.

Fibre alignment is a key determinant of stiffness in the alignment direction and strongly influences the maximum FVF possible and the compaction forces required to achieve it. The performance hierarchy for composites moves downwards from unidirectional (UD) long fibres, UD layered plies and stitched UD fabrics, 2D spread tows, wovens, then 3D knitted and woven thick plies, combination mats and stitched discontinuous aligned fibre fabrics, random chopped strand mats and finally short fibre nonwovens and random orientation filled materials

Fibre length is also important, particularly for transfer of structural loads across large components. Recycling processes usually reduce both the length and strength of fibres, and often break up fibre bundles, and so recovered/recycled carbon fibre can rarely be a 'drop-in' replacement for virgin materials. Finding the way to maximise the benefit of new rCF intermediates in products is therefore key.

Fibres recovered thermally or chemically will have had the sizing removed so may need retreating or sizing before they are resin impregnated if being reused back into a thermoset composite product. The fibres may have sustained some surface damage and while they will retain most of their stiffness, there will be a drop-off both in fibre strength, and the interfacial strength between matrix and fibre. For stiffness-dominated applications, such as bulking plies in prepreg tooling or interior plies in semi-structural panels, this may not be such of an issue. The lack of fibre size could also potentially be an advantage in applications that require new specific sizing or fibre treatments, or in thermoplastic composites where the fibre-to-matrix bond is physical rather than chemical, such as is the case with polypropylene thermoplastic composites. See also section 8.11.1 on recycled fibre surface properties, and chapter 8 generally for a comparison of recycling processes.

4.3.1 Long fibres recovered from fabric or pre-form

CF recycling processes have the potential to recover intact CF architecture from out-of-life prepregs, or panel type products, provided they are fairly uniform and not so thick that hot processing damages the surface fibres excessively before the resin is burnt off.

Recovery of full fabrics or pre-forms is a bespoke rather than standard activity for commercial CF recycling companies. While no 'standard' product formats of this sort are available 'off the shelf', toll or contracted-out materials recovery might be an option to consider if you have a suitable waste stream and re-use opportunity.

A research project involving B&M Longworth, the National Composites Centre and Cygnet Texkimp has demonstrated recovery of intact tows from a carbon fibre over-wrapped pressure vessel using pressolysis. Cygnet Texkimp was able to reuse the tows in manufacture of a new pressure vessel.⁵⁸

⁵⁸ 'UK team successfully recycles reclaimed continuous carbon fibres from composite pressure tanks', National Composites Centre, 3/5/22 <https://www.nccuk.com/news/uk-team-successfully-recycles-reclaimed-continuous-carbon-fibres-from-composite-pressure-tanks/>

4.3.2 Highly aligned recycled fibre formats

The universities of Nottingham and Bristol have both developed processes to align short fibres, which can use fibres from pyrolysis, solvolysis or from offcuts / edge trim, etc, from fabric conversion processes.⁵⁹ A more aligned fabric or tape can lead to improved FVF and hence better mechanical properties of the finished composite. Lineat Composites is commercialising the HiPerDiF process from University of Bristol as 'Aligned Formable Fibre Technology' (AFFT™). The AFFT tapes are highly aligned discontinuous fibre tapes which can be used as a direct substitute for continuous fibre UD tapes, but with improved formability with strains up to 20% as fibres can move relative to each other during moulding. This technology has recently been demonstrated in collaboration with Wilson Labs, fabricating a tennis racquet incorporating 50% reclaimed carbon fibre from a broken racquet.⁶⁰



Carbon fibre tennis racquet incorporating 50% reclaimed carbon fibre, aligned using Lineat technology. Photo courtesy of Lineat

4.3.3 Random and partially aligned carded nonwoven fabrics and yarns

Some fibre formats use waste materials from fibre to fabric conversion processes and are available direct from the fabric suppliers and converters. These waste streams, such as the edge trim from looms, end-of-roll fabric and returned or unwanted stock, retain the sizing and can be reused in different ways. Typically, they are chopped up and processed into random mats or felts, but it is possible to align them and stabilise them in various ways so they can provide a semi-aligned ply.

Recycled CF fabrics have been produced using a carding process where up to 85% of the fibres are aligned. Research projects have also demonstrated production of CF/thermoplastic yarn product where chopped CFs are spun alongside continuous thermoplastic fibres, e.g polypropylene or rPET, to provide high recycled content yarns. These yarns can then be pultruded or converted into woven fabrics. However, some commercialisation routes have indicated that the gain in mechanical properties from these partially aligned formats were not sufficient to justify the extra cost. A higher degree of alignment is needed to make substantial gains in FVF.

Random oriented nonwoven rCF mats are available commercially, whether from “virgin” waste from fabric converters or dry fibre offcuts, or from prepreg offcuts which have been thermally processed to recover the fibres. 100% rCF mats from 50-500 gsm can be infused with thermoset resins or made into prepregs. Due to the relatively lofty fabric form, they are best suited for compression moulding processes in either dry or prepreg forms, and have excellent drapability and a good ‘flow’ into complex mould shapes e.g. as overmoulding material. They are also used today in vacuum infusion (dry mats) and autoclave (prepreg mats) processes.

The mats can also be produced comingled with a range of thermoplastic fibres, typically with 20-45 wt% CF in aerial weights from 100-500 gsm. Again, these are best suited to compression moulding, or can be pressed into pre-consolidated sheets (organosheet), or tailored into dry fabric thermoplastic composites preforms. Thermoplastic pre-forms can be vacuum formed in ovens or heated tooling directly into net shape components.

⁵⁹ Liu, Turner et al, 'Effect of fibre length and suspension concentration on alignment quality of discontinuous recycled carbon fibre', 20th International Conference on Composite Materials, Copenhagen, 19-24th July 2015

⁶⁰ 'World's first recycled carbon fibre tennis racket utilising Lineat AFFT technology', Lineat 9/6/22 <https://lineat.co.uk/worlds-first-recycled-carbon-fibre-tennis-racket-utilising-lineat-afft-technology/>

At relatively modest carbon contents and with thermoplastic matrices, these products offer a good balance of stiffness, toughness and cost somewhere between a virgin GF and virgin CF product.

These materials are aimed primarily at relatively thick structural or thinner semi-structural components, sometimes in conjunction with virgin aligned fabrics where stresses are highest. Applications are in low volume automotive, aerospace interiors, wind energy, marine and tooling. Commercial products include those from Gen 2 Carbon⁶¹ and Sigmatex⁶² in the UK. See Prodrive case study below, and Sigmatex case study at section 6.3.

4.3.4 Other random oriented formats

Most composite recycling processes rely on chopping and shredding technology to reduce the size of the waste to be reprocessed. The 'long' fibres recovered are therefore usually between 12 and 25mm, depending on the process. Thermal / chemical processes also remove sizing and change the surface activity of the fibres, which can significantly affect the interfacial strength between fibre and matrix. The fibres are recovered dry from pyrolysis, and wet from solvolysis, and longer fibres can be made into discontinuous fibre intermediates, mostly mats and veils, as described above.

Longer dry fibres in the 10-25mm range are often recovered as a fluffy tangle because the fibre bundles and tows in the original format are split by the process. Handling the fluff and getting the fibres back into a useable nonwoven format requires different methods compared to making a nonwoven mat or tissue from virgin fibre chopped strands, and the rCF products process differently in terms of wettability, required compaction force, infusion characteristics etc.

Wet fibre recovery processes offer the opportunity to re-size or surface treat the fibres during the recovery process and use wet-lay techniques more like paper making, to produce nonwoven formats. These formats conform more closely to performance expectations from virgin material sourced products and can deal with fibre lengths much shorter than dry processes, usually to make fine rCF veils and tissues but can also be directly deposited while wet into net shape preforms. These wet-laid veils provide an excellent surface finish and are available from Technical Fibre Products.⁶³

Chopped rCF sprayed onto wire mesh preform tools, or even direct into tooling can be used to make semi-structural parts or be selectively reinforced with virgin long fibre or even metals to add structural capability. Wet-press and thermoplastic stamping processes which typically have short liquid or melt flow-paths, provide high levels of compaction to gain FVF, while overcoming lower infusion rates and permeability issues with rCF nonwovens. The chopped spray approach has also been explored for pressed panel type products and to produce semi-aligned preforms by masking and spraying the fibre through slots or extruding through nozzles. Hybrid product formats have also been developed that use rCF short fibre reinforced thermoplastics as low cost but stiff cores, foams and honeycombs between metal or reinforced thermoplastic 'organosheet' skins for hot stamping processes.

Composite products such as sheet moulding compounds (SMC), bulk moulding compounds (BMC) or long fibre reinforced thermoplastics typically use bulk chopped fibre and the compounding process can readily include compatibilising agents rather than separately re-sizing the fibre. The fluffiness of recycled fibres presents a challenge in incorporating in traditional SMC as the fibres may not be free flowing, so often the fibres are first made into a felt. Recycled content and recyclable components using these materials can offer advantages for the automotive sector where they can make a significant difference when trying to meet End-of-Life Vehicle (ELV) Directive objectives for recyclability and re-use, while also keeping weight down and performance competitive. BMW have led the field by acquiring or corralling a captive supply chain for materials and production expertise and designating non-cosmetic structural and semi-structural components within their i-series cars to accommodate the in-process waste, converted to SMC, from their structural and high cosmetic carbon waste streams.⁶⁴

⁶¹ Gen 2 Carbon Products <https://www.gen2carbon.com/products/>

⁶² Sigmatex Recycled Fabrics <https://www.sigmatex.com/recycled-fabrics>

⁶³ Technical Fibre Products <https://www.tfpglobal.com/products/composite-materials>

⁶⁴ Joachim Starke, 'Carbon composites in automotive structural applications' EuCIA: Composites and Sustainability, 19/3/16, <https://eucia.eu/userfiles/files/Starke-Eucia%202016-V4-Druck%20b.pdf>

Case study: Reclaimed carbon fibres for cost-effective, lightweight automotive body panels

Matt Bradney, Prodrive Composites

Prodrive believes that the use of waste streams within a re-use or re-manufacturing application is vital to the sustainability of composite applications. They developed a unique process of combining reclaimed carbon fibres (rCF) with a liquid resin to create cost effective lightweight automotive body panels.

This was demonstrated in a project in partnership with Brahms Electric Vehicles, HPL Prototypes & ELG Carbon Fibre (now Gen 2 Carbon). Large exterior body panels (tailgate, roof, A-Pillars and body sides) were produced in rCF composite for an electric hearse, looking for cost reductions and increased production rates. The largest of these panels were produced using a low-cost infusion process, which has additional benefits from an environmental and sustainability perspective. Mould tools were also produced using reclaimed rCF prepreg tooling material which was hand laminated onto a traditional tooling board pattern.

Building upon this and other projects, Prodrive has now industrialised the applications to enable production of automotive structures, components and assemblies. A key structural panel is a bodyside which is bonded to an extended steel chassis to create an incredibly stiff and strong structure. This is a single piece moulding produced from rCF, with strategic virgin carbon fibre at the loading points for additional safety and structure. These components and mould tools can be put through a recycling process to give the composite materials a third, and possibly more, useful lifetimes – a circular process for sustainable composites manufacturing.



Recycled carbon fibre tooling for hearse tailgate structure. Photo courtesy of Prodrive Composites



Wilcox hearse with recycled carbon fibre bodyside. Photo courtesy of Prodrive Composites

4.3.5 Milled and short fibre

Even shorter recovered carbon fibres, replacing virgin milled fibres, are currently the most commercially viable secondary material format, and have both high-end niche applications and bulk volume uses.

Short and milled carbon fibre is used in a surprising variety of products, such as carbon reinforced concrete, brake discs, high strength adhesives, conductive and anti-static coatings and short-fibre carbon reinforced high performance thermoplastics.^{65 66} The fibres are mainly dispersed into intermediate formats before manufacturing, such as into short fibre masterbatch pellets, or doughs for extrusion or press moulding. This has advantages in that it minimises the handling and health and safety issues associated with dry fibres, which because they are electrically conductive, can also cause issues with equipment.

The materials selection case for replacing virgin cut and milled fibre with rCF (lower cost, and 10 to 20 times lower environmental footprint⁶⁷) is often easy to make. Using rCF, with perhaps only minor formulation tweaks, can completely change the profitability and marketability of a high-performing product and open up new markets and applications. Using rCF to replace other fibrous, crack-stopping additives, glass, thermoplastic and metal fibres in bulk materials can give interesting intermediate properties that reduce weight and/or the thickness of material required to achieve the required strength or stiffness, and so create competitive performance advantages as well as cost benefit.

4.4 Materials from recycled glass fibre reinforced polymer (GFRP) composites

Glass fibre is a much cheaper and less energy intensive material than carbon fibre. Made substantially from natural mineral silicate sands, the various glasses used in composites, with E-glass being the most commonplace, all have specific constituent contents required to achieve the desired mechanical, electrical and corrosion resistance properties and processing temperatures.

The commodity nature of glass fibre means that the savings to be made by recycling it are harder to achieve. Even at the glass fibre manufacturing stage itself, it is often uneconomic to recycle the in-process waste fibre back to be remelted in the kilns. The alumina-borosilicate which is the main constituent of E-glass is also undesirable in normal bottle glass (A Glass) cullet recovery schemes as the high boron content has an adverse effect on the melt viscosity needed for blown glass. Regardless of boron content, glass constituents that make low melt viscosities ideal for pulling fine diameter fibres through bushings, are not ideal for bottle blowing which needs higher glass melt viscosities. Reducing the boron content is a health and safety goal for the glass manufacturers so the lower boron content E-CR glass and zero boron glasses are now becoming the norm, replacing standard E-glass in many GFRP applications and delivering superior water and acid resistance at the same price and mechanical performance.

4.4.1 Repurposed GFRP products

The preferred option in the traditional waste hierarchy is always to repurpose or life-extend a product, or disassemble structural elements of it for reuse, rather than break it up to recycle constituent materials.

Charity and community schemes exist that take offcut or unwanted GFRP panel and sheeting, dismantled truck parts etc, and repurpose them into bespoke sheds and shelters. By cutting and trimming the original part and assembling it into something else, these projects retain the original attributes of water and weather tightness, corrosion resistance and structural stiffness, creating sustainable products that would otherwise utilise new materials.

⁶⁵ Milled carbon fibre powder, easycomposites <https://www.easycomposites.co.uk/milled-carbon-fibre-powder>

⁶⁶ Milled Fibers, Toray https://www.cf-composites.toray/products/carbon_fiber/milled.html

⁶⁷ Meng et al. 'Comparing Life Cycle Energy and Global Warming Potential of Carbon Fiber Composite Recycling Technologies and Waste Management Options'. ACS Sustain Chem Eng. 2018; 6:9854-65



Figure 4.2: Greenhouse made from GFRP sheets & composite door edge offcuts. Photo courtesy of Paul Ridley, [Cabinz](#)

On a larger scale there have been a variety of demonstration projects for end-of-life (EOL) wind turbine blades, including children's playgrounds, municipal sculptures, modular housing pods and even pedestrian and light traffic bridges. This approach, while worthy, probably isn't scalable to the volumes of end-of-life turbine blades projected, as each use tends to be based on one-off 'bespoke' designs, and processing the blade is expensive compared to using commonly available materials. In the UK, the turbine blades that have so far been scrapped (relatively few to date), have unfortunately mostly been downsized locally and sent to landfill as the most economic disposal route; however, this may change as demonstration projects have now shown routes to use glass fibre recyclate back into items of 'blade furniture'. As first-generation blades reach the end-of-life, provided the turbine itself is still functioning well, replacement blades can be upgraded by adding new features to them such as swept tips, surface ribs to induce vortices etc, to get better performance and energy capture out of the same swept area. (See also 8.2 'Reuse and refurbishment'.)

4.4.2 Recovered glass fibre

The lowest cost and least energy-intensive glass fibre recovery processes from composites have been shown to be downsizing, shredding, crushing, and cyclone separation. Fairly long fibres can be recovered this way, and they can be recovered with minimal surface damage, and the sizing intact, compared with thermal and chemical recovery processes, though they have resin particles still attached. There is still a 'dust' fraction that has to be bagged and disposed of as it has little residual value. Successful technical trials were done to incorporate long fibres into mats using a wet-laid process, to re-use in continuous sheet product. While cost effective for in process waste it was not found to be economic to scale up to include end-of-life or product returns with the prevailing landfill tax regime at that time. Fibres separated from ground GFRP waste have also been used to add crack resistance to polymer concrete flooring in place of polypropylene fibres.⁶⁸

Recovery of cleaner glass fibres using pyrolysis or chemical processes has been developed, but so far is not commercially active. For more information see chapter 8. Economic viability may be achievable with economies of scale, accompanied by a) recovery of glass fibre strength with treatment and re-sizing, and b) producing intermediate short fibre products which can be used as replacements for virgin products, such as BMC, glass filled thermoplastic pellets, short fibre mats or veils. One such project, using catalysed fluidised bed with a fibre recovery process, is proven at lab scale and is now being developed at pilot scale in the PRoGrESS project, led by Composites UK, with lead industrial partner Aker Offshore Wind.⁶⁹

⁶⁸ Recy-Fib 100 (Fibre for concrete), Design en Bretagne <http://www.designenbretagne.com/formations/>

⁶⁹ 'Wind Turbine Blade Recycling Project Kicks Off', Composites UK, 13/5/22 <https://compositesuk.co.uk/wind-turbine-blade-recycling-project-kicks-off/>

4.4.3 Ground/shredded GFRP waste

Most GFRP manufacturing operations have a considerable amount of waste from edge trim, cut-outs and overspray. Grinding this to a fine filler has consistently been found to be uneconomic, since it costs more to recover than the cheap mineral fillers it might replace, but grinding to retain some fibre length and so reinforcing value is more valuable.



Roofing sheet incorporating recovered glass fibres, used in a campervan roof. Photo Stella Job.

Several UK manufacturers have independently researched and invested in recovery plant to recycle their in-process scrap, grinding it and reusing it back into products such as gutter strips on continuous sheeting lines, or pressed moulding compound products. In a study by Exeter University, regrind was shown to be useable in press moulding doughs, substituting 10-20% virgin fibre without significant mechanical property changes.⁷⁰

Another successful approach to deal with this in-process waste in spray-up manufacturing is to crush or kibble the FRP waste to a chunky grit consistency and respray it with a small amount of binding resin as a core material, replacing wood, plyboard or foam stiffeners in sandwich panels.

Eco-Wolf Inc.⁷¹ (Florida) produce a low-energy two-stage grinder with a relatively small footprint, and a spray head

compatible with most spray chop machines that blows the crushed FRP to a hopper and dispenses via a generous diameter pipe to a chute on the spray gun, where it spreads out, is wet by a fan of resin as it drops off and is projected onto the part. Alternatively, a macerator/mixer pre-mixes the regrind with resin fillers and additives. This allows an operator making a caravan part or boat transom to add core stiffness by picking up a different spray head in between the two chop spray operations. It eliminates the time and cost of kitting and adhering wood panel or other core materials and then waiting for that to harden before spray chopping and consolidation of the backing laminate. The core produced has a certain amount of void content, dropping the density compared to fully consolidated FRP, and a random orientation of short fibres already fully wet out and cured. The crushed GFRP core has the advantage that the bond between the core and laminate is excellent, being essentially the same resin co-cured throughout, and fixings generally have better pull-out strengths. The recycled core is not susceptible to swelling when wet and unlike wood will not delaminate from the surface laminates. These same advantages are achievable from other sprayable syntactic core products, which can be as strong and lower in density, but these typically use virgin chopped glass and glass microbubble fillers, and so are relatively expensive.

Chopped and ground GFRP waste, with the addition of fresh resin and fillers tailored to add back properties such as fire retardancy, can also be used to make panel and heavy-duty construction products. These can be cast products, similar to synthetic marble or onyx, or thinner press consolidated panels similar to high pressure laminate. They make a durable replacement for MDF or fibreboard or an alternative to marble and solid surface countertops. They can be coloured for a granular stone effect or left semi-translucent to be backlit. The short fibres in the regrind add strength, and the chunky regrind even has its own 'recycled chic' aesthetic. Italian firm Gees Recycling produce a variety of products in Recomplex™ material including Listino panelling supplied to stores such as Gucci.⁷²

Some recent examples showing good circularity include the regrind of old FRP shop mannequins and their reconstitution back into retail shelving, shop furniture and point of sale display panels by MCD and Thriv3 working with Gees Recycling. (See case study at section 8.7.)

⁷⁰ Ghita, Savage et al, 'Successful closed-loop recycling of thermoset composites', Composites: Part A 40 (2009) 490–498

⁷¹ Ecowolf <http://ecowolfinc.com/frp.php>

⁷² Gees Recycling <https://www.geesrecycling.com/>

4.5 Resins made with recycled PET bottles

Polyethylene terephthalate PET is a linear polyester made from terephthalic acid and ethylene glycol. It is a highly versatile thermoplastic polymer with good strength and transparency, suitable for blow-moulded drinks bottles and is widely recycled, shredded to flake, and formed into masterbatch pellets to make more bottles, or extruded and spun to make polyester yarns and fabrics. Polyester fabrics are themselves used in composite manufacture as surface veils to provide resin-rich corrosion barriers to prevent print-through, as a carrier fabric in combination fabrics and core-mats, flow media and 'breather fabrics' or even in some cases as woven fabric ply reinforcement for improved impact resistance, or as a printed fabric for a surface aesthetic.

Terephthalic acid and ethylene glycol are also building blocks in the manufacture of thermoset polyester products with good toughness and high heat distortion temperatures. Recycled PET flake can be readily utilised to make new unsaturated polyesters and substitute a significant proportion of virgin acid and glycol to make thermoset polyesters with mechanical properties comparable to those from virgin materials. Most major polyester resin manufacturers have now developed resins with recycled PET content, usually between 25-30%, which sit alongside their standard portfolio and other sustainable resin offers including raw materials that are from bio-sources, and materials sourced from other waste streams.

4.6 Recycled thermoplastic composites

Most engineering thermoplastics can be repeatedly softened and remoulded, or shredded and re-pelletised, with minimal loss of matrix properties, and it is quite normal for injection moulding shops to collect their in-process scrappage and noodle waste and re-pelletise it to be used back into product. While it is feasible that a damaged or end-of-life fibre-reinforced polypropylene/glass fender panel, could be reheated, stripped of any metallic fixings, and remoulded or over-moulded in a press to retain fibre length shape and function, it is more likely that it will be shredded, re-pelletised and used for injection moulding or overmoulding.

This ability to be repeatedly recycled without significant loss of properties is not however universal. Some high-performance polymers require specific thermal processing parameters to achieve the right level of crystallinity for ultimate stiffness and strength and remelt options may not always achieve the same mechanical performance. Likewise, there are semi-crosslinking thermoplastics, which don't soften or remelt effectively, or when they reharden do not retain their properties.

When looking to make composites with high recycled content, it is certainly appropriate and valid to look at recycled thermoplastics to combine with recycled fibres. Recycled thermoplastics can be commercially available 'drop-in' masterbatch pellets, perhaps with marginally less forgiving process parameters, and a broader spread of mechanical properties, or themselves be already in fibre format, e.g. rPET yarns from bottle waste, nylons from carpet or fishing line, synthetic fabrics and geotextiles. An example is where waste PP fibres from carpet manufacture are commingled with natural fibres to form a felt for hot pressing into automotive interior panels.

4.7 Using recycled materials from non-composite waste streams

Fibre reinforced composites are, almost by definition, a means to get better value and performance by combining other materials, and therefore performance wins can potentially be made by putting together almost any fibre waste, with any potential binding matrix. Even packaging film waste can be utilised to bind and interlayer recovered fibres and fabric. While this kind of thinking is currently more in the artistic than the commercial space all such options should be kept under consideration going forward. At the NCC a project using nylon bagging film waste and fabric offcuts from sources as diverse as safety netting and delivery sacks were able to be reprocessed using little more than a toaster powered by solar panels to pre-heat, and a manual press to shape, so producing a variety of simple but strong and functional articles with a 'recycled' aesthetic.



Ecotechnilin flax/PP 1600 g/m² felt, used in Opel Insignia boot trim, using PP fibre waste from carpet production. Photo Stella Job

4.8 Potential issues to overcome with recycled materials

The main barriers to the use of recycled materials back into composites products include lower and more variable mechanical performance, processing issues, security and continuity of supply, certification and warranty of quality, and performance and traceability of sources. Many of these can be overcome if a component and manufacturing process is actively designed for recycled content, with the necessary allowances made for potential performance variability, by establishing long term supply arrangements for certified and warranted secondary materials, or by retaining source and quality control by prioritising recycling of your own in-process and product return waste streams.

4.8.1 Material performance degradation from reprocessing.

Materials performance degradation is mainly due to two factors; (i) size loss from thermal processing, and (ii) fibre surface damage and breakage during downsizing and handling. The properties most affected are interlaminar and interfacial adhesion in the case of size loss, and strength and impact resistance in the case of fibre damage. In general stiffness is the property *least* affected by reprocessing and so stiffness dominated reuse applications make the most sense in terms of cost/performance benefit.

4.8.2 Material variability and design

In general, sources of recycled fibres are not as constant and well defined as virgin materials, and will have a broader distribution of properties, and often some variability in physical appearance. Some manufacturers of recycled formats take care to minimise this variation through blend selection, and will provide materials within a well specified performance range, but it is important when designing with recycled content to establish that they will perform consistently, and make additional allowance in the design to accommodate variability. Process design should have the ability to adjust, or tolerate, the measured batch variance and still create compliant parts. See section 2.6 for further comments on designing for variability and with short fibres.

4.8.3 Processing issues

Many of the most common recycled fibre formats are nonwoven tissues, veils, mats and felts. Valid applications for these recycled fibre formats are to add surface uniformity and reduce print-through from aligned fibres, to improve flow between aligned fibre layers, or use as bulking plies to add stiffness. Flow characteristics may not be as good as the equivalent weight/loft virgin fibre formats, due to more variation in fibre length and fluffiness caused by defibrillation in the recycling process. This may result in more resin uptake and reduced FVF and may mean adjustments in flow pressures and length of flow path in resin transfer moulding or vacuum infusion applications. Some of the short fibre recycled carbon formats have performed better when press moulded and wet-pressed i.e. in processes that have shorter or through thickness rather than in-plane flow paths.

4.8.4 Security of supply

Recycled materials of all kinds depend on a steady source of 'waste'. The balance of recycled to virgin formats in a design should ideally reflect this. All waste volumes, particularly in-process waste streams, will inevitably reduce under pressure from increased efficiency and automation. But waste cannot be completely eliminated from many traditional composite processes. The relatively few current recyclers of carbon fibre have more waste than they can handle and are therefore able to direct efforts to delivering the highest value back into the supply chain. The increasing adoption of composites for their low weight and durability will inevitably lead to a wider availability of end-of-life sources. As the number of secondary materials providers grows, we can expect to see wider availability and variety of formats at ever more competitive prices.

4.8.5 Traceability, certification and warranty

Recyclers are required by legislation to identify and record their sources, in order to provide the required waste documentation and traceability. However recycled fibres will often be from a 'mixed source' process, and as such need to be re-certified as 'secondary material' with a new set of defined performance and quality warranties. One way to reduce complexity and simplify traceability is for the recycled materials never to go offsite as waste, but instead to be re-purposed on site, retaining the original virgin material traceability. An alternative is for this service to be contracted out, retaining waste segregation.

The claim of ‘Recycled Content’ is covered by the ISO 14021:2016 standard.⁷³ Certifying bodies within different industry sectors also accredit third party auditors to carry out independent product assessments. Recycled content can include specifically recycled fibres into textiles, or post-consumer plastics into plastic products, and these can be aggregated to composites components or products. Recycled content certification is only one metric to assess environmental sustainability of a product, but can be important within other assessment schemes such as BREEAM or LEED in the construction sector.

Certification routes for claims of recycled content include:

- [The Association of Plastics Recyclers | APR PCR Certification \(plasticsrecycling.org\)](https://www.plasticsrecycling.org/)
- [Recycled Content Certification | SCS Global Services](https://www.scsrecycled.com/)
- [Recycled Content Verification | Intertek](https://www.intertek.com/recycled-content-verification/)
- [Global Recycled Standard | GCL](https://www.gcl.com/)

4.9 Future prospects and drivers for more circular use of recycled composites

4.9.1 Climate change, emissions and end of life waste and recycling legislation

Legislation and environment, social and governance (ESG) pressure on organisations to behave ever more sustainably is growing, and in future there will undoubtedly be more composite parts designed to be made cost effectively from secondary materials. Chapter 7 discusses sustainability reporting and ESG ratings and chapter 910 shows how regulations and policy are driving expectations of increased circularity and use of recycled materials.

Industry uptake of carbon fibre and composites to meet light-weighting and reduced emission targets is growing fast, especially in transport applications of all kinds, but also in almost any moving equipment parts. The hydrogen economy is already beginning to demand large volumes of composite pressure tanks and pipes. For carbon fibre, this will present an ongoing challenge to global production capacity, and we should see increasing opportunities for rCF fabrics and ply formats to be used alongside virgin materials within stiffness dominated applications to fill these anticipated medium-term supply chain gaps.

The combination of the End-of-Life Vehicle Directive, and low/zero exhaust emission targets in the automotive sector are a major factor in the move from metal to composite solutions by this sector. Pragmatic and high-rate processing solutions, such as wet press and injection overmoulding to reduce reliance on complex intermediates, have been adopted and hybrid solutions used where appropriate, using metals to add local or global stiffness to short fibre format components.

4.9.2 Short fibre products in 3D printing and additive manufacturing

3D printing and other additive manufacturing techniques will grow quickly as the Industry 4.0 agenda and “Internet of Things” revolution changes the way we manufacture. The trend to digital design, digital twin process validation, and full automation of composite processes will increase demand for slit tape, towpregs and short fibre aligned products suited to robotic deposition using automatic tape lay, automatic fibre placement, larger format 3D print and extrusion heads, and robotic spray chop application. As the percentage cost of labour per part reduces and material costs dominate, focus will shift to more effective use of materials to gain profitability and margin.

For many applications, continuous UD fibres will not be required throughout a component, and there will be scope for aligned discontinuous fibre products tailored to such production. There will therefore be potential for more rGF and rCF reinforced thermoplastics, and a significant proportion of these could use recycled fibres and recycled or bio-sourced resins and polymers.

⁷³ ISO 14021:2016 ‘Environmental labels and declarations — Self-declared environmental claims (Type II environmental labelling)’, ISO <https://www.iso.org/standard/66652.html>



Injection moulded part using glass fibres recovered from GRP regrind compounded with polypropylene. Photo: Stella Job

4.9.3 Waste vs secondary materials transport

Moving waste will become increasingly difficult and expensive as legislation bites and there will therefore be opportunities for portable or site-based downsizing, crushing separation and re-treatment machinery, either sold as a service in the same way waste compactors work today, or brought in-house to generate secondary material from process wastes for re-use on site routinely.

The opportunity for crushed GFRP secondary material formats has huge growth potential once large volumes of material throughput become routine, especially from end-of-life wind turbines, but also from end-of-life GFRP boats and other waste stream and redundant products. It may become routine to send old composite tools to recyclers rather than keep them in the yard, especially as often the master shape will now be fully digitised, and a repeat or repair component will likely be made more cost and time effectively from a 3D printed or robotically machined temporary tool, perhaps itself made from recycled materials, than by refurbishing and repairing the tool in the yard.

4.10 Your products and recycled content?

Given all the above factors, it is time to think hard and think afresh about where recycled materials can fit into your products, how you might profitably and sustainably repurpose your own waste streams, and whether to work with the growing number of experienced and capable composites recyclers or develop your own internal solutions and perhaps offer this service more widely once established to achieve economies of scale.

Achieving the circularity required for the carbon “net zero” economy of the future will undoubtedly require much greater use of recycled materials and therefore the time to start moving down this path is now.

5. USING BIO-BASED MATERIALS

Author: Malcolm Forsyth

5.1 Introduction

The very first composite materials created by humanity used bio-materials before these were replaced by synthetic fossil-fuel-based chemicals and materials through the 19th and 20th centuries and the increased focus on sustainability in recent years has revived interest in once more using bio-based materials for these applications, and the composites industry is no exception to this. For many years, there has been significant interest in the use of natural fibres in composite parts, driven partly by a desire to be more sustainable and partly by the specific end-use properties that natural fibres can bring. More recently, there has been a growing interest in the development and use of matrix bio-based resins, derived in part or fully from natural raw material sources. This chapter seeks to summarise the full range of bio-based materials used in composites (fibres, resins and core materials) available for suppliers of composite parts to use, and also to explore more deeply the potential benefits and issues linked to the use of bio-based materials in place of fossil-fuel-based materials, to ensure that all value chain players understand the true value that such bio-based materials can bring, and the potential issues which may be faced in the future.

A very comprehensive overview of all the potential bio-based materials for use in biocomposites can be found in the “Technology Overview: Biocomposites” document published by the Knowledge Transfer Network and NetComposites.⁷⁴

5.2 Terminology

There are a number of terms used in relation to biocomposites and to ensure clarity, an appropriate definition for each is given below in Table 5.1.

Table 5.1: Definitions of Bio-based material terms, most based on BS EN 16575:2014⁷⁵ (marked ^a) and PAS 600:2013⁷⁶ (marked ^b)

Term	Definition
Bio-based	Derived from biomass. Biomass can have undergone physical, chemical or biological treatment(s). ^a
Bio-based content	Fraction of a product that is derived from biomass. Normally expressed as a percentage of the total mass of the product. ^a (See BS EN 16785-2:2018)
Bio-based polymer	Polymer in which constitutional units are totally or in part from biomass origin <i>Note: Bio-based polymers are not identical to bio-polymers. Bio-based polymers can be made synthetically from monomers derived from biomass, while bio-polymers are made entirely by the living organisms.</i> ^b
Bio-based product (or material)	Product (or material) derived wholly or partly from biomass. <i>Notes: The bio-based product is normally characterised by the bio-based carbon content or the bio-based content. For the determination and declaration of the bio-based content and the bio-based carbon content, see the relevant standards of CEN/TC 411. Product can be an intermediate, material, semi-finished or final product.</i>

⁷⁴ ‘Technology Overview: Biocomposites’, published by KTN and NetComposites, March 2014 –

<https://netcomposites.com/media/1211/biocomposites-guide.pdf>

⁷⁵ BS EN 16575:2014 ‘Bio-based products. Vocabulary’, BSI <https://knowledge.bsigroup.com/products/bio-based-products-vocabulary/standard>

⁷⁶ PAS 600:2013 ‘Bio-based products. Guide to standards and claims’, BSI <https://knowledge.bsigroup.com/products/bio-based-products-guide-to-standards-and-claims/standard>

Term	Definition
	<i>The term “bio-based product” is often used to refer to a product which is partly bio-based. In those cases, the claim should be accompanied by a quantification of the bio-based content.^a</i>
Biocomposite	Composite material where at least one of the constituents is derived from biomass origin ^b
Biodegradable plastic (or polymer)	A plastic whose degradation results from the action of microorganisms such as bacteria, fungi and algae ^b <i>Note: A plastic may be degradable, but not biodegradable – for example, if it is degraded by light. Some bio-based materials are also not biodegradable e.g. polyfurfuryl alcohol (PFA) and yet some petrochemical products are biodegradable (e.g. PVA).</i>
Biomass	Material of biological origin excluding material embedded in geological formations and/or fossilized. Examples: (whole or parts of) plants, trees, algae, marine organisms, micro-organisms, animals, etc. ^a
Bio-polymer	Polymer made entirely by living organisms ^b
Bio-waste	A solid or liquid biomass product stream which would ordinarily have no sales value and need to be discarded, with cost implications. <i>Note: In the Waste Framework Directive 2008/98/EC ‘bio-waste’ means ‘biodegradable garden and park waste, food and kitchen waste from households, offices, restaurants, wholesale, canteens, caterers and retail premises and comparable waste from food processing plants’. In this chapter we are using the term to include any biomass wastes.</i>
Natural fibres	Fibres from vegetable and animal origin, including all natural cellulosic fibres (such as cotton, jute, sisal, coir, flax, hemp, abaca, ramie, etc.) and protein-based fibres such as wool and silk <i>Notes: Excluded here are mineral fibres, such as asbestos, that occur naturally but are not bio-based. Also excluded are dietary fibres or supplements.</i> <i>Fibre can be taken from three parts of a plant: the stem, the seed and the leaf. Natural fibres are mainly composed of cellulose, hemicellulose and lignin.^b</i> <i>Basalt fibres are not natural fibres or bio-based.</i>

These definitions are used throughout this chapter.

5.3 Are biocomposites really sustainable?

On the surface, this question may seem strange since intuitively, we are inclined to answer “Yes, of course they are” but in reality, it is not a straightforward question to answer, and there are several considerations which need to be explored before a definitive answer can be given, including the ethical question of whether it is more appropriate to grow crops for biocomposite industrial use than to grow crops for food when a significant proportion of the global human population continues to face food shortages.

An objective answer to this question must include a specific life cycle assessment (LCA) of the specific crop (or bio-waste stream) being used, with all the aspects of growing, harvesting, processing and transportation included, as part of a LCA assessment for the composite part itself. This includes the impacts from processing the bio-based material into a semi-finished material (such as a yarn or a fabric), the impacts of the part manufacturing process, the in-use impacts of the part and finally the end-of-life treatment process assumed to be used when the part needs to be disposed of, ideally by some form of recycling. This LCA for the composite part must then be compared with a parallel exercise for the same part using fossil-fuel-based raw materials so that the benefits (or otherwise) of using bio-based materials can be objectively judged. This task is clearly no small undertaking but is vital if objective answers to the question “how sustainable are bio-based materials really?” are to be obtained.

In addition, the source of the bio-based materials being used for the biocomposite part must also be properly understood, so that an objective assessment of the potential alternative land-use can be made, and the potentially negative impact on food availability, water use and any human toxicity aspects of the bio-based material crop, identified and quantified. There are of course a number of potential positive aspects to growing crops to be harvested as natural fibres for biocomposite use – such as rapid growth cycles enabling multiple crops/year (for crops such as bamboo) and an ability to grow on otherwise non-productive land for food. These also need to be taken into account in the overall assessment and subsequent decision-making.

Given the potential for conflict over land-use with food production, the optimum source of bio-based materials for biocomposite parts can be a waste stream from other agricultural production activity, and this should be a prime consideration when looking for bio-based material sources, since this removes the ethical question of competition with food sources and should bring clear benefits in terms of material costs and LCA values. There can be challenges of quality consistency when using waste streams and therefore careful assessment of the variability in a bio-waste stream, and the effect of this variability on biocomposite processing and material properties, is an essential activity. However, assuming the level of variability can be accepted, the use of an existing bio-waste stream can be the ideal solution for biocomposites, enabling a clear demonstration of the true sustainability of such biocomposite parts, and with a positive sustainability impact significantly greater than that which can be achieved with an identical part made from fossil-based materials.

A clear example of such an optimum outcome is the use of sugar cane production waste (“bagasse”) as the raw material for the production of furfuryl alcohol which is then further converted to polyfurfuryl alcohol (PFA) resins, which, when combined with suitable fibres, can be used to make composite parts with very high fire-retardant properties. This value chain takes a bio-waste stream of limited value, which would otherwise require costly disposal, and generates a high-value, high-performance part, bringing clear safety and sustainability value to human society.

In conclusion, the question of whether biocomposites are really sustainable can only be answered properly with a systematic, quantified and analytical approach for each potential use or application but there is no doubt that biocomposites can be the most sustainable option available, especially if they are sourced from an existing bio-waste stream, and/or from crops on marginal land which would otherwise be unsuitable for human food production.

5.4 Natural fibres

Although there are animal-based fibres (such as hair, silk and wool) and mineral fibres (such as asbestos, fibrous brucite and wollastonite) available from natural sources, none of these are considered realistic sources for use in biocomposites at this time, or for the foreseeable future, and so only vegetable-based fibres will be considered here. There are 4 categories of vegetable-based fibres which can be considered for biocomposites use as follows:

5.4.1 Bast fibres

Bast fibres are found in bundles towards the outer stem of the plant, and once harvested, are processed via a series of enzymatic and mechanical steps to generate the fibres in a form in which they can be used in an industrial process for the creation of biocomposite parts. Typical bast fibres are flax, hemp, jute, ramie and kenaf and some key features of these individual fibre types are described below. Many of these fibres have good damping properties and can be formed into felt mats.

Flax – grows readily across north-western Europe, is compatible with a wide range of bio-based resins and synthetic resins and provides excellent damping properties (against vibration and noise) in biocomposite parts, making it well-suited to applications in sports & leisure, automotive, marine and architecture.

Hemp – grows readily across Europe and North America, although current legislation concerning cannabis does apply some restrictions to hemp cultivation. The fibres can be formed into felt mats which can in turn be compression-moulded into 3D shapes, and hemp is widely used in composite parts for transport applications.

Jute – grown widely across India and Asia, and its low weight and good vibration damping properties, together with its fibres having similar stiffness to standard glass, make it well-suited to non-structural automotive components

Ramie – a flowering plant, native to eastern Asia, has some of the strongest known natural fibres which can retain their strength when wet (unlike other natural fibres) but does also require extra processing to be able to extract the fibres. Can be used in combination with other fibres to give very strong, durable biocomposite parts.

Kenaf – grown in south-east Asia and has similar properties to jute, with its main applications being in non-structural parts for automotive applications.

5.4.2 Leaf fibres

Typical leaf fibres are sisal, banana and curaua with more details as follows:

Sisal – easily cultivated and widely used as a reinforcement, with short renewal times

Banana – fibres are ligno-cellulosic in nature, with the leaf traditionally used to make textiles in many Asian countries. The fibres can be extracted by biological, chemical or mechanical methods.

Curaua – derived from the pineapple family, with fibres giving a higher mechanical strength than other natural fibres, making it a potential glass replacement. Poorer fibre-resin interaction and compatibility is an issue and it is most commonly used as a filler in automotive part applications.

5.4.3 Seed fibres

Typical seed fibres are cotton, oil-palm and coir (coconut) with more details as follows:

Cotton – heavily used as a material in textiles – seeds and cotton fibres need to be separated first

Oil-palm – extracted from empty “fruit” bunches but poor adhesion with matrix resins, mean most applications are in packaging and MDF-type applications

Coir/coconut – once separated, husks are beaten to extract fibres, with thicker brown fibres coming from older coconuts and finer white fibres coming from younger coconuts. Typically used in roofing, insulation and building products

5.4.4 Grass fibres

Typical grass fibres are bamboo, cereal straw and reed canary, which are normally extracted by chemical or mechanical processes, with more details as follows:

Bamboo – rapidly-growing material, grown mainly in Asia, which can be used both for fibres or pulp, with the biocomposite fibre used typically for sports & leisure or automotive applications.

Cereal straw – grown across north-western Europe, most often used as an alternative to wood flour, typically melt-blended and then injection, extrusion or compression moulded

Reed canary – most suitable for applications needing short fibres, and typically used as a filler or in paper production, since performs poorly in structural applications

5.5 Bio-based resins and polymers

There are several different families of bio-based resins as follows:

5.5.1 Thermoplastic bio-based polymers

There are three distinct categories of thermoplastic polymers as follows:

Bio-based but not biodegradable

This category is the most frequently used bioplastic. These plastics are chemically identical, with identical or very similar properties and applications, and hazard profiles, to synthetic versions but are derived from biomass rather than crude oil fractions.

Examples include bio-PET (bio poly-ethylene-terephthalate), bio-PE (polyethylene), bio-PP (polypropylene), bio-PU (polyurethane), bio-PVC (poly-vinyl-chloride) and bio-PA (polyamide), all of which can be used as direct “drop-in” substitutes for their synthetic versions. Of these, bio-PET and bio-PE are the best known, are the most price competitive and are sold in the highest volumes. Bio-PET is used by Coca-Cola for its soft drinks packaging⁷⁷ and is typically 70% terephthalic

acid (TA) (synthetically derived although alternatives such as furandicarboxylic acid derived from natural sources are available) and 30% bio-based using mono-ethylene glycol (MEG) derived from bioethanol, which is itself produced from crops like sugar cane. Bio-PE is derived directly from bioethanol and is produced in large volumes (60 million tpa), with a benefit that 70% less energy is used in its production than in the production of synthetic PE. At end of life, these bio-based resins are fully recyclable in the same way that their synthetic versions are, but they are not biodegradable, and so must be separated and processed through a plastics recycling route. Some of these could potentially be used in thermoplastic composite applications but there has been limited commercial use made of these bio-based polymers/resins to date in biocomposites.

Not bio-based but biodegradable

There are fewer examples in this category with the best known being PBAT (polybutylene adipate terephthalate) and polycaprolactone. Generally, these products have lower properties and are more expensive, but they do have some niche applications, especially in the biomedical field where the biocompatibility of these polymers can be utilised. Again, commercial use in biocomposites has been limited so far.

Bio-based and biodegradable

There are several polymers in this category, and these are now gaining greater acceptance and use, which in turn, helps to drive their costs down closer to those of their synthetic competitors. Prime examples in this category are PLA (polylactic acid), PHAs (polyhydroxyalkanoates), PBS (polybutylsuccinate), starch blends and CA (cellulose acetate). Their primary applications currently are in food or disposable packaging and agricultural films, where their biodegradability can be best utilised. They are typically more expensive than the synthetically produced alternatives, and therefore they are largely used in applications where their other benefits (bio-sourcing and biodegradability) have a clear commercial value. Like the other categories, use of these resin/polymer types in biocomposites has been limited so far.

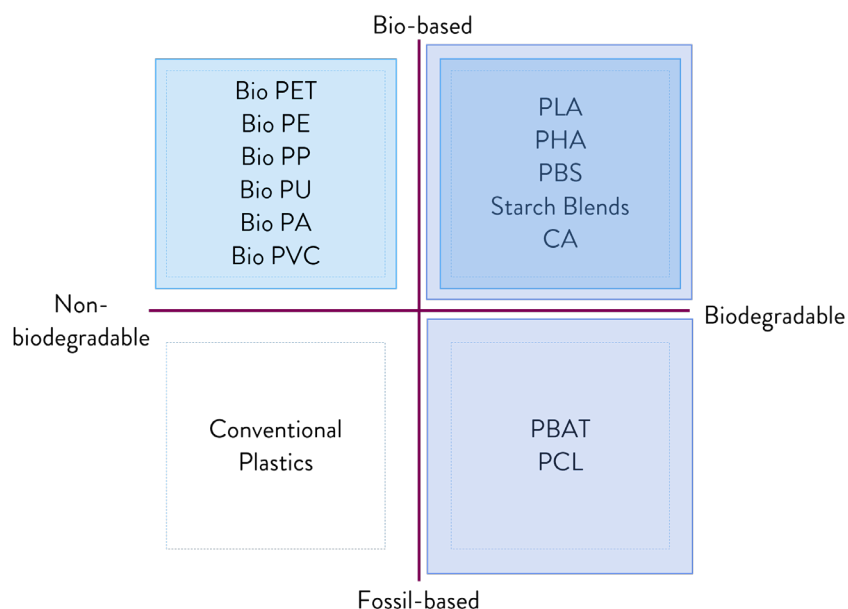


Figure 5.1: Bio-based and biodegradable thermoplastics

⁷⁷ ‘New 100% bio-PET will scale for Coca-Cola’, Sustainable Nonwovens, 5/11/21 <https://www.nonwovensnews.com/features/15689-new-100-bio-pet-will-scale-for-coca-cola>

Case study: Fire and heat resistant composites using resin derived from food waste

Nick Smith, SHD Composite Materials Ltd

SHD have developed and commercialised composite materials using polyfurfyl alcohol (PFA) resin formulations for high temperature and stringent flame, smoke and toxicity (FST) applications. The base PFA resin is derived from waste arising from cane sugar production and SHD have been developing the material since 2015 to the point where the products are now entering high volume production. Two formulations are offered, both with bio-derived material contents of >90%.

High temperature and battery protection applications – PS200

PS200 has been optimised for heat shielding and battery protection. For heat shielding applications, PS200 has been tested to the FAA Powerplant Fire Penetration Test meeting standards FARs 25.867, 25.865, 25.1191, and 25.1193 including nacelle skins, engine mounts and firewalls. In this test a 3mm carbon/PS200 laminate was subjected to a flame from a propane burner at 1200°C for 15 minutes without burn-through – rating the material as ‘non-combustible’.

PS200 is in serial production for battery boxes and cell dividers used for protection from Li-ion thermal runaway events. Homologation testing has been carried out for road vehicle and aircraft applications and the material is approved by EASA for powertrain use in electrically powered aircraft including the Pipistrelle series. It is also specified in the battery box of several production electric hypercars. The material is used with carbon and glass reinforcement and a full mechanical characterisation has been completed to aid designers and engineers.

FST applications – FR308

FR308 is optimised for FST compliant materials in mass-transit applications. It has been tested to CS 25.853 and meets all requirements and is also compliant to EN 45545-2 HL3, rendering it suitable for all aero and rail interior applications respectively.

Active programmes with aerospace OEMs and tier 1s are underway and the material has been used by Percival Aviation in a refurbishment programme for Boeing 757 aircraft to replace overhead luggage lockers previously made from phenolic material. A weight saving of 1kg per locker was achieved giving a 35kg saving overall.

The material is in serial production for rail applications including use on the Mumbai metro system and further rail orders are imminent.



Figure 5.2: PS200 glass fibre PFA battery box undergoing fire test. Photo courtesy of SHD Composite Materials Ltd

5.5.2 Thermoset bio-based resins

Like the thermoplastic bio-based polymers above, there are three distinct categories of thermoset bio-based polymers/resins, as well as a category where a portion of the thermoset resin is derived from bio-sources, as follows:

Natural oil-based resins

These products (of which there are many different types) are formed by modification of the double bonds of the unsaturated oils they contain, into groups which are capable of cross-linking. The most interesting from a biocomposites point of view are linseed oil, castor oil and soya bean oil, since these can give the best properties and can also be mixed with synthetically derived ingredients to give good physical property performance with a higher bio-content. Epoxidised linseed oil is the most commonly used such resin, with a high number of epoxy groups, making it an interesting choice for biocomposites as well as adhesives and laminates.

Saccharides

There are two main saccharide-derived platforms of interest for bio-composites – isosorbides and furfuryl alcohol. Isosorbides are made by the hydrogenation of glucose to sorbitol and then the dehydration of sorbitol, and can be used as a safer alternative to BPA (Bisphenol A) in polycarbonates (but not epoxy resins). Furfuryl alcohol is a monomer of growing interest due to its combination of bio-sourcing (often from biomass waste streams) and excellent fire retardancy or fire, smoke, toxic fume (FST) performance in the polymer form (polyfurfuryl alcohol, PFA). Furfuryl alcohol is produced from furfural which in turn is obtained from hemicellulose (often a waste product (such as sugar cane bagasse) from food production). See Focus box below.

These PFA resins can give a similar level of fire performance to phenolic resins (but without the toxic fume generation associated with phenolic resins), process in a similar way to phenolics (with acid-based catalysts in a condensation polymerisation reaction) and offer the advantages of being bio-sourced and also less hazardous for workers to handle. In addition, if combined with a bio-fibre, either in prepreg form or co-processed, PFAs can give a 100% bio-based high performance composite laminate which could be of significant interest to the transport sectors, especially aerospace and trains, where high FST performance is mandated, and lightweight parts are needed.

Polyphenols and Phenols

These products are phenolic compounds derived from plants or nuts, in the form of tannins and cardanol (e.g. from cashew shell nut liquid), and can be used as raw materials in epoxy resins, either as monomers or as alternatives to BPA.

Polyester and epoxy resins using naturally derived raw materials

There is significant opportunity for producers of epoxy and polyester resins to change some of their raw materials from 100% oil-based ones to bio-sourced feedstocks and a number of producers have started to do this. Unsaturated polyester resin manufacturers are now using bio-based glycols and acids (from feedstocks such as succinic acid), enabling resins with 25-30% bio-content to be made commercially available, and epoxy resin manufacturers are following a similar path, to generate resins with 25-30% bio-content, and in some cases, almost 100% bio-content if natural oil-based resins (described above) are used.

Focus: Sugar-Based Chemicals

Steven Brown, Scott Bader Company Ltd

Sugars are abundant in nature and are readily available from a large number of food and non-food-based crops. Cellulose (a polymer prepared from 6-carbon sugar monomers) and hemicellulose (a polymer prepared from 5-carbon sugar repeat units) are both great sources of biomass for biobased resins.

Hydrogenation of glucose via an aldehyde reduction reaction, yields sorbitol which is used in many food, medical and cosmetic applications. However, the double dehydration of sorbitol yields isosorbide which is a very useful diol which can impart stiffness and high temperature performance into polyester and polyurethanes. Furthermore, isosorbide has been positioned as a safer bioderived alternative to bisphenol A for the synthesis of polycarbonates.

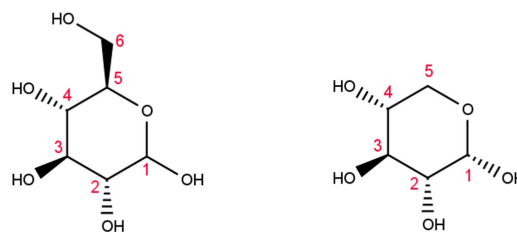


Figure 5.3: Glucose (left) and xylose (right) – monosaccharides derived from cellulose and hemicellulose respectively. Glucose belongs to the hexose family of sugars and xylose belongs to the class of sugars known as pentoses.

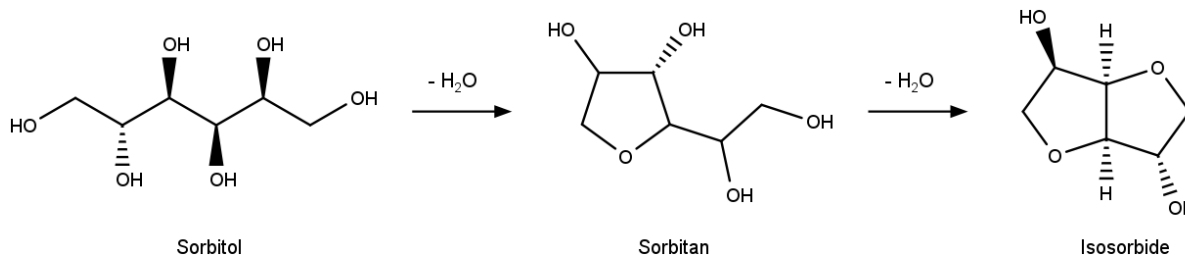


Figure 5.4: Dehydration of sorbitol to yield isosorbide

Glucose is used as a precursor for the synthesis of succinic acid; a key raw material for many synthetic biodegradable polymers. During one particular biosynthetic route, glucose (C6 sugar) is split to give two equivalents of pyruvic acid (C3 material). CO₂ is then added to the mix (leading to the potential for net negative resins) to eventually yield succinic acid (C4 molecule). Succinic acid can be used as an alternative to adipic acid in many formulations where flexibility is desired. Adipic acid has a particularly large carbon footprint due to the unavoidable emission of N₂O during its synthesis. Thus, large reductions in carbon footprint can be made by switching these acids.

Under reductive hydrogenation conditions, succinic acid can be converted in high yield to butanediol which can also be used to impart flexibility to resins and composites. Polybutylene succinate (PBS) is a synthetic bioderived and biodegradable polymer with properties similar to HDPE and PP.⁷⁸ However, if incorporated into a thermosetting resin (i.e. UPR), all biodegradability potential is lost.

Hemicellulose is present in all lignocelluloses and in particular the husks and hulls of food crops. Bagasse, the non-edible fibrous material left over from the pressing of sugarcane, contains up to 35% hemicellulose and from this, furfuryl alcohol can be obtained in an atom efficient process, as shown in Figure 5.5.

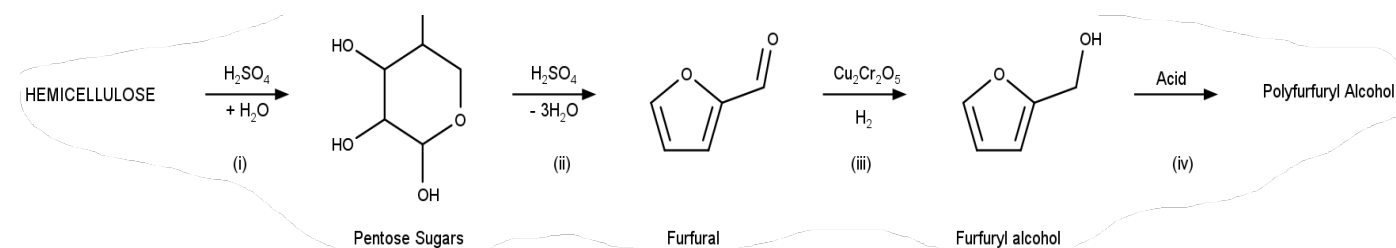


Figure 5.5: Hydrolysis of hemicellulose to pentose sugars such as xylose (i), dehydration to furfural (ii), hydrogenation to furfuryl alcohol (iii) and polymerisation to polyfurfuryl alcohol (PFA).

PFA resins polymerise under similar conditions to phenolic resins, through exposure to acid catalysts and the application of heat. The reaction produces water, which must be removed to help drive the reaction forward, and the polymer obtained has exceptional fire resistance. Furthermore, the resin produces virtually no toxic fumes under combustion, unlike many of the synthetic fire-retardant resins they compete with. PFA resins are used with natural, glass or carbon fibre and are most suitable for rapid hot press curing. This is perhaps the best example of a low embodied carbon, bioderived resin available in large volumes and without compromising on performance.

⁷⁸ Long Jiang, Jinwen Zhang, in Applied Plastics Engineering Handbook (Second Edition), 2017

5.6 Bio-based sandwich core materials

There are a number of types of bio-based core materials as follows:

5.6.1 Materials directly from trees such as balsa and cork

These are the most commonly used types of bio-based core materials and can be 100% sustainable if harvested in a managed way. Balsa is kiln-dried when used for composite core applications and is used in an “end-grain” configuration (with the grain of the balsa wood running through the thickness of the core). A range of densities are available, with balsa tending to be denser than other honeycombs and foams, and balsa provides good strength and stiffness, and excellent impact and indentation resistance. Its fire resistance is also superior to polymer foam core materials, making it a material of choice for many naval and marine applications. With the move away from the use of cork for bottle stoppers, cork sheet has been developed as an alternative use for cork, with the sheet being made by bonding cork crumb with polyurethane adhesive. Cork sheet has excellent thermal insulation and damping properties, opening up several potential biocomposite applications.

5.6.2 Bio-based polymer honeycombs

Honeycomb geometries can make very efficient and light-weight sandwich cores and although these are typically made from aluminium foils or resin-coated paper (Nomex or cellulosic) or cardboard, other polymer material can also be used, including bio-based polymers. An example of a bio-based polymer honeycomb is one using 100% bio-based PLA polymer which has been developed by Econcore⁷⁹ although its maximum operating temperature of 55°C does limit its applications to some extent. Cellulosic paper and cardboard honeycombs are also available as 100% bio-based structures but their susceptibility to moisture is a barrier to their use in many applications, including biocomposites.

5.6.3 Bio-based polymer foams

Synthetic polymer foams are widely used as a core material in composite parts, especially foams made using polyvinyl chloride (PVC), polyurethane (PU) and polyetherimide (PEI). Similar foams using polymers derived from bio-based sources can also be made, although their properties are generally compromised in one or more key respects (e.g. temperature resistance, mechanical properties) which have to date largely ruled out their use in mainstream biocomposite applications.

5.6.4 Nano-cellulose foams

It is possible to create a cellular, foam-like structure using nano-fibrils of cellulose, and trial materials have been developed by research institutions although not yet at commercial scale. This option therefore remains some distance from commercial availability but may become an option in the future.⁸⁰

5.7 Bio-based materials commercially available today

Although there are many different types of bio-based materials (fibres, matrix resins and core materials) potentially available for use in composite parts, there are a limited number which are fully commercially available today for industrial use by composite part manufacturers based in the UK.

The Composites UK trade association maintains on its website an up-to-date list of ‘Materials with bio/recycled content’, which are commercially available from Composites UK member companies.⁸¹

The bio-based materials available today from Composites UK member companies can be separated into the following categories and a brief summary of their main benefits is included in. For more details on their properties, contact should be made with the supplier, either directly or via Composites UK. The list in Table 5.1 may not be fully comprehensive as new suppliers are emerging all the time and any companies listed may change their offering in future.

⁷⁹ Econcore <https://econcore.com/en>

⁸⁰ ‘Nano-Cellulose and Bio-composites’, Brunel University <https://www.brunel.ac.uk/research/Groups/Resilient-Structures-and-Construction-Materials/Nano-Cellulose-and-Bio-composites>

⁸¹ ‘Materials with Bio/Recycled Content’, Composites UK <https://compositesuk.co.uk/industry-support/environmental/materials-with-bio-recycled-content/>

Table 5.1 A selection of commercially available bio-based materials for composites applications supplied by Composites UK members

Category	Current suppliers	Key characteristics & benefits
Epoxy resins	Bitrez Gurit Matrix Composites/Sicomini Wessex Resins/Entropy resins	These resins are made from a variety of renewably resourced biomass streams, often by-product or waste streams from other processes, with bio-content between 25 and 50%. A variety of benefits are claimed for these resins, over and above their use of bio-waste streams, such as lower VOC emissions, improved worker safety and improved temperature and chemical resistance. All claim that their products are fully competitive performance-wise against standard petrochemically-derived epoxy resins.
Epoxy preregs	SHD composites	This prepreg uses cashew nut shell liquid and contains about 30% bio content, and can be offered with a range of reinforcements, both synthetic (carbon, aramid, glass, thermoplastic) and natural (flax).
Polyfurfuryl alcohol (PFA) resins	Bitrez	This resin is derived from sugar beet and bio-based materials and has 96% bio-content.
PFA preregs	Composites Evolution SHD composites	Both suppliers offer a very high-performance fire-retardant product, capable of matching or bettering phenolic resin performance, with the added benefits of a lower toxicity product for improved operator safety and a lower environmental impact. Both offer a range of reinforcement types (both synthetic and natural fibres), with the natural fibres version providing a biocomposite product with almost 100% bio-content. Products are available for a range of processes such as autoclave, vacuum bagging and press moulding.
Core Materials (Balsa, Cork)	Gurit Matrix Composites	Gurit offers Balsa-flex - an end-grain balsa wood core, which is 100% bio-based, is available in a range of densities, thicknesses, formats and finishes, is DNV-GL and Lloyds approved, and is suitable for a range of end-market applications from wind turbines to transport parts. Matrix Composites offer CoreCork, a composite core material made from cork granules and a specific binder, which is 100% bio-based, is compatible with a wide range of matrix resins, and offers low density, high compressibility and excellent recovery characteristics.

5.8 Example applications where bio-based composite materials are used today

Automotive

Panels made of nonwoven flax in a PFA matrix with a cardboard core are used as the floor in the bootspace of many cars.⁸² Compression-moulded hemp-reinforced polymers are widely used by Mercedes in a number of non-structural elements (dashboard, door liners, door modules etc.).⁸³

Aerospace

The wing skins of early aircraft were canvas (i.e. cotton) waterproofed with cellulose acetate dope. Fire resistant polyfurfuryl alcohol (PFA) resins from sugar cane waste were introduced in galley carts in 2014 using Ecotechnilin's material, and now have applications using SHD Composites' prepregs in aircraft interiors and battery boxes with potential for jet engine components.⁸⁴

Electrical and electronics

Cotton phenolic was used as early as the 1910s for its electrical insulation performance. Printed circuit boards using cotton-phenolic or cotton-epoxy first emerged in the 1950s and are still used today. There are many suppliers e.g. Attwater in Preston⁸⁵ and Tufnol in Birmingham. Recently there has been work by Jiva Materials to use a bio-based resin in place of the petrochemical thermoset typically used today.⁸⁶

Mechanical

Natural fibres are wear resistant, and importantly do not generate abrasive particles when they wear (unlike glass or carbon). Cotton-phenolic and jute-phenolic are used as bearing materials or to make gears, examples being Feroform F21⁸⁷ from Tenmat and B10 from Attwater⁸⁸.

5.9 Future challenges with bio-based materials

There is no question that the use of bio-based materials will grow as consumers increasingly seek non-fossil-fuel based products and materials, but the rate of that growth will depend on many factors. Ultimately, to achieve a true circular economy with composite materials, either the whole structure of composite parts must be 100% bio-based and biodegradable, to allow the recovery of the carbon and energy content through biological waste processing routes such as composting and anaerobic digestion, or the composites industry must operate a fully closed loop system so that all composite parts are fully recyclable and are fully recovered. Since this latter option looks technologically and societally very challenging, some combination of these two options (increased use of bio-based materials in composite parts and greater closed-loop recycling of composite parts) will be needed to achieve full circularity with composites. We should therefore expect a significant increase in the use of bio-based materials in composite applications in the future.

As highlighted earlier, this will either require greater land-use to grow natural fibres specifically for composite applications, and crops for conversion to bio-based resins, or better, the use of existing bio-waste streams to generate the bio-based resins needed, and potentially some of the natural fibres as well. As a result, players in the bio-based material value chain will need to develop closer relationships with other players in the food and agriculture markets, to identify existing waste streams which may be suitable. In addition, the opportunity for growing bio-fibre (and bio-based resin source) crops on non-

⁸² 'Growing it alone' Composites in Manufacturing, 20/2/14 <https://www.composites.media/growing-it-alone/>

⁸³ 'What role does Hemp play in the Automotive Industry?', Signature Products, 9/6/22 <https://blog.signature-products.com/hemp-automotive-industry/>

⁸⁴ 'NATEP - the Project Brochure', NATEP, Nov 2021. <https://www.natep.org.uk/wp-content/uploads/sites/33/2021/11/NATEP-Directory-210x210-Final-Full-Brochure-compressed.pdf>

⁸⁵ See <https://www.attwater.com/paper-based-laminates-srbp.html>

⁸⁶ See <https://www.jivamaterials.com/>

⁸⁷ See <https://www.tenmat.com/downloads/tenmat-feroform-f21-datasheet.pdf>

⁸⁸ See <https://www.attwater.com/products/b10>

productive marginal land, both in the UK and globally, must be explored to minimise the potential conflict between land use for food purposes and land use for biocomposite raw materials. Industry-wide initiatives as well as individual company actions, will be needed to make progress in this area, and to enable the availability at large scale of the natural fibres and bio-based resins of most interest. There may also be a need for significant government grants and investment to enable interesting technologies to be scaled up and validated, to enable large scale adoption. Composites UK, academic institutions, the National Composites Centre (NCC) and the Composites Leadership Forum (CLF) will all have a key role to play in securing government support to get these developments moving.

Given the inherent variability that will always be present to some extent in a bio-based raw material, due to the impact of global and local climate variations, careful application selection will be needed for potential biocomposite use so that the performance of the end composite part can be maintained within the required performance boundaries. This may require a rethink of the performance properties actually needed as part of product development, the need to design products with this variability in mind and the deployment of appropriate manufacturing techniques to control this variability to the required level. This inherent variability highlights some of the choices that lie ahead for consumers and producers alike, in striking the right balance between performance properties and truly sustainable solutions, in the face of the climate emergency and the need for much more sustainable solutions for the long-term stability of the climate and the survival and prosperity of humanity.

Finally, the ability to demonstrate the value provided by the use of biocomposites will require robust LCA data, and this is an area where further work will definitely be needed. This further work must ensure there is a comprehensive and readily available database of relevant data on greenhouse gas emissions, sequestered CO₂ and embodied energy, for both bio-based materials and synthetic materials, so that genuine quantitative comparison can be made between bio-based materials and synthetic materials, and the benefits of bio-based materials in environmental terms clearly demonstrated.

5.10 Useful publications

For more detail on this subject, the following are recommended:

- a. 'Technology Overview: Biocomposites', Knowledge Transfer Network and Netcomposites, 2014
- b. '12 Principles of Green Chemistry' ACS, outlines a framework for making a greener chemical, process, or product, taken from the following book
- c. 'Green Chemistry: Theory and Practice', Paul Anastas and John Warner, Oxford University Press; Revised ed. edition (25 May 2000)

5.11 Conclusions

Biocomposites have been commercially available for many years in selected applications but until recently, they have been mainly restricted to applications where there was a clear demand and need for a bio-sourced product, and the cost and performance differences, compared with using oil-based materials, were acceptable. In recent years, awareness of the specific benefits that a biocomposite part can bring (such as vibration and noise dampening in automotive parts) has started to raise the profile of the use of biocomposites, and encourage greater use (for example in automotive interiors), and this now looks set to increase sharply as consumers have become aware of the climate emergency, and are increasingly demanding more naturally-derived products in place of those derived from fossil-fuels. A wide range of natural fibres has been available for some time, each bringing specific combinations of properties at commercially competitive prices, and there are now many more commercially available bio-based resins, with attractive properties and pricing, which can be used in combination with natural fibres, to produce biocomposite parts, made wholly from bio-based materials. This greater availability of competitive bio-based materials should help to drive much greater adoption and use of bio-based materials in composite parts going forward.

It is clear that there remain a significant number of major obstacles in the path of increased use of biocomposites but with an increasing and urgent need to address the sustainability of composite parts, there is also an undeniable logic and rationale for greatly increasing the use of bio-based materials in composite parts going forward. Ultimately, the use of bio-based materials may be demanded by consumers and then by governments legislating on their behalf, and with the climate challenges increasing, these demands may emerge much sooner than previously expected. However, for this much greater use of bio-based materials to be realised at industrial and fully commercial scale, there will also need to be an ongoing,

significant investment of time and money by both individual companies and the industry as a whole, over a period of several years, to ensure there is a robust supply chain, and robust data on properties and processing available for users to make use of.



Ecotechnilin Fibricard, flax / PFA with paper honeycomb core, as used in Jaguar F-type boot load floor, 2013. Photo Stella Job

6. RESOURCE EFFICIENCY AND PROCESSING

Author: Malcolm Forsyth

6.1 Introduction

As is often the case, what's good for the environment is also good for business economics and nowhere is this saying truer than when considering waste and efficiency. If an organisation wastes less of the raw materials it uses, it reduces costs, while at the same time reducing the environmental burden of both manufacture and disposal of the wasted materials. So, it makes eminent sense for every producer in the composites value chain to carefully review all its processing activities and look for ways to increase yields and reduce waste of raw materials, as well as other resources such as energy and labour costs.

This chapter will look at some established tools and methodologies, and address how companies can best manage and operate some of the more specific processing methods for manufacturing composite parts, so that yields are maximised and waste is minimised, bringing both economic and environmental benefits.

This chapter is concerned with processing / manufacturing. General workplace good practice in waste and energy management at company level is covered in chapter 7. The good practice described in this chapter could contribute to an environmental management system (EMS) for which standards and certification routes are described in section 7.6.

6.2 Lean manufacturing

“Lean manufacturing” is defined as “A methodology that minimizes waste in manufacturing systems whilst simultaneously maximizing productivity”. In this context, “waste is seen as anything that customers do not believe adds value and are not willing to pay for”. Some of the benefits of applying lean manufacturing techniques are “reduced lead times, reduced operating costs and improved product quality”.⁸⁹ For a general introduction to the concept of “lean manufacturing” refer to the links in the footnotes.^{90 91 92}

In this guide, we will consider the following 3 well-established lean manufacturing methodologies and highlight where they can be deployed by composite part producers for greatest benefit: 5S, TIMWOODS and Value Stream Mapping.

6.2.1 5S

“5S” is a workplace organization method, originating in Japan from a focus on “Just in Time” manufacture, that uses a list of five Japanese words: *seiri* (整理), *seiton* (整頓), *seiso* (清掃), *seiketsu* (清潔) and *shitsuke* (躰). These have been translated in English as:⁹³

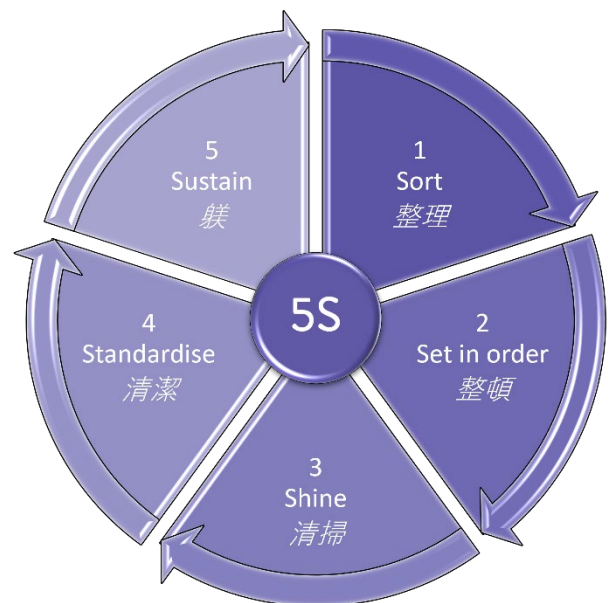


Figure 6.1: 5S methodology for workplace efficiency

⁸⁹ ‘lean manufacturing (lean production)’, TechTarget, <https://searcherp.techtarget.com/definition/lean-production>

⁹⁰ ‘The 8 Essential LEAN Techniques You Need to Know’, Master of Project Academy <https://blog.masterofproject.com/8-lean-techniques/>

⁹¹ ‘Lean Manufacturing Explained’, Reliable Plant <https://www.reliableplant.com/Read/30267/lean-manufacturing-techniques>

⁹² ‘Addressing Sustainability with Industry 4.0 Advancements’ Reliable Plant <https://www.reliableplant.com/Read/31861/sustainability-industry-4-0>

⁹³ ‘What is 5s?’, 5S Today, <https://www.5stoday.com/what-is-5s/>

- Sort
- Set in order
- Shine
- Standardize
- Sustain

This list describes how to organize a workspace for efficiency and effectiveness by identifying and storing the items used, maintaining a workplace area and items required, and then sustaining this new way of doing things. The decision-making process usually comes from a dialogue with employees about standardisation, which builds understanding among employees of how they should do the work and how they can maintain an efficient and effective workspace. Other than being a specific stand-alone methodology, 5S is also frequently viewed as an element of a broader construct known as visual control, visual workplace or visual factory. Under those (and similar) terminologies, many Western companies have been applying the underlying principles of 5S before its publication in English as a formal methodology.

As a brief summary, each stage can be defined as follows, with the benefits shown alongside:

Stage	Definition	Benefits
SORT	Sorting through all the items in a location and removing all unnecessary items from the location	- Increases the amount of usable, effective space - Improves safety by removing unnecessary obstacles - Reduces time required to locate an item by having only the minimum number of genuinely required items available - Reduces the chance of distraction or error by reducing the number of items available - Simplifies future inspections
SET IN ORDER	Putting all the necessary items in the optimal location to fulfil their purpose in the workplace	- Makes the workflow as efficient and safe as possible - Makes all items easy to find in logical and easy to reach locations for the tasks they are required for - Makes spotting missing items easy and immediate - Makes spotting incorrectly stored items easy and immediate
SHINE	Cleaning and inspecting the workplace and equipment on a regular basis	- Improves the production process efficiency and safety, reducing waste and preventing errors and defects - Keeps the workplace safe, clean, easy and pleasing to work in - Enables observers unfamiliar with the workplace to quickly spot any non-conformances or deviations
STANDARDISE	Establish and standardize fixed processes and responsibilities for sorting, ordering and maintaining the workplace	- Establishes procedures and schedules to ensure ongoing repetition of the first 3 “S” activities - Ensures everyone knows their responsibilities for the sorting, organising and cleaning phases - Ensures standards are maintained through the use of visual images showing the expected layout and standard of the workplace - Provides a standard template for follow-up audits
SUSTAIN	Maintain the optimal standards and layout without any managerial intervention needed	- Ensures the initial benefits are retained long-term - Maintains a strong sense of discipline and team-working, and a positive morale, as well as a safe and efficient working area

This methodology has been applied successfully by numerous companies globally and is a foundational step towards having a resource-efficient manufacturing process and a safe and effective working environment for workers. Further details and a free guide can be found at [5S Today](#).⁹³

6.2.2 TIMWOODS

TIMWOODS is an acronym for “the 8 wastes of lean”, which summarize how value can be lost in any manufacturing process through a variety of different inefficiencies or wastes^{94, 95}. These are summarised in Figure 6.2.

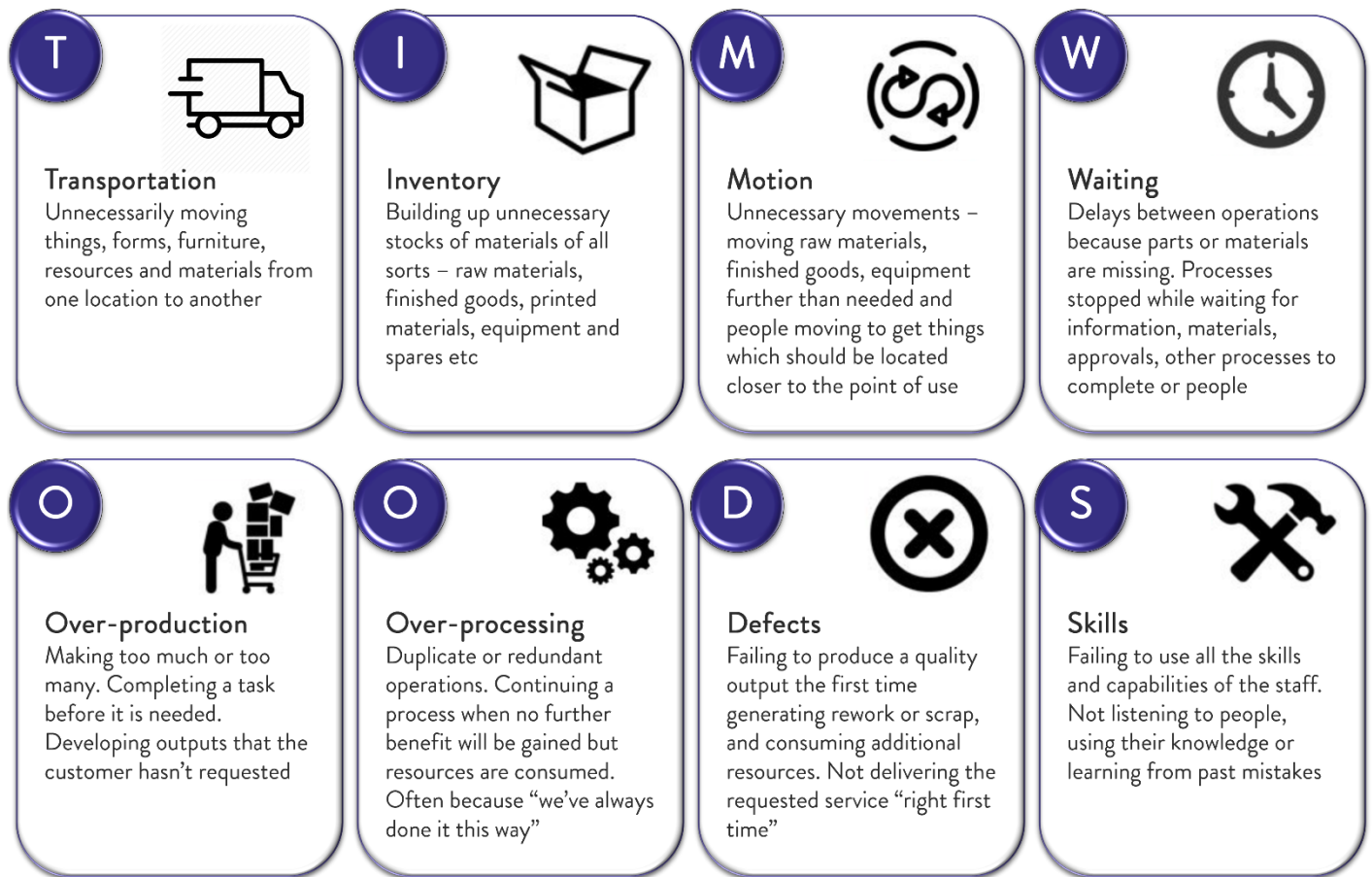


Figure 6.2: TIMWOODS: The 8 wastes of lean

Every manufacturing organisation is at risk of generating some, if not all, of these different types of waste, and therefore all manufacturing organisations can gain from a systematic application of lean principles, centred around these potential areas of “waste”. Progress in each one will result in both economic gain and environmental gain but each manufacturer also has to be willing to invest time and resources to evaluate their current activity, and so each company will need to find its own optimum balance of effort and investment needed and benefits available. The use of a Lean consultant to help smaller organisations may also be worth pursuing and there are many organisations across the UK offering this type of consultancy service. Qualifications and certification in Lean can be achieved through several organisations such as the [Lean Six Sigma Institute](#).

⁹⁴ <https://theleanway.net/The-8-Wastes-of-Lean>

⁹⁵ <http://worksmartertogether.ucd.ie/who-is-tim-woods/>

6.2.3 Value Stream Mapping (VSM)

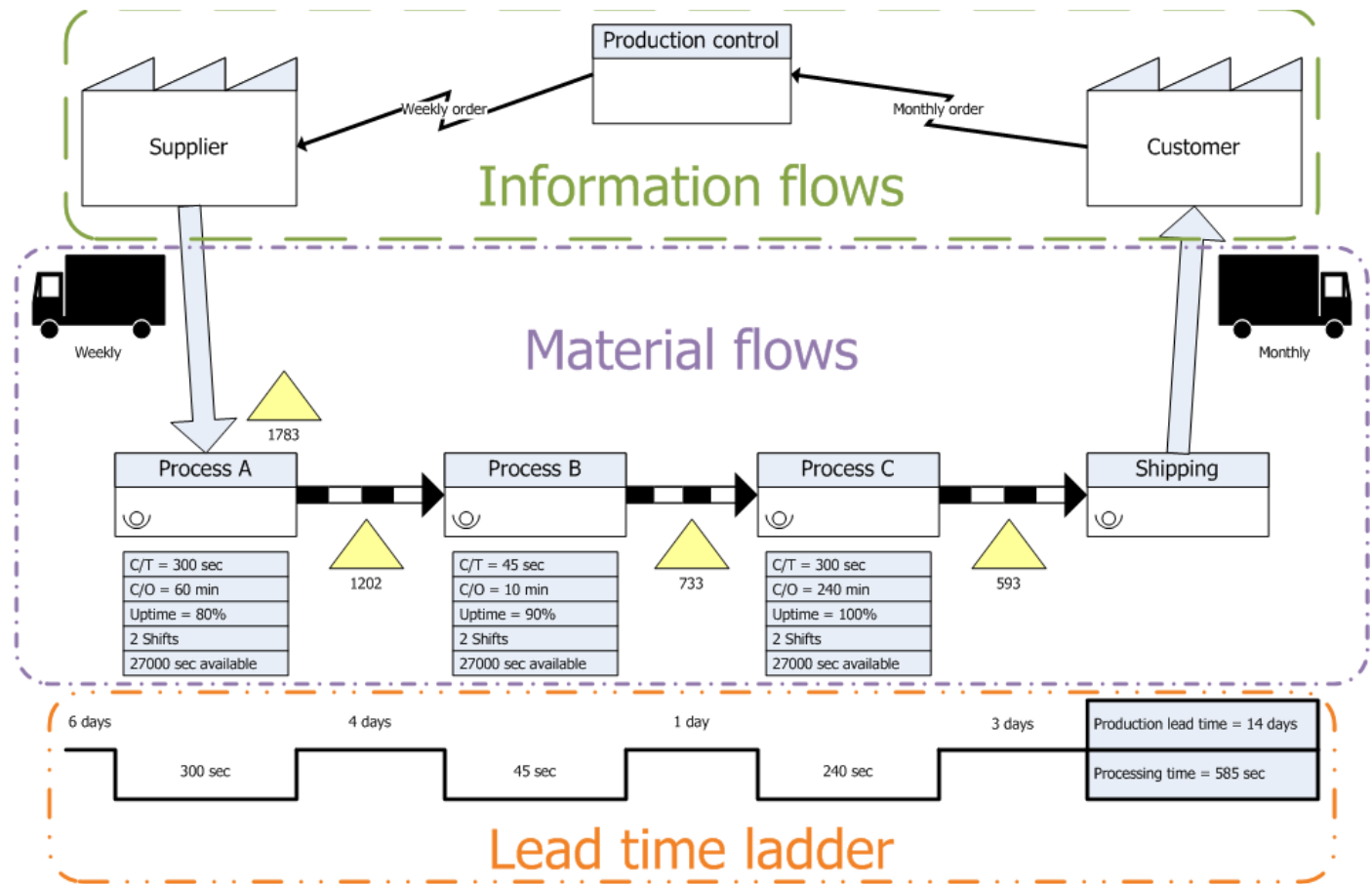


Figure 6.3: Value-stream mapping usually employs standard symbols to represent items and processes, therefore knowledge of these symbols is essential to correctly interpret the production system problems. Image [Daniel Penfield](#) licensed under [CC BY-SA 3.0](#)

Value Stream Mapping (VSM) is another lean management tool which can be very beneficial in designing an optimum manufacturing process with minimised waste across all its individual steps.⁹⁶ VSM, also known as “material- and information-flow mapping” is a method for analysing the current state and designing a future state for the series of events that take a product or service from the beginning of the specific process under review until it reaches its final destination at the customer. A value stream map is a visual tool that displays all the critical steps in the process, and quantifies the time and consumption at each stage, displaying all the flows of both materials and information as they progress through the process. The primary purpose of VSM is to identify and remove or reduce “waste” in value streams to increase the efficiency of that value stream, and therefore once again, there is both an economic and environmental benefit to be gained through its application, making it an important contributor to the sustainability of the product and organisation going forward.

VSM has supporting methods that are often used in “Lean” assessments to analyse and design flows at a system level (across multiple processes), and it should be noted that although VSM is most associated with manufacturing processes, it can also be applied to good effect in logistics, supply chain, product development and administrative/office processes as well.

There are again many consultancies able to offer support with this technique and composite part manufacturers looking to apply VSM to their processes may well find it useful to seek out local consultants in their region to support them and help them apply the methodology correctly and effectively.

When applying these 3 tools and methodologies, it is important that appropriate people resources are made available to ensure that all the relevant corporate knowledge on a process is accessed and fully utilised, and that sufficient time is made available to carry out all the steps in the different methodologies or the full benefits may not be gained. Whichever tool is selected, it is important to recognise that there will need to be a significant investment of time made up-front, if significant lasting gains are to be first identified and then secured for the long term.

⁹⁶ <https://kanbanize.com/lean-management/value-waste/value-stream-mapping/>

6.3 Specific composites processes with resource efficiency opportunities

The composites industry uses a wide range of processing methods to convert fibres and matrix resins to finished composite parts and each has the potential to be quite wasteful of material and energy if not carefully set up, controlled and measured.

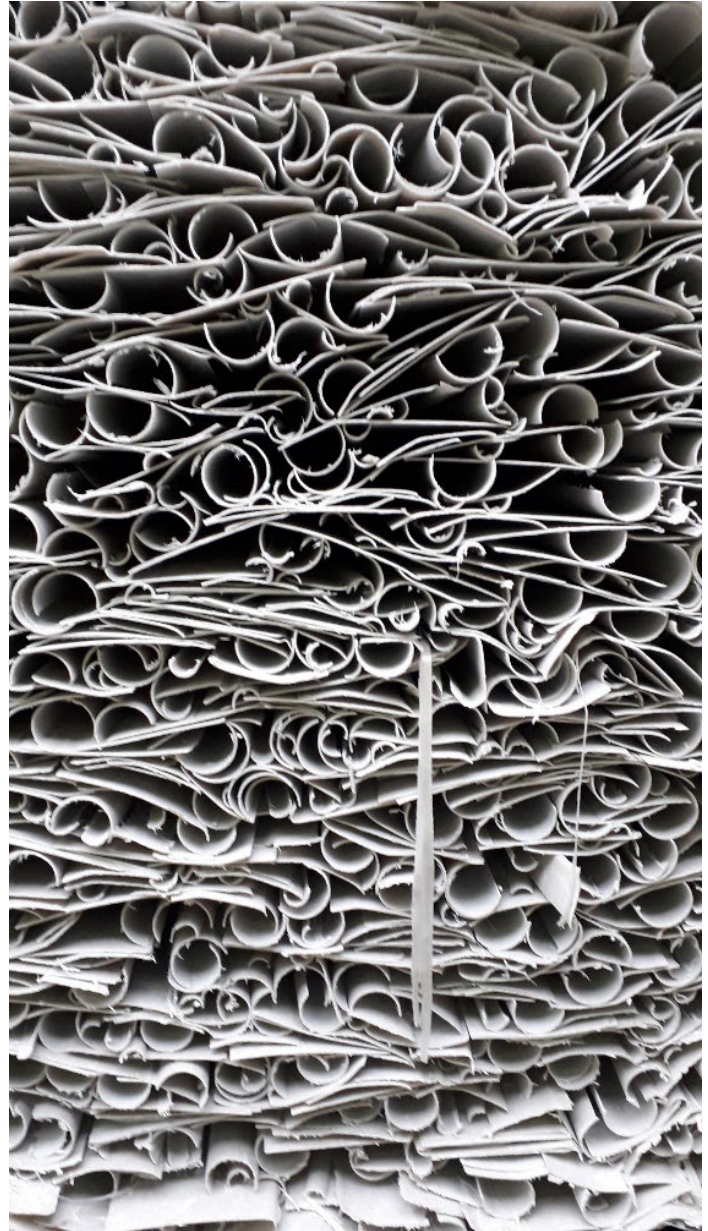
As part of any company's drive towards true sustainability, every effort should be made to design the manufacturing process so that as little material is wasted as possible (especially if expensive materials like carbon fibre are used), and so that, where possible, any waste produced can be reincorporated into the manufacturing process, either for the same part or potentially for other parts with less demanding requirements. Key questions to consider are:

- Can the process be modified to reduce waste, edge trim etc?
- Can different processes and/or materials be used which would be more material-efficient?
- Can the waste generated be put back elsewhere into the processes employed by the company? Or at a nearby company?
- Can energy be used more efficiently?

There have been several good examples of reductions achieved with different processes, such as Filon reducing their line waste from their continuous roof sheet production line from 20% to 10%, through more accurate material feeding, reduced side width tolerances and reduced start-up and run-out waste. Sourcing outlets for packaging waste and sacrificial films have also helped reduce their waste disposal costs further. Another example is Sigmatex who have developed a process to use their carbon fibre waste in nonwovens, which can reduce their landfill contribution by up to 90% (approx. 150 t p.a.). (See case study on next page.) Far-UK is also reducing waste by providing dry fibre offcuts to small businesses in the area and to students completing research projects. (See case study at 7.3.)

Whenever a detailed study on process waste is done, a proper financial evaluation will be needed, to understand the balance of the savings available and the investment needed to achieve these (whether capital cost through machine investment and/or revenue cost through the deployment of people) so that the right balance is struck, and if possible, an economic gain is realised as well as an environmental one. In addition, a life cycle assessment could be carried out so that the true environmental gain is quantified.

Smaller composites manufacturers may not have the required expertise in-house and if this is the case, they can seek support from various process consultancies or research organisations who may be able to carry out a funded study for them to determine the scope for efficiency improvement and the economic and environmental gains as a result.



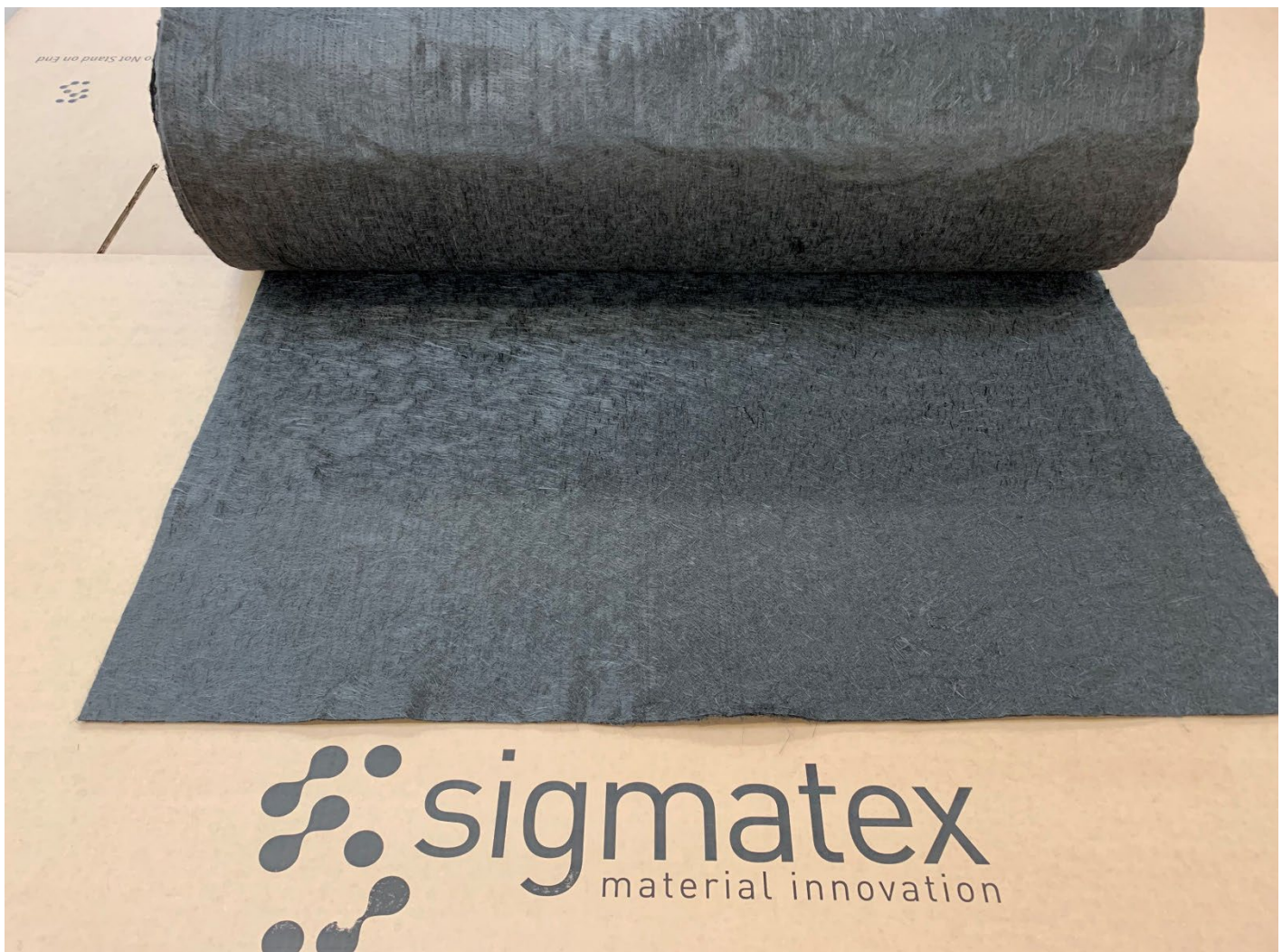
Edge trim from continuous sheet process. Photo Stella Job

Case study: Carbon fibre nonwovens from production waste

Peter Sestic, Sigmatex

Up to 30% of all carbon fibre produced ultimately ends up as waste within the manufacturing supply chain. Waste reduction is a major issue in the composites industry. Sigmatex has a strong motivation to minimise their environmental footprint, therefore they have developed a technology to recover their carbon fibre waste and to transform it into nonwoven fabrics. Their nonwoven fabric is made from virgin / sized fibre to maximise resin compatibility within the composite stack. It is an economical way to add stiffness and bulk. The fibres are typically 30-70mm in length and are randomly oriented. Most importantly this invention can reduce their landfill contribution by up to 90% (approx. 150 tonnes per annum). The technology in question is only a fraction of the size of a weaving machine and so fits within a small footprint, adding only marginal additional energy consumption. It's a true win-win situation for the environment and the composites industry.

Alongside the technology development the product development has grown to a level of consistency, demonstrating that a stable product can be manufactured repeatedly using very traditional textile processing equipment. Namely, fibre preparation and machine feeding, carding processes, fibre pile laying and nonwoven bonding / fixation, resulting in a 100% recycled carbon fibre nonwoven at various fabric weights depending on the requirement. By blending a polymer with the fibre preparation prior to the carding stage a thermoplastic product can be made using a variety of chosen polymers thus opening the opportunities for thermoformed parts as well as resin infused items. Wind, automotive and consumer electronics are just some of the industries working with the recycled materials developed at Sigmatex.



Sigmatex nonwoven fabric from high quality recovered virgin carbon fibre waste. Photo courtesy of Sigmatex

6.3.1 Net shape processing

Near net shape (NNS) manufacturing is a term given to processes that aim for the initial fabrication of a component to be close in size and shape to the finished product. This approach reduces production costs and times associated with subsequent finishing steps, such as trimming and machining, and initial raw material investment costs.⁹⁷

This approach has been adopted by a number of automotive OEMs who have used automated fibre placement with robots to lay multiple narrow tapes in exactly the right shapes and locations, and different numbers of fibre plies in specific locations to ensure the part shape is optimal with minimal waste material. Similarly, as an example, rather than use one large, moulded part for the side of a car, and then have to cut out several holes for the doors, automotive OEMs have used several smaller pieces and co-cured them together to create a large side part moulding, with limited waste.

Examples of near net shape processes relevant to composites are 3D printing, automatic tape laying, braiding, filament winding, pultrusion (as long as lengths are cut so as not to waste offcuts). BMC can potentially be used as near net shape if correctly measured, or at least overflow from the mould can go into the next charge.

6.3.2 Part consolidation

Composites provide the opportunity for part consolidation, where multi-part assemblies are achieved with a single part, with significant savings in labour and fixings. SMC is an excellent material for this, and can be used with strategically placed fabrics to strengthen the part if needed. Overmoulding with short fibre filled compounds can also achieve this effectively, whether thermoplastic or thermoset.

6.3.3 Nesting

For fabrics and prepregs, efficient nesting allows for the plys cut from a fabric roll to fit together more effectively so saving wasted offcut material. Nesting software is available to enable this, and it can generate very good returns economically as well as environmentally.

A simple application of this approach is the use of pre-cut fabric or core “kits”, whereby a kit-cutting company pre-cuts the base material to the exact shape needed by the part manufacturer, and then delivers the kits to the part manufacturer, ready to be placed in the moulds with no further preparation needed. This approach means that the trimming is done by the material provider who can then incorporate the material trimmed off into other products and so minimise expensive material wastage. This approach saves time and labour as well as material, and so can bring many benefits for the composite part manufacturer, although there needs to be sufficient throughput of parts to justify the pre-cutting costs involved.

6.3.4 Reusable silicone vacuum bags

Silicone reusable vacuum bags can eliminate disposable vacuum bag waste where volumes from a single mould are high enough to justify their use. Suppliers claim they are easy to mix and apply using spray-on silicone, can also reduce labour costs by up to 90% and are more heat resistant than typical disposable vacuum bags. Materials are supplied by several UK suppliers who can provide advice on how to use them.

⁹⁷ Adapted from TWI <https://www.twi-global.com/technical-knowledge/faqs/what-is-near-net-shape>

Case study: 95% energy reduction for consolidation of braided thermoplastic parts

Steve Barbour: Composite Braiding Ltd

The core strategy at Composite Braiding Ltd (CBL) is to fill a gap in the market for higher-volume, lower-cost, more sustainable structural parts using braided thermoplastic composites. One aspect has been how to consolidate the materials efficiently. Autoclave or oven-processing is fine for proof-of-concept, prototyping or low volume, but with braiding rates of up to a mile a day per shift, the time and energy used is prohibitive.

CBL applied for and obtained an Innovate UK loan and over three years have developed game-changing capability in high-volume, low thermal mass, low energy usage tooling. Energy reduction versus in-oven processing is typically 95% to 99%. For example, a grab pole in the oven uses around 70 kWh of energy, but in the new process uses 1.5 kWh of energy. Parts are consolidated in minutes, rather than hours, which is critical given the high rate of the braiding process.

The tooling is very flexible and has modular capabilities, opening up new opportunities for larger and/or more complex components. The faster processing cycle means that consumable bladders that are capable of one or two cycles in the oven, can last for 14 cycles or more in the new tooling.

In a study, CBL looked at replacing over 3000 structural steel poles with their glass fibre thermoplastic structural poles. With production, installation and other savings they estimated over 7,700 tonnes CO₂e could be saved on that one project versus imported steel.

6.4 Energy efficiency

Energy efficiency is discussed further in chapter 7 but there are some aspects which are specific to composite processes. Autoclaves are among the most energy intensive pieces of equipment used in composites. Savings can be made by ensuring the autoclave is well maintained, well insulated, and using it efficiently, e.g. processing the right number of parts in a batch. Where heat is applied to cure materials, directly heated tooling or the use of infra-red or microwave may be possible. In the curing of large parts, such as boat hulls, the design of the “oven”, its insulation and air-tightness could make a huge difference to the energy used. In some cases, it may be possible to use secondary heat, either from in-house processes, or by co-locating with other high temperature processes. Heating air and relying on convection is inherently inefficient and technologies are emerging to heat tools and parts much more directly and efficiently.

Monitoring energy use and making use of half-hour usage data, which is available from most commercial energy suppliers, can help to identify opportunities for improvement.



Composite Braiding 128 braider. Photo courtesy of Composite Braiding

6.5 Measurement of progress and collection of data

It is always important to quantify the gains made in any resource efficiency-focussed project and all composite parts manufacturers should ensure that they are accurately recording the materials being used and operators involved in each process step, to identify the biggest opportunities for improvement. It is also important to ensure that accurate data-logging continues after any improvement step is introduced so that the level of sustained improvement over months and years is clearly visible. Wherever possible, data from moulding operations should be collected automatically to enable faster data analysis but if not, then a reliable method for capturing and inputting process data should be put in place to ensure it is recorded systematically.

Several organisations supply product lifecycle management (PLM) software tailored to composites. PLM software is a solution that manages information and processes at every step of a product lifecycle across globalised supply chains. This includes the data from materials, processes, documentation, etc. This means that if a fault is found beyond the factory gate, it can be traced to the specific material batches, equipment used and operators involved to trace the cause of the problem.

Manufacturing operational data is key to enabling significant increases in manufacturing productivity, especially where there is a manufacturing process with a high level of regularity and repetition, and sharing of this data with upstream and downstream partners may also be very beneficial in generating further improvements for the manufacturer and for the value chain as a whole. Computer-aided engineering (CAE) simulation when done well with a ‘design for manufacturing’ approach, will result in reduced waste in production with better quality assurance and so help to eliminate recalls, scrappage and rework. This is discussed further in section 2.6.

6.6 Sources and destinations of waste

A manufacturer’s physical waste is typically from four sources:

1. Process waste, e.g., edge trim, offcuts, consumables, etc
2. Human or machine error, scrap parts, materials past their shelf life
3. Wrong orders
4. Prototyping, material testing and qualification

The proportion of waste produced by manufacturers using similar processes can vary widely, depending on how they manage these three areas. We tend to think first of wastes inherent to the processes used, which has been addressed in section 6.3. On the second point, keeping machines well maintained and ensuring staff are well-trained, with an expectation of continuous improvement can make a huge difference. It is good practice to track the product lifecycle as noted in section 6.5.

The third point can result in very large volumes of waste. While the customer making a wrong order may not be the manufacturer’s “fault”, it is good practice to work with the customer to make sure they fully understand the specification they are requesting and that it is fit for purpose. In the unfortunate event that wrong orders occur, there may be opportunities for donating or selling parts at low cost to organisations who take B-grade parts to sell on.

The fourth point may be small volumes, though in high value sectors such as aerospace there may be extensive qualification processes using materials with high environmental impact and value. Effective use of modelling and a ‘virtual design of experiments’ approach can reduce physical testing needs, which reduces physical waste and may accelerate innovation.

The scrap material that cannot be avoided needs to be disposed of. Recycling processes are slowly developing and there are clear routes for dry fibre scrap. Some consumables can also be recycled, if not heavily contaminated. The increasing use of thermoplastic matrices are allowing additional options for re-purposing and re-use. Composites UK has a page ‘[What can I do with my waste?](https://compositesuk.co.uk/industry-support/environmental/what-can-i-do-with-my-waste/)’ providing details of various routes.⁹⁸

As discussed above, non-physical waste is also very important to consider and will include the other categories of TIMWOODS discussed in 6.2.2 above.

6.7 Engaging the team

In order to move towards a more resource and energy efficient organisation, engaging the whole team from the shop floor to senior management is essential. At a basic level, procedures need to be simple and clear, communicated well and regularly. Do all the staff know in which recycling bins to put different types of scrap? Toolbox talks for health and safety are common good practice. (i.e. short, regular team talks often delivered by a different person each time.) Could there also be toolbox talks for sustainability?

Encouraging all the staff in sustainability thinking integrated with an open innovation approach offers people the freedom to share ideas for change. They then need management support to be provided with the systems, resources and training to implement those ideas in a ‘fail fast’ framework where positives and negatives are tracked and learned from. In short, make sustainability everybody’s job, and make it part of your innovation strategy.

⁹⁸ ‘What can I do with my waste?’, Composites UK <https://compositesuk.co.uk/industry-support/environmental/what-can-i-do-with-my-waste/>

6.8 Conclusions

A focus on high resource efficiency can enable any composite part producer to achieve both economic and environmental gains, and by doing so, make a tangible and worthwhile contribution to the sustainability of their organisation, as well as wider society. It is therefore worthwhile for all players to do a serious investigation, to determine the scope for improvement in their various processes, and be able to prioritise and focus their efforts on the areas offering the greatest return in economic and environmental terms. There are a multitude of approaches that can be taken, and this chapter has touched on just a few of the more established and proven techniques, to highlight the focus that can be taken, and the support and resources available to help a manufacturing company drive up their resource efficiency and drive down their waste, creating major benefits economically and environmentally. As raw materials and energy become more expensive, along with the cost of waste disposal, there will be major benefits economically for those players who can achieve high resource efficiencies, as well as opportunities to publicise their sustainability credentials and attract further customers as a result.

7. TARGETS, OFFSETS, REPORTING AND ESG

Author: Stella Job

7.1 Introduction

The expectation for companies to have individual “net zero” targets, to monitor energy use and manage environmental impact is growing rapidly, whether required by regulation, customers or an in-house desire to improve. This is accompanied by transparency and reporting requirements as investors increasingly want to see Environmental, Social and Governance (ESG) ratings and regulations develop. A host of standards for Environmental Management System (EMS) procedures, reporting, ESG ratings and certification have emerged which can be difficult to navigate. However, the benefits of embracing ESG, provided focus on one strand does not detract from the others, are significant in terms of attracting investment, customers and quality staff.

This chapter seeks to outline the current landscape, acknowledging that it is evolving rapidly, and give pointers to further information. It is concerned about whole company energy and impacts, rather than sustainable design or product specific impacts which are addressed in the preceding chapters.

The information here is believed to be current at publication, but please check the latest regulations and guidance.

7.2 Energy trends

Total electricity supplied in UK peaked in 2005 and fell by 17% from 2005 to 2021 due to increasing efficiency. The same period has seen a dramatic change in electricity generation, with renewable energy effectively replacing coal. See Figure 7.1. Growth in the electrification of transport, heat pumps and demand for green hydrogen is likely to see electricity demand rising again before 2030.⁹⁹

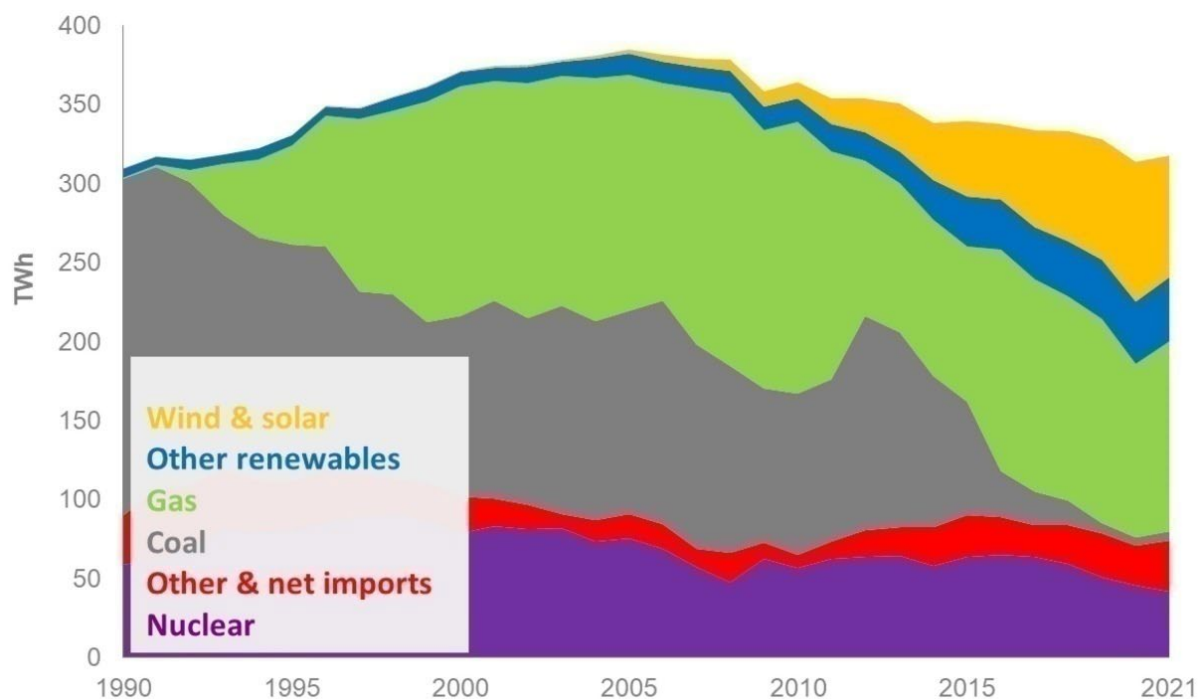


Figure 7.1: Electricity supplied by fuel type, 1990 to 2021. Image from 'UK energy in brief 2022'¹⁰⁰

⁹⁹ 'Future Energy Scenarios in five minutes', National Grid ESO, July 2022
<https://www.nationalgrideso.com/document/263861/download>

However, in the UK in 2021, burning fossil fuels still accounted for around 45% of electricity generated and 78% of energy consumption overall, including fuels used for heating, transport and industrial processes.¹⁰⁰ It should also be noted that non-fossil energy still has an environmental impact, albeit much lower than the combustion of fossil fuels.

Even as renewable energy increases, it is vital that we continue to improve energy efficiency in all areas, as our path to decarbonisation will still be limited by the availability of renewable energy for decades to come. Many companies will have already robustly addressed energy efficiency in the past, but there is a need to reassess and improve targets, putting appropriate monitoring in place. As in the case of material efficiency, energy efficiency has clear economic benefits as well as reducing environmental impact, though the time it takes to pay back investments will vary. However, it will invariably achieve better ROIs than investment in renewables alone.

7.3 General good practice in the workplace

At a simple level, companies can start with basic good practice, much of which is common sense, e.g.:¹⁰¹

- Switch to LED bulbs with sensors, auto-switch off / timings
- Insulate buildings
- Use rooflights / natural light where possible
- Consider destratification fans where ceilings are high
- Adjust heating and cooling system timings, temperatures and rooms
- Install a smart meter, make use of half-hour usage data
- Procure energy from low carbon sources
- Install your own renewable electricity or heating
- Minimise the waste from your products, packaging and public areas
- Reuse or recycle the waste that can't be avoided as much as possible
- Electrify your vehicle fleet, install EV charging points, e-bike schemes for employees
- Locate premises with easy public transport access, introduce a cycle to work scheme
- Ensure investments, pension fund, etc are in ethical / sustainable funds.



A destratification fan installed in the workshop at Far-UK is saving 2.7 tonnes of CO₂/yr- equivalent to a year's gas use for a four bed home. Rooflights allow natural light, reducing energy demand for lighting. Photo courtesy of Far-UK.

For general business waste reduction, there are some useful tips from edie.¹⁰² The suggestion to appoint a waste prevention team and do a waste audit are good starting points. Ethical Consumer provides some useful guidance on ethical purchasing and pension plans.¹⁰³

¹⁰⁰ UK energy in brief 2022, Department for Business, Energy & Industrial Strategy, 28/7/22
<https://www.gov.uk/government/statistics/uk-energy-in-brief-2022>

¹⁰¹ List adapted from 'Steps you can take to cut your emissions', UK Business Climate Hub <https://businessclimatehub.org/uk/#steps>

¹⁰² 'Zero waste: Top 20 tips to reduce waste in the workplace', edie <https://www.edie.net/news/5/Top-20-tips-to-reduce-waste-in-the-workplace/>

¹⁰³ Ethical Pensions, Ethical Consumer 26/10/20 <https://www.ethicalconsumer.org/money-finance/shopping-guide/ethical-pensions>

The Carbon Trust has published a wide range of free guides and tools to help SMEs and start-ups tackle net zero, energy efficiency and procurement, and carbon reduction.¹⁰⁴ Numerous other resources are available online, including advice from Invest NI on Efficiency and Environment.¹⁰⁵ Local councils may have schemes to support, or provide free energy audits.

For manufacturers, industrial use of energy may be your greatest direct impact (scope 1 and 2 emissions). Resource and energy efficiency in processing has been discussed in chapter 6, and the Carbon Trust resources include a specific guide for manufacturing businesses.

For many companies, their greatest impact is in their supply chain (scope 3 emissions). For composite manufacturers in particular, the ‘cradle to gate’ carbon footprint of your products is likely to be heavily dominated by your upstream materials supply chain. It is important to talk to your suppliers and ask how they are reducing their emissions. The GHG Protocol Scope 3 Standard notes that “while a company has control over its direct emissions, it has influence over its indirect emissions”.¹⁰⁶ For larger companies, it may be appropriate to require some reporting from your materials suppliers, not least so you can benchmark your own products.

¹⁰⁴ ‘Carbon reduction and net zero for SMEs’, Carbon Trust <https://www.carbontrust.com/resources/carbon-reduction-and-net-zero-for-smes>

¹⁰⁵ ‘Efficiency and environment’, Invest NI, <https://www.nibusinessinfo.co.uk/content/efficiency-and-environment>

¹⁰⁶ GHG Protocol, Corporate Value Chain (Scope 3) Accounting and Reporting Standard, September 2011, p. 27

Case study: Reducing organisational environmental impact at Far-UK

Helena Job O'Connell, Far-UK

Far-UK Ltd is a design and manufacturing company based in Nottingham that specialises in providing lightweighting solutions for complex engineering challenges. As an SME with a strong interest in developing more sustainable technology, the company is eager to also reduce its own environmental impact; it is therefore in the process of implementing step changes that will result in reduced Scope 1, 2, and 3 emissions.

The company is using energy monitoring devices to collect and assess energy usage data with support from the local universities and the city council. As a result, it has identified and implemented measures to reduce energy consumption, such as installing LED lighting, providing an electric car charging point and joining a council e-bike scheme. Installation of a destratification fan in the workshop has had a major impact, and is expected to save around 2.7 t CO₂e/year – equivalent to a year's gas use for a four-bed home.

Far is also working to help establish a local circular economy, reducing waste by providing dry fibre offcuts to small businesses in the area and to students completing research projects.

Additionally, Far is ensuring employees are provided with information on sustainable investment options available through the company pension scheme, giving them the ability to switch their investments should they so choose.

Far-UK Ltd aims to make a difference to the planet through the development of better technology, and the steps it is taking to reduce its operational environmental impact complement these goals.



7.4 Metrics and targets

Energy and/or emission intensity metrics appropriate to a specific organisation can be established to monitor progress. Reducing overall energy may not be representative of energy efficiency for a company whose product outputs are growing. Targets can then be set for energy and emission reduction. Emission intensity (which can also be referred to as emission factor, intensity ratio or carbon intensity) is the emission rate of a given substance, often carbon dioxide, relative to the intensity of a specific activity, or an industrial production process. For manufacturing, it could be related to mass or value of product, e.g. kg CO₂e/kg product or kg CO₂e/£ sales revenue. (kg CO₂e refers to the greenhouse gas emissions expressed as equivalent to the mass of CO₂ in terms of their effect on climate warming.)

The Science Based Targets initiative (SBTi) provides a clearly-defined pathway for companies to reduce greenhouse gas (GHG) emissions by setting emission reduction targets in line with climate science and the Paris Agreement goals.¹⁰⁷ This involves:

1. COMMIT: Submit a letter establishing your intent to set a science-based target
2. DEVELOP: Work on an emissions reduction target in line with the SBTi's criteria
3. SUBMIT: Present your target to the SBTi for official validation
4. COMMUNICATE: Announce your target and inform your stakeholders
5. DISCLOSE: Report company-wide emissions and progress against targets on an annual basis

Committing to targets strengthens brand reputation, helps to drive innovation, often gives a competitive advantage, boosts investor confidence, and increasingly is helping companies become resilient against upcoming regulation such as TCFD (see 7.8). However, it does not currently or appropriately assess actions beyond baseline formulation.

7.5 Carbon neutral, net zero and carbon markets

7.5.1 Carbon neutral and net zero

The terms carbon neutral and net zero are often used interchangeably, but are not the same. Both refer to emissions of all GHGs, not just carbon. (Some websites say “carbon neutral” refers only to carbon emissions, but the standard for carbon neutrality, PAS 2060,¹⁰⁸ relates to all GHGs. Likewise, “carbon offsets” often refer to any GHGs.) More details are on this Carbon Trust page¹⁰⁹, but briefly:

- Carbon neutral certification allows an organisation (or product) to be declared carbon neutral. It doesn't need to include scope three emissions, though this is encouraged, and allows offsets which avoid or reduce emissions as well as remove GHGs.
- Net Zero is a pathway to reduce emissions, including scope three, as far as possible with offsetting as a last resort. Those offsets must remove GHGs from the atmosphere.



Estimating carbon stock in a mangrove forest. Photo by [Daniel Murdiyarto/CIFOR](#), licensed under [CC BY-NC-ND 2.0](#)

There are two types of market for carbon, voluntary and compliance.

7.5.2 Voluntary carbon markets

Companies may wish to offset the emissions that are difficult to reduce, or even to offset historical emissions, having achieved carbon neutrality. The term “carbon offset” may refer to a reduction in CO₂/GHG emissions or removal of GHGs from the atmosphere in order to compensate for CO₂/GHG emissions elsewhere. Offset activities may include such things as renewable energy development; reducing emissions from forestry; efficient cookstoves in developing countries. Units or credits are usually measured in tonnes CO₂e and are traded between organisations.

¹⁰⁷ Science Based Targets initiative <https://sciencebasedtargets.org/>

¹⁰⁸ PAS 2060:2014 ‘Specification for the demonstration of carbon neutrality’, BSI
<https://knowledge.bsigroup.com/products/specification-for-the-demonstration-of-carbon-neutrality-1/standard>

¹⁰⁹ <https://www.carbontrust.com/what-we-do/assurance-and-certification/carbon-neutral-certification>

The rapidly growing voluntary carbon market (VCM) was reported to be worth nearly \$2 billion in 2021.¹¹⁰ Schemes are verified by certification through organisations such as Verified Carbon Standard (Verra), Gold Standard, Climate Action Reserve and others.¹¹¹ Alignment of the various standards is underway through the Integrity Council for the Voluntary Carbon Market (Integrity Council, IC-VCM) which is developing a set of “Core Carbon Principles”, based on the Paris Agreement, to define global standards for high-quality carbon credits.

7.5.3 Compliance carbon markets

The largest compliance carbon market is the EU Emissions Trading Scheme (ETS),¹¹² now mirrored since Brexit by the UK ETS.¹¹³ It is mandatory for operators of power stations, sites where combustion units with a total rated thermal input exceeds 20MW (except waste incineration) and aircraft for domestic and European flights. This is unlikely to be relevant for the composites industry except perhaps for large chemical companies or fibre manufacturers.

7.6 Environmental management systems

An Environmental Management System (EMS) is a set of processes and practices that enable an organization to reduce its environmental impacts and increase its operating efficiency.¹¹⁴ It is a “system and database which integrates procedures and processes for the training of personnel, monitoring, summarizing, and reporting of specialized environmental performance information to internal and external stakeholders of the firm ”.¹¹⁵

Securing top management commitment, as well as involving employees, are key to the success of an EMS (as with any management or innovation scheme). Once goals are set, it will typically follow a Plan > Do > Check > Act cycle.

Numerous organisations provide free online resources for developing an EMS, such as Invest NI¹¹⁶, the US Environmental Protection Agency¹¹⁴, and Green Small Business has a free handbook accompanied by paid services. ISO 14001 (environmental management) formally describes EMS processes, but for a small company it may be sufficient to have concise EMS action plan with a realistic timeframe showing a positive impact at the same time as business benefit.

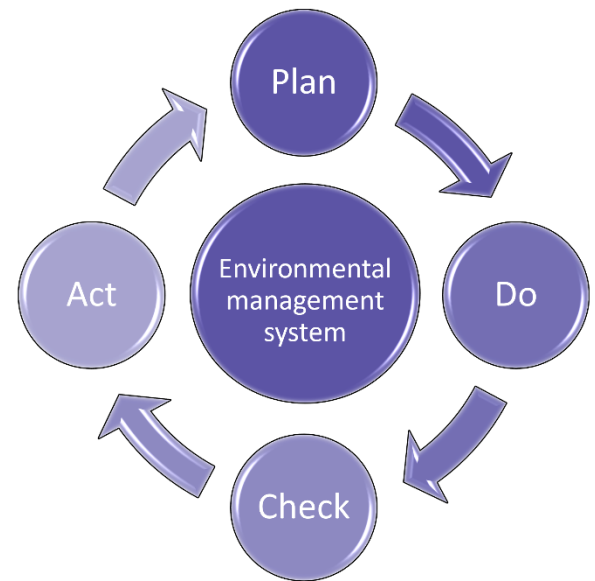


Figure 7.2: EMS Plan > Do > Check > Act cycle

7.7 Certification routes

There are many certification routes available for organisations (rather than products) in the area of environmental management. Some of these are listed here:

- **ISO 14001 Environmental management:** This specifies the requirements for an EMS and several organisations can certify a company to the standard.¹¹⁷ It can be a strong addition alongside certifications like ISO 9001 for

¹¹⁰ 'VCM Reaches Towards \$2 Billion in 2021', Ecosystem Marketplace, 3/8/22 <https://www.ecosystemmarketplace.com/articles/the-art-of-integrity-state-of-the-voluntary-carbon-markets-q3-2022/>

¹¹¹ Verified Carbon Standard <https://verra.org/project/vcs-program/>; Gold Standard <https://www.goldstandard.org/>; Climate Action Reserve <https://www.climateactionreserve.org/>

¹¹² EU Emissions Trading Scheme https://ec.europa.eu/clima/eu-action/eu-emissions-trading-system-eu-ets_en

¹¹³ UK Emissions Trading Scheme <https://www.gov.uk/government/publications/participating-in-the-uk-ets/participating-in-the-uk-ets>

¹¹⁴ Environmental Management Systems (EMS), US EPA <https://www.epa.gov/ems>

¹¹⁵ Sroufe, Robert. "Effects of Environmental Management Systems on Environmental Management Practices and Operations." *Production and Operations Management*. 12-3 (2003): 416–431

¹¹⁶ Set up an environmental management system (EMS), Invest NI <https://www.nibusinessinfo.co.uk/content/set-environmental-management-system-ems>

¹¹⁷ ISO 14001:2015 'Environmental management systems — Requirements with guidance for use' <https://www.iso.org/standard/60857.html>

quality management and ISO 45001 for occupational health and safety management. ISO 14001 focuses on the process and systems more than purpose and driving change, and considers environmental impact but not social and human impact.

Smaller companies may find ISO 14001 requires too much resource and is unnecessarily complex, though more recently ISO 14005 has been published for SMEs, to meet the requirements for an EMS in a phased, flexible way.¹¹⁸

- **ISO 50001 Energy management:** This is based on the same model of continual improvement as other ISO standards.¹¹⁹ When actioned to incorporate fleet, it can be used in place of Energy Savings Opportunities Scheme (ESOS) (see 7.8). A [free guide](#) is available from British Standards Institution (BSI).¹²⁰
- **EMAS:** The EU Eco-Management and Audit Scheme (EMAS) is a voluntary environmental management tool for companies and other organisations to evaluate, report and improve their environmental performance. It is a step up from ISO 14001 but has been little adopted outside of Europe.¹²¹
- **Ecovadis:** EcoVadis is a rating system (not technically certification) geared towards managing supply chains and sharing B2B sustainability performance information. The assessment framework uses four pillars: Environment, labour & human rights, ethics, sustainable procurement. There is also a carbon management scorecard, based on commitments, action and reporting.¹²²
- **B Corp:** B Corp Certification is more holistic and demonstrates high standards of performance, accountability, and transparency on factors from treatment of employees and charitable giving to supply chain practices and input materials. Certification is through the non-profit, [B Lab](#), and includes membership of their network. The first stage is the [B Impact Assessment](#) which you can do for free. It has around 200 questions which give good ideas for improvement.¹²³
- **Planet Mark:** The Planet Mark Business Certification Scheme recognises the commitment to continuous improvement, measuring and reducing a business' carbon emissions, energy and water consumption, travel and waste. Social value can also be included.¹²⁴
- **Carbon Trust:** Whilst no longer an independent and impartial body, the Carbon Trust provides certification in several areas including:¹²⁵
 - [Route to Net Zero](#) (replaces Carbon Trust Standard) – manage emissions, create carbon reduction strategies, and set targets for the future
 - [Carbon neutral certification](#) for an organisation to PAS 2060, the international standard for carbon neutrality. This can also be used for a product.
 - [The Carbon Trust Standard for Zero Waste to Landfill](#)

There are numerous other frameworks which may or may not provide certification, several of which are listed with a useful comparison table by [Greener Matters](#).¹²⁶

¹¹⁸ 'New standard helps SMEs get ahead with ISO 14001', ISO, 2019 <https://www.iso.org/news/ref2393.html>

¹¹⁹ ISO 50001:2018 'Energy management systems — Requirements with guidance for use' <https://www.iso.org/standard/69426.html>

¹²⁰ 'ISO 50001:2018 - Guide ISO 50001:2018', BSI <https://www.bsigroup.com/en-GB/iso-50001-energy-management/ISO-50001-2018-Guide/>

¹²¹ 'What is EMAS?', European Commission https://ec.europa.eu/environment/emas/index_en.htm

¹²² 'What is the EcoVadis assessment process?', EcoVadis <https://support.ecovadis.com/hc/en-us/articles/115002653188-What-is-the-EcoVadis-assessment-process->

¹²³ B Impact Assessment, B Labs, <https://www.bcorporation.net/en-us/programs-and-tools/b-impact-assessment/>

¹²⁴ Planet Mark <https://www.planetmark.com/>

¹²⁵ Assurance and Certification, Carbon Trust <https://www.carbontrust.com/what-we-do/assurance-and-certification>

¹²⁶ 'The top 13 sustainability certifications for UK businesses', Greener Matters, 19/8/21 <https://greenermatters.com/sustainable-business/the-top-13-sustainability-certifications-for-uk-businesses/>

Case study: A strategy for emission reduction and environmental management

Laxman Sivanathan, Jo Bird and Co Ltd

Jo Bird & Co Ltd design and manufacture GFRP enclosures for storing and protecting fire safety and lifesaving equipment in hazardous environments, such as offshore energy and marine.

Sustainability is core to the company's future growth plans. They achieved accreditation to ISO 14001 environmental standard in 2008. As part of their corporate strategy, they have pledged to achieve net zero in (Scope 1, 2 & 3) by 2050. Since 2008 they had concentrated on Scope 1 & 2 impacts: LED lights, and Solar panels etc. However, they now estimate that 80% of their carbon emissions are generated in Scope 3, and therefore this is their priority.

Jo Bird & Co Ltd believe that they can make significant reductions, in carbon and environmental impacts generally, and these are considered at all stages of product design. Through their investment into R&D they can now optimise the product design, manufacture using the most sustainable process (RTM closed mould technology) and use the most sustainable materials. For example, changing resin to one containing recycled PET reduced the carbon content by 25% and re-used 360,000 plastic bottles.



GFRP enclosures for fire safety equipment in the offshore energy market. Photo courtesy of Jo Bird & Co Ltd.

At the time of publication only large companies are required to report energy and emissions, though this is expected to change. The following schemes are mandatory in the UK:

- **Taskforce on Climate-related Financial Disclosures (TCFD)** ¹²⁷

The TCFD is a taskforce set up by the G20 Financial Stability Board which recommends that organisations provide climate-related financial disclosures on exposure to transition and physical climate risks as well as strategy to both mitigate these risks and harness opportunities to decarbonise. It includes reporting of scope 3 (supply chain) emissions. Reports are through the Directors' Report in the annual filing, so this adds to the SECR requirement (see below) which is likely to be streamlined to align with TCFD. TCFD came into force in April 2022 for very large companies, typically 500 employees or more and a turnover of more than £500m. A helpful overview has been published by [edie](#) ¹²⁸ and the London Stock Exchange Group (LSEG) has produced guidance for listed companies ¹²⁹. TCFD reporting is expected to be mandatory for all UK companies, including SMEs, by 2025.

- **Energy Savings Opportunity Scheme (ESOS)** ¹³⁰

Every four years audits are required of the energy used by buildings, industrial processes and transport to identify cost-effective energy saving measures. Reports must be completed by a qualified ESOS Lead Assessor and notified to the Environment Agency every four years. This is required for any UK company which, itself or as part of a corporate group, either:

- Employs 250 or more people
- Has an annual turnover over £44m, and an annual balance sheet total in excess of £38m

- **Streamlined Energy and Carbon Reporting (SECR)** ¹³¹

Requirement to report UK energy use and associated scope 1 and 2 greenhouse gas emissions as a minimum relating to gas, electricity, F gases (refrigerants) and transport fuel, as well as at least one intensity ratio (a way of defining your emissions data in relation to an appropriate business metric) and information relating to energy efficiency action. Reports are through the Directors' Report in the annual filing. SECR replaced CRC in 2019 and is required for all quoted companies, and any UK companies which meet two of the following three criteria, unless they use less than 40,000 kWh/yr:

- Employ 250 or more people
- Has an annual turnover over £36m
- An annual balance sheet over £18m

¹²⁷ <https://www.gov.uk/government/news/uk-to-enshrine-mandatory-climate-disclosures-for-largest-companies-in-law>

¹²⁸ 'TCFD mandate: Everything you need to know about the UK's new climate disclosure requirements', [edie](https://www.edie.net/tcfd-mandate-everything-you-need-to-know-about-the-uks-new-climate-disclosure-requirements/), 5/4/22

¹²⁹ 'Your guide to climate reporting', London Stock Exchange, October 2021
https://docs.londonstockexchange.com/sites/default/files/documents/LSE_guide_to_climate_reporting_final_0.pdf

¹³⁰ Energy Savings Opportunity Scheme (ESOS) Guidance, BEIS & EA, 2022 <https://www.gov.uk/guidance/energy-savings-opportunity-scheme-esos> More info at <https://www.carbontrust.com/resources/the-carbon-trust-guide-to-esos>

¹³¹ Environmental reporting guidelines: including Streamlined Energy and Carbon Reporting requirements, BEIS & Defra, 2019
<https://www.gov.uk/government/publications/environmental-reporting-guidelines-including-mandatory-greenhouse-gas-emissions-reporting-guidance>

Some more energy intensive companies may also report voluntarily through Climate Change Agreements (CCAs), voluntary agreements made between UK industry and the Environment Agency to reduce energy use and carbon dioxide emissions, in return for which operators receive a discount on the Climate Change Levy (CCL) energy tax. (CCAs differ from the CCL exemption scheme for carbon fibre manufacturers which Composites UK operates with Briar. This gives 100% exemption from CCL for energy use related to carbon fibre manufacturing,¹³² and is based on the Min-Met scheme.¹³³) The EU also requires large companies to disclose ESG information annual under the Non-Financial Reporting Directive (NFRD).

While ESOS and SECR are not yet mandatory for smaller companies, ESOS phase 4 looks likely to include companies meeting just one of the SECR threshold criteria in mandatory reporting. As such it is good practice to understand and monitor carbon emissions and energy use, identifying areas where improvements can be made. Also, the inclusion of scope 3 emissions means that there may be pressure on supply chain companies to report, so their clients can meet their requirements.



Figure 7.3: TCFD Pillars

7.8.1 Sustainability reporting standards

Numerous standards for reporting sustainability risks and metrics have emerged, but several of the major standards have been consolidated (in 2022) into the International Sustainability Standards Board (ISSB), created after COP26 by the International Financial Reporting Standards Foundation. ISSB now includes the Value Reporting Foundation (Sustainability Accounting Standards Board (SASB) and Integrated Reporting Framework (IRF)) and the Climate Disclosure Standards Board.¹³⁴ Discussions for collaboration with the larger Global Reporting Initiative (GRI) are ongoing.¹³⁵ The ISSB standards are aligned with the four pillars of the TCFD framework – governance, strategy, risk management, and metrics and targets.

A brief comparison of the major standards is as follows:¹³⁶

- **GRI** standards are the most-used standards for sustainability reporting and are freely available. They are divided into four groups: Universal, Economic, Environmental and Social.
- **SASB** standards focus on information impacting financial performance, and feature multiple standards for different industries.
- **IRF** recognizes that organisations draw on different resources which are referred to as the Capitals: Financial, Manufactured, Natural, Human, Social, Intellectual. It supports thinking holistically and strategically.

ISO 14001 differs from these as it is a standard for focusing on the processes for EMSs. As mentioned in 7.4, the SBTi provides a standard for selecting science-based targets with appropriate metrics.

¹³² More info at <https://compositesuk.co.uk/industry-support/climate-change-levy-discount>

¹³³ Exemptions from climate change levy for mineralogical and metallurgical processes <https://www.gov.uk/government/publications/exemptions-from-climate-change-levy-for-mineralogical-and-metallurgical-processes-guidance>

¹³⁴ 'IFRS Foundation and VRF vote to approve consolidation from 1 July' IFRS 22/6/22 <https://www.ifrs.org/news-and-events/news/2022/06/ifrs-foundation-and-vrf-vote-to-approve-consolidation-from-1-july/>

¹³⁵ 'ISSB and GRI provide update on ongoing collaboration', IFRS, 23/6/22 <https://www.ifrs.org/news-and-events/news/2022/06/issb-and-gri-provide-update-on-ongoing-collaboration/>

¹³⁶ 'Four Sustainability standards you should know about!', SustainLab, 30/9/21 <https://sustainlab.co/blog/four-sustainability-standards-you-should-know>

For carbon footprinting, standards are generally based on the Greenhouse Gas Protocol standards, which cover corporate accounting and reporting, including scope 3 emissions, as well as product life cycle. The International Aerospace Environmental Group (IAEG) has produced guidance specific to GHG reporting for the aerospace industry.¹³⁷ IAEG is also active in developing good practice for supply chain sustainability, REACH compliance and other aspects.

The 17 UN SDGs and 169 associated targets also provide a framework for companies to consider while strategically setting their goals - see section 1.2.

7.9 ESG Ratings

Investors are increasingly scrutinising companies' exposure and resilience to long-term, financially relevant environmental and social risks as well as corporate governance. These are often assessed by the investor as ESG ratings, which give a broader view of a company's long-term potential and exposure to risks. ESG – Environment, Social and Governance – is about where sustainability has business relevance and impacts the financial risks faced by a company. It's not only about environmental sustainability, though it includes energy and environmental impact reporting, as can be seen from Table 7.1.

One of the most widely referenced ESG rating systems is the MSCI ESG score, which broadly categorises impacts as shown in Table 7.1. The 35 key issues are scored (0-10) based on exposure and management metrics: How exposed is the company to / How is the company managing each material issue? Not all the key issues are relevant to every industry, so issues are chosen and scores are weighted relevant to the industry, with high impact and short-term issues (<2 years) having more weight than low impact or long-term issues, e.g. worker safety in a manufacturing environment has a higher weight as being an immediate risk with significant financial implications. These weighted scores are normalised relative to industry peers and may be combined with specialised insight to deliver an overall ESG rating from CCC "Laggard" to AAA "Leader".

MSCI also has an "Implied Temperature Rise" metric which indicates whether companies are aligned to the Paris agreement goal of limiting the global temperature increase to 2°C in the year 2100, compared to pre-industrial levels, or the aspirational goal of 1.5°C.¹³⁸

Another methodology from Sustainalytics, part of the Morningstar group, assesses 20 ESG issues to provide an ESG Risk Rating from negligible to severe.¹³⁹

¹³⁷ 'GHG Reporting Guidance for the Aerospace Industry – A Supplement to the GHG Protocol Corporate Accounting and Reporting Standard', IAEG, May 2019 available at <https://www.iaeg.com/workgroups/wg3>

¹³⁸ Implied Temperature Rise, MSCI <https://www.msci.com/our-solutions/climate-investing/net-zero-solutions/implied-temperature-rise>

¹³⁹ 'Material ESG Issues Resource Center', Sustainalytics <https://www.sustainalytics.com/material-esg-issues-resource-center>

Table 7.1: MSCI ESG categories¹⁴⁰

Environment	Social	Governance
Climate change: • carbon emissions • product carbon footprint • financing environmental impact • climate change vulnerability	Human capital: • Labour management • Health and safety • Human capital development (training) • Supply chain labour standards	Corporate governance: • Ownership and control • Board (in terms of diversity and independence) • Pay • Accounting
Natural capital: • Water sourcing • Biodiversity and land use • Raw material sourcing	Product liability: • Product safety and quality • Chemical safety • Consumer financial protection • Privacy and data security • Responsible investment • Health and demographic risk	Corporate behaviour: • Business ethics • Tax transparency
Pollution and waste: • Toxic emissions and waste • Packaging material and waste • Electronic waste	Stakeholder opposition: • Controversial sourcing • Community relations	
Environmental opportunities: • Clean technology • Green building • Renewable energy	Social opportunities: • Access to communication • Access to finance • Access to healthcare • Opportunities in nutrition and health	

7.9.1 Do ESG ratings matter for SMEs?

SMEs are not usually expected to write detailed annual ESG or sustainability reports, and the focus tends to be on improving the sustainability of products. However, there are some basic aspects that investors or customers may look for, especially where the SME is an important part of a large OEM's supply chain:

- Walk the talk. Have a sustainability culture, incorporating sustainability thinking in all your activities and decisions, from leadership down to the shop floor.
- Develop an environmental management system or action plan appropriate to your business.
- Certifications are easy to see (e.g. with logos on your website and list them in the Composites UK Hub). Certification to ISO 14001 may be appropriate (also ISO 9001 for quality management. ISO 50001 for energy management and ISO 45001 for health and safety) but see 7.7 for comments about ISO 14001 and smaller companies.
- Understand your stakeholders and choose reporting / systems based on what will attract your customers, investors and talent pool.
- Benchmark. See what competitors or similar companies are doing and stay ahead.
- Transparency – where you have made an action plan and collected data, summarise it in a few pages or on a website. Telling the world what you are doing will also encourage others to step up and take action.

¹⁴⁰ 'MSCI ESG Ratings Methodology' MSCI, June 2022 <https://www.msci.com/documents/1296102/21901542/ESG-Ratings-Methodology-Exec-Summary.pdf>

The need for companies to monitor energy use and manage environmental impact is growing rapidly. At the time of publication, reporting is only required for large companies in the UK. There is a general trend for environmental reporting to become mandatory for all companies, which is likely to happen through TCFD by 2025 in the UK. The need for accountability in developing appropriate metrics and science-based targets is recognised. The landscape for standards for environmental reporting and certification is complex, but is consolidating to some extent. There is good guidance available for developing an EMS, which can be formally certified through ISO 14001.

The benefits of having strong sustainability activity and an EMS are significant in attracting investment, customers and talent, and are often accompanied by cost savings as energy efficiencies are realised. ESG ratings are increasingly considered by investors, and a company's reporting, EMS and certifications in this area will all contribute to the ESG score.

Figure 7.4 and the text below indicates how environmental targets, reporting, management and certification could be connected for an organisation.

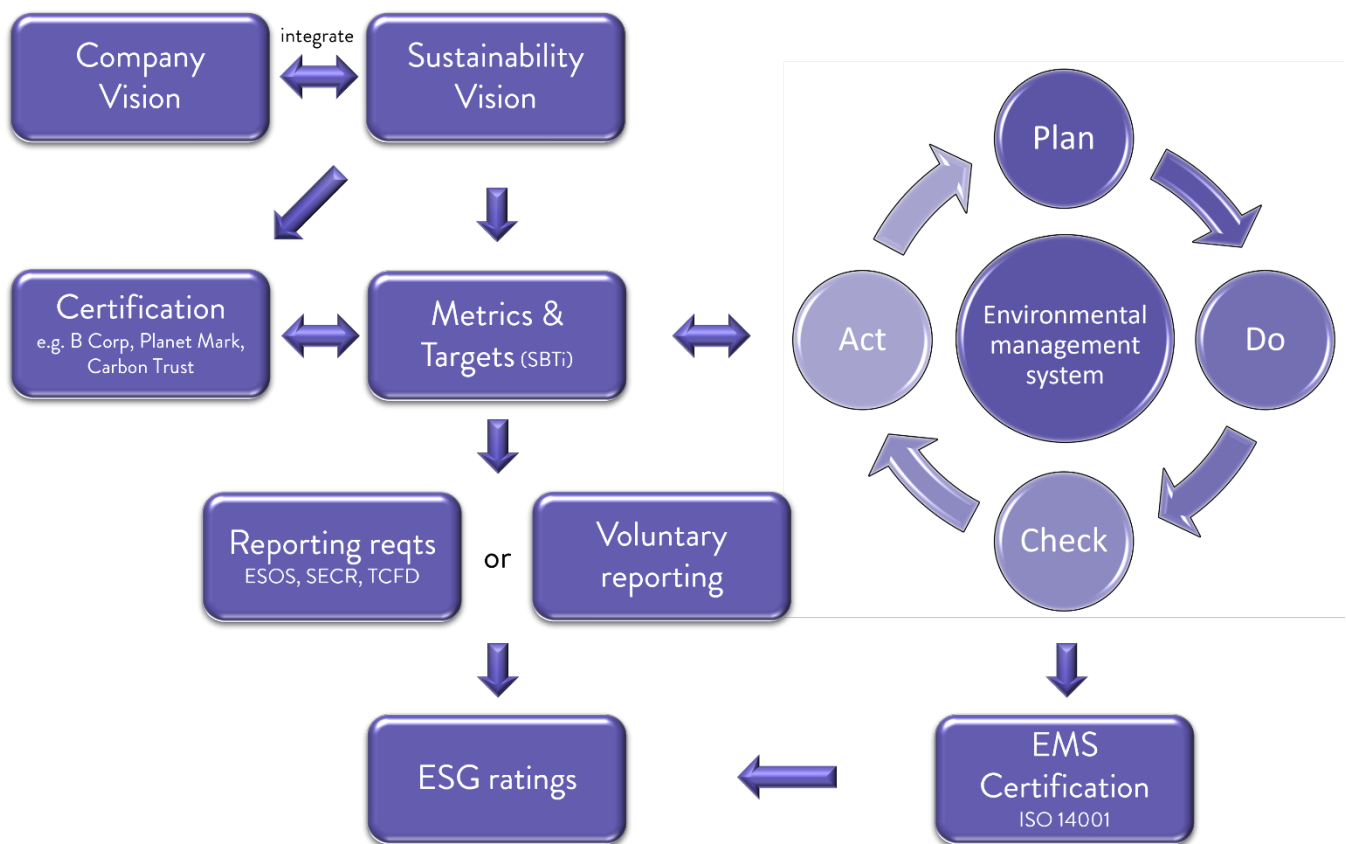


Figure 7.4: Environmental targets, reporting, management and certification

- **Vision:** The company recognises the need for a more sustainable approach, and a vision is developed. If this does not start at the highest level of management, it is important for management to be brought on board and fully supportive from the earliest possible stage, and the vision should be integrated with the company's overall vision.
- **Metrics & Targets:** The vision is applied by adding detail and deciding on appropriate metrics and time-bound targets. These targets can be set through the Science based targets initiative.
- **Environmental Management System:** The metrics, targets and other aspects of environmental management can be developed with an EMS, which in turn can be certified through ISO 14001, or other routes if required for smaller companies.
- **Certification:** The company may choose to pursue other more holistic certification routes which address social aspects as well as environmental, such as B Corp or Planet Mark, or demonstrating a path to net zero, or zero waste to landfill, through the Carbon Trust. Many routes are available.
- **Reporting:** If the company is large, they are already required to report energy and environmental metrics through ESOS and SECR, and also risks around climate resilience and other factors through TCFD. If the company is smaller, they may still need to report if they are part of a supply chain that needs to report scope 3 emissions, and

voluntary reporting is increasingly encouraged and will prepare for mandatory reporting which is likely to be required through TCFD by 2025.

- **ESG:** All of these activities will contribute positively to the environmental and social aspects of the company's ESG ratings if they are assessed by investors, as well as raising their profile as a responsible and sustainable company.

8. END OF LIFE AND RECYCLING

Author: Stella Job

8.1 Introduction and volumes

It is often said that composites can't be recycled but this is not the case. Composites can be recycled. Both carbon (CFRP) and glass fibre (GFRP) composites are being recycled commercially and have been for over a decade. However, the combination of multiple materials in the composite which make it stiff, strong and durable, also means an inherent resistance to being broken down for recycling. Supply chains for commercial recycling routes are limited, processes are generally not closed-loop and higher value routes still struggle to be economical for end-of-life material. There is still much work to do, but progress is being made. A change in mindset is needed to see all by-products as a resource, not as waste, nor as somebody else's problem, and to circulate materials at the highest value that can be achieved, working to eliminate waste and pollution. This is the circular economy.

This chapter discusses processing routes for end-of-life and recycling. For policy and legislation in this area, including classification of wastes and EWC codes, see section 9.3 'Regulations on disposal and end-of-life' and for use of recycled materials in products see Chapter 4 'Using recycled materials'.

Composites UK estimates there are around 75 to 80,000 t.p.a. of GFRP end-of-life waste in UK, plus perhaps 15,000 t.p.a. GFRP manufacturing scrap. CFRP production has been growing much faster than GFRP, and there is still little EOL waste, though process scrap rates tend to be high, so there may be around 3 to 4,000 t.p.a. of CFRP manufacturing waste in the form of cured trim, uncured prepreg and dry carbon fibre. These volumes are relatively small at less than 0.05% of the total of 222 million tonnes of waste¹⁴¹ and 2% of around 5 million tonnes of plastic waste in the UK every year.

Very little composite waste in the UK is recycled at present. Most still goes to landfill or energy from waste (EfW). Some CFRP scrap is recycled by pyrolysis. The following recycling and disposal routes exist for composites. More technical detail about the recycling processes is available in 'Composites recycling: Where are we now?'.¹⁴² Recycling routes currently available in the UK are listed at 'What can I do with my waste?'.¹⁴³

8.2 Reuse and refurbishment

Reuse of EOL products in applications similar to their original use, which may involve some refurbishment, may be a good solution, though it is not always the case. Decommissioned lifeboats and minesweepers have been refurbished for alternative applications, where the composite hull is still in good condition. Considering wind farms, environmental and cost analyses, along with non-destructive testing and inspection, are needed to choose between life extension (refurbishment where most of the original turbine remains) and repowering (replacing the turbines with new, more



BladeBridge installed on the Midleton Youghal Greenway, Cork County.
Photo courtesy of the Re-Wind Network

¹⁴¹ Latest figures from Defra, including construction and demolition waste, for 2018, from Defra, 'UK Statistics on Waste' 19/3/20 see <https://www.gov.uk/government/statistics/uk-waste-data>

¹⁴² 'Composites recycling: Where are we now?', Composites UK 2016 <https://compositesuk.co.uk/industry-support/environmental/end-of-life-and-recycling/>

¹⁴³ 'What can I do with my waste?', Composites UK, <https://compositesuk.co.uk/industry-support/environmental/what-can-i-do-with-my-waste/>

efficient models). Repowering is often the best choice, though challenging due to slow and complex permitting procedures.^{144 145}

Reuse of parts in different applications, e.g., using a wind turbine blade in a footbridge structure, can be viable, as demonstrated in the Re-Wind project.¹⁴⁶ A significant factor in establishing viability will be whether the structural properties of the composite are being used effectively – are they replacing a low cost, low impact material, or are they replacing a high-performance structural part? Nevertheless, use of, for example, wind turbine blades in non-structural applications can be a powerful communication tool to convey the need for a more circular future. Re-Wind has published a design catalogue with numerous examples of applications for reuse of wind blades.¹⁴⁷

Some schemes exist for reuse of off spec or surplus materials, especially in the construction industry. (See section 4.4.1.) Opportunities exist in other sectors, but often will only be attractive if accompanied by the right business models. For example, a strong, carbon fibre car chassis could be made to last much longer than current car lifetimes if a leasing model allowed for refurbishment and refitting.

Design for repair and refurbishment is critical to enabling long lifetimes and reuse potential. Also records of initial design, materials and manufacturing, repair, service intervals and load cycles during use can all help to provide the information needed to enable an optimum next life for a part. Regulations and business models can be key drivers or blockers for reuse and refurbishment.



Podium manufactured from a wind turbine blade by ReBlade for the Scottish Green Energy Awards. Photo: Tim Winterburn

¹⁴⁴ 'Repowered wind farms show huge potential of replacing old turbines', WindEurope 23/3/22

<https://windeurope.org/newsroom/news/repowered-wind-farms-show-huge-potential-of-replacing-old-turbines/>

¹⁴⁵ Spyroudi, 'End-of-life planning in offshore wind', Offshore Renewable Energy Catapult, April 2021 https://ore.catapult.org.uk/wp-content/uploads/2021/04/End-of-Life-decision-planning-in-offshore-wind_FINAL_AS-1.pdf

¹⁴⁶ 'Re-Wind Network successfully installs repurposed wind blade pedestrian bridge', Composites World, 31/1/22 <https://www.compositesworld.com/news/re-wind-network-successfully-installs-repurposed-wind-blade-pedestrian-bridge>

¹⁴⁷ 'Re-Wind Network publishes 2nd Edition of its Design Catalog', Re-Wind Network, 27/10/22 <https://www.re-wind.info/update/2022/10/27/re-wind-network-publishes-2nd-edition-of-its-design-catalog>

8.3 Landfill

Landfill is the linear option, allowing for no material circularity or reuse, though it does have the advantage that the fossil carbon is effectively sequestered. Landfills have been closing due to lack of financial viability caused by the increasing tax and a lack of space for additional waste, so landfill capacity has dramatically reduced in the UK. With the current UK landfill tax of £98.60 per tonne (2022-23) and a gate fee from £19 to £30 per tonne, total landfill gate fees are typically £118 to £129, for non-hazardous waste. (This compares to a £92 to £116 gate fee for EfW.)¹⁴⁸ With a fee to the handler, a company would typically pay £125 to £150 per tonne plus transport costs, to send waste to landfill and this figure will continue to rise.

8.4 Incineration

A significant amount of UK GFRP manufacturing scrap is being diverted from landfill to incineration. This burns the organic part to recover energy and may repurpose the inorganic fibres and filler into aggregate.

The waste hierarchy prefers this at face value, though a life cycle assessment may not favour incineration over landfill, where fossil-derived resins are being burnt to release greenhouse gases, unless it directly replaces combustion of mined fossil fuels. The increasingly renewable electricity mix in the UK means that electricity generated from EfW is becoming less positive from an environmental impact perspective compared to the electricity it displaces.



Inside Lakeside EfW, Colnbrook. Photo: Stella Job

Large EfW plants typically make more money from the gate fee (per tonne) than from the energy produced. This means that high calorific value (CV) waste is not preferred, as the incinerator capacity is limited by the CV of fuel burnt, rather than the mass. Waste that goes to EfW is often referred to as refuse derived fuel (RDF). There is no standard specification for RDF, and while some incinerators do not have strict requirements for incoming material, others may have a tighter specification on size and content. The incinerator bottom ash (IBA), which for GFRP would contain any glass fibres or mineral filler, is either landfilled or reprocessed into aggregate. This does not count as “recycling” according to the Waste Framework Directive (see section 9.3.2).

Solid recovered fuel (SRF) is covered by BS EN 15359 and its underlying standards. Quality is strictly controlled, though varies by application. The SRF typically still replaces fossil fuels in cement kilns, power stations or blast furnaces, though in time this could be replaced with biomass or hydrogen fuels.¹⁴⁹

There is currently no tax on incineration of waste in UK, but it is under debate, and it is quite possible that one will be introduced in the coming years. In addition to the release of CO₂ from any fossil-derived plastics in the waste, it has been argued that the recent rapid increase in energy from waste plants has detracted from development of recycling infrastructure.

8.4.1 Incineration of CFRP not recommended

While CFRP has a very high CV, it is not recommended for incineration. In Germany landfill is prohibited for any organic material (including any polymer composite) but even difficult to recycle carbon fibre waste is not incinerated. This is primarily because of a risk of small diameter carbon fibres being produced which may be carcinogenic. Such fibres may be safely caught in filters, but that would add to the hazardous air pollution control residue (APCr) and the full extent of the risk is yet to be determined. Another factor that makes CFRP undesirable in EfW plants is that the conductive carbon fibres can cause shorting in electrostatic flue gas filters. Recycling of carbon fibre is therefore clearly preferable.

¹⁴⁸ July 2022 prices, see <https://www.letsrecycle.com/prices/efw-landfill-rdf/efw-landfill-rdf-2022-gate-fees/>

¹⁴⁹ ‘How to Power a Steel Blast Furnace Using Only Hydrogen’, Popular Mechanics, 15/11/19
<https://www.popularmechanics.com/science/green-tech/a29813424/steel-blast-furnace-hydrogen/>

8.4.2 Incineration of bio-based materials

From a theoretical circularity perspective, incineration is a reasonable approach for fully bio-based composites, as the carbon they contain is not fossil-based, so the CO₂ emissions from incineration match those absorbed by the original agricultural feedstock. However, if bio-based materials can have another life through recycling or reuse, before energy is recovered and/or carbon dioxide is captured when they are incinerated, this is clearly preferable.

An alternative to use pyrolysis and recover syngas and biochar has been proposed, which could be undertaken with other biomass wastes. The biochar may have applications for soil improvement.¹⁵⁰



For large items like wind turbine blades, downsizing is a challenge before any recycling route can be pursued. Photo courtesy of Reblade

8.5 GFRP recycling by co-processing in cement kilns

In cement kiln co-processing the resin is burnt for energy, typically replacing coal, and the glass fibres and mineral fillers are recycled into the cement clinker, replacing mined feedstocks. This is operated as an established composite recycling programme by Neowa in Germany, which has capacity to take 30,000 t of GFRP per year, supplied as SRF to a local cement kiln. The ban on landfill for composite (or any organic) waste in Germany provides a secure supply of feedstock. Some other operations around Europe are sending smaller quantities to co-processing in cement kilns, generally mixed with other waste to regulate calorific value. Co-processing in cement kilns is accepted as a combination of recycling and recovery in the EU Waste Framework Directive.¹⁵¹

Although the value of the recyclate is low, co-processing in cement kilns compares favourably to landfill or EfW in environmental analysis where the polymer replaces coal, though as noted above, over time cement kilns could move to biomass or hydrogen fuels¹⁵². Until more circular routes are scaled up, it is a good route which can be operated at scale. At present this is not formally available in the UK, but Composites UK is working with members and waste management companies to establish this as a future GFRP recycling route.

¹⁵⁰ 'Should we recycle natural fibre composites', Ben Andrews, SHD Composites, (presentation) Advanced Engineering 2/11/22

¹⁵¹ See p.32, 'Guidelines on the interpretation of key provisions of Directive 2008/98/EC on waste', EC, 2012 http://waste-prevention.gr/waste/wp-content/uploads/2015/10/2012_Guidance%20interpretation%20Directive%2098-2008-EC_EN.pdf

¹⁵² 'Fuel switching to hydrogen', Hanson, 10/8/22 <https://www.hanson.co.uk/en/news-and-events/fuel-switching-to-hydrogen>

Scrap material must be shredded to around 30 mm pieces to be fed to the burner through pipes, and to enable rapid combustion. Shredded waste may be mixed with other polymeric or paper waste to regulate calorific value (CV), producing SRF. Required CV varies by kiln, but would often need to be at least 17-20 MJ/kg. The CV of pure resin is about 30 MJ/kg, so the CV of the composite depends on its resin content (plus any combustible fillers).

Batches must be tested to be within strict limits for certain chemicals. Of particular relevance to composites, limits for halogens are very low, typically around 0.8% for chlorine and 0.25% for bromine, which effectively rules out GFRP containing high levels of halogenated fire retardants. Class 3 fire retarded GFRP may be possible to include with blending. Ash content is usually limited to 15-20%, which would rule out GFRP for SRF altogether, except that the “ash” – E-glass (alumino-silicate) and mineral fillers (typically calcium carbonate i.e. limestone) – is valuable as cement feedstock.

It is difficult to achieve an economical pathway due to transport costs, unless suitable equipment for shredding GFRP, which is more abrasive than typical SRF, can be co-located with blending operations close to the cement kiln. A further challenge is that GFRP waste volumes are relatively low in the context of cement operations. It should be noted that cement manufacturers see SRF supply as a material supply contract rather than a waste management solution, and consistency of material and chemical content is a priority. Negotiations with individual cement kilns are needed to establish a supply chain as the material differs from their usual specifications, and different cement kilns have different handling processes.

Incineration in a cement kiln would not be considered a recycling route for CFRP since the carbon fibre would burn like coal. See also comments above in 8.4.1 about incineration of CFRP.

8.6 Pyrolysis / gasification for fibre recovery

CFRP has been recycled commercially for over 10 years using variants of pyrolysis, gasification or hybrid processes. The resin is thermally decomposed in limited oxygen leaving relatively clean carbon fibres. The resin products are mainly gases and an oil fraction which technically could be recovered as chemicals, but in practice are typically burnt, in some cases with energy recovery.

The resultant clean recycled carbon fibre (rCF) is sold as short chopped or milled fibres, or in nonwoven mats, which can be infused with resin or co-mingled with thermoplastic fibres for hot-pressed applications. Short fibres for compounding with polymers are expected to be the largest markets in the longer term. See Chapter 4 for more information on using rCF.

Several universities and companies have demonstrated GFRP recycling by pyrolysis, where resins are thermally decomposed into oils and gas for use as fuels and fibres are recovered for reuse. Pyrolysis plant marketed for GFRP recycling is available from several companies, but as yet, no companies appear to be taking GFRP waste commercially. Reasons for this may include the challenges of removing char from the fibres, the high-energy input required for pyrolysis (which is endothermic, though depending on resin content the process may be powered by syngas produced, once it has reached operating temperature), loss of mechanical properties due to high temperature processing¹⁵³ and removal of the fibre sizing, and the high throughput needed to gain economies of scale.



Carbon fibre recycling.
Photo courtesy of Gen 2 Carbon

For high resin content GFRP, pyrolysis may be economical where the focus is on recovering syngas for fuel from the organics, leaving a reduced volume – fibres and filler – for landfill. If the carbon (char) content is low enough, this could then qualify for the lower landfill tax rate. Fossil-based CO₂ will then be emitted when the syngas is burnt. This is clearly not

¹⁵³ J L Thomason et al 2020, 'Upgrading and reuse of glass fibre recycled from end-of-life composites', IOP Conf. Ser.: Mater. Sci. Eng. 942 012002 <https://iopscience.iop.org/article/10.1088/1757-899X/942/1/012002>

a circular or climate-friendly solution, though if a recycling route could be found for the fibre / filler / char then it would be slightly better.

8.7 Mechanical processing

Mechanical grinding of GFRP has been tried in many places over the last 50 years, and has low energy input, though the recyclate value is also reduced. Milling or grinding to fine filler has consistently been found to be uneconomical, as the value of the filler it replaces is very low. The finer the output material, the higher the cost in terms of energy, as it may need several passes through a milling machine. For in-house reuse of manufacturing waste, it may be viable where there is also value for marketing reasons, or if disposal options are very limited or costly.

8.7.1 Grinding with fibre length retention

Grinding with fibre length retention is more successful, as less grinding energy is needed and the reinforcing value of the fibres is at least partially retained. This was demonstrated in 1973 by Wolfgang Unger, founder of Eco-Wolf¹⁵⁴ in Florida, USA, which still sells equipment for grinding FRP and incorporating it into pre-existing spray-up equipment. Conenor¹⁵⁵ in Finland has developed a process for extruded thermoplastic composites with GFRP regrind in single- or multi-layer components, which is now being commercialised in the UK by Gen 2 Plank. Gees Recycling¹⁵⁶ in Italy takes FRP waste from other companies and manufactures it into board products for use in bathroom interiors, shop-fittings and furniture. Continuum¹⁵⁷ in Denmark is also claiming to have developed and be scaling up a suitable process for processing GFRP composite waste (e.g. from wind turbine blades) into building products (such as panels). Recycling by mechanical grinding is economically challenging and feedstock dependent, which has thus far limited it to relatively small-scale applications, mainly in-house and small business to business collaborations. Grinding has rarely been used for CFRP as the value of the fibres demands a higher value recycling route.



MCD and Thriv3 provide a take back service that renovates, repurposes or recycles end of life GFRP shop mannikins. Photo courtesy of Thriv3.

¹⁵⁴ <http://www.ecowolfinc.com/>

¹⁵⁵ <http://www.conenor.com/recycling-thermoset-frpwaste/>

¹⁵⁶ <https://www.geesrecycling.com/>

¹⁵⁷ <https://www.continuum.earth/>

Case study: Shopfit display panels from end-of-life FRP mannequins

Aimee Weller, Thriv3

Sister companies MCD and Thriv3 worked exclusively with Frasers Group. They were asked to find a solution for end-of-life FRP mannequins that had been broken or replaced in current stores. Their research had shown them that, due to several reasons, there was no solution for the end of life.

Considering the logistical elements of mannequins being located across the UK, they worked with existing routes and store managers to get all feedstock into one location. After all this had been confirmed and documented, they then collated all of this into one central distribution centre. From there, they worked with their warehouse team to develop a cost and time effective process to remove all metal parts and crush the mannequins into large pieces to be shipped to our plant, utilising space in empty containers. It was key for us to ensure CO₂ impact was minimised.

MCD and Thriv3 worked with Gees Recycling, our partner based in Italy, to produce repurposed FRP panels with brand specific finishes from the end-of-life FRP. Once quality checked, the panels were sent to our fabricators to be built into shopfit displays.

As a Group this was managed solely inhouse with no impact on the client's schedule or need for any outsourcing. MCD took the design lead on the project, Thriv3 managed the logistics and LCAs to make sure the project was a sustainable as it could be.

The social and environmental impact was a huge success. 150 mannequins were saved from landfill and 50 panels were produced which will be repurposed again when they are taken from store. The result was not only a reduced impact to the environment but looked aesthetically amazing!

8.7.2 Aligned chips

Fairmat, in France, has developed a mechanical recycling technique for CFRP where the composite is sliced and delaminated by a proprietary technique and the resulting chips are bound together into a board using an adhesive. They use a robot to identify the alignment in each chip and position it in the layup to produce unidirectional or cross-ply sheets. This preserves the mechanical performance of the material.¹⁵⁸ This is not expected to be economical for GFRP due to the lower material value.

8.7.3 Moulding compounds from uncured prepreg offcuts

Several companies have looked at using prepreg chips to produce laminates. In theory it should be possible to take the residual skeleton after ply cutting and cut this into small pieces which can be compression moulded in a manner similar to sheet moulding compound, HexMC®, or “forged carbon”. However, there is the challenge of consistently removing 100% of the release film/paper from small chips. It is easier to remove the release paper prior to cutting the prepreg, but either the cutting blades gum up or a lot of energy is used keeping the prepreg cold and not tacky. Work is ongoing to achieve a commercially viable solution.



Complex moulded part using moulding compound produced from uncured prepreg waste. Photo: Stella Job

¹⁵⁸ <https://www.fairmat.tech/>

8.8 Chemical and thermochemical processes

Chemical recycling is gaining a great deal of attention across Europe as a solution for thermoplastic waste generally. It is seen as a complementary solution to ‘mechanical recycling’ where the latter proves to be inefficient in case of difficult to recycle plastics, i.e. not properly sorted, multi-layered or heavily contaminated waste.¹⁵⁹ (In this case ‘mechanical recycling’ means shredding pure thermoplastic wastes for melt recycling.)

A European task force¹⁶⁰, including EuCIA, has recently defined chemical recycling:

Chemical recycling converts polymeric waste by changing its chemical structure to produce substances that are used as products or as raw materials for the manufacturing of products. Products exclude those used as fuels or means to generate energy.

The focus here is on the polymer, rather than the fibre. Technologies include pyrolysis, gasification, chemical depolymerization, catalytic cracking & reforming, and hydrogenation. Plastic waste is converted into feedstock, i.e. monomers, oligomers and higher hydrocarbons that can be used to produce virgin-like polymers to create new plastic articles.

8.8.1 Pyrolysis with chemical recycling

Pyrolysis for fibre recovery from thermoset composites (covered above) has not generally been referred to as chemical recycling since the products from the polymer are usually burnt for energy. In theory it is possible to recover the chemicals but this has not been done in commercial processes where carbon fibre recovery is the primary aim, probably for economic reasons. This may change in future as market drivers change.

8.8.2 Solvolysis

Processes which chemically decompose the resin, usually by solvolysis, to recover both fibres and resin chemicals, have been the subject of numerous research projects around the world. These have often used solvents at high temperature and pressure, such as propanol, methanol, acetone or supercritical water. The temperature, pressure and chemicals add to environmental impact, but very clean fibres can be recovered, with excellent mechanical properties.

Vartega is commercially active in the USA, recycling scrap sourced from various dry fibre and prepreg sources, selling mainly pelletised rCF/thermoplastics. Vartega’s facility in Denver has a planned capacity of 2,000 tonnes per year.¹⁶¹ V Carbon is currently scaling up a solvolysis process for CFRP in Switzerland and is now moving forward as a full life-cycle solution, with in-house know-how to process the recycled fibres through intermediate materials into parts in automotive, hydrogen storage and other sectors.¹⁶² V Carbon has been awarded an EU LIFE Grant to establish a recycling facility in Germany which is expected to be fully operational in 2024.

Better circularity can be achieved if either the resins are decomposed and recovered for chemical feedstock, or if resins are 100% bio-based. Both may be achievable in future, though economic and environmental impact would be needed to assess viability. These are important aims for future research.

8.9 Fluidised bed recycling processes

Fluidised bed is a process where a fluid, typically a gas is passed through a bed of solid particles, e.g. sand, causing the particles to behave like a fluid. It is used in chemical processes and in the efficient burning of coal or wastes for power generation. More recently it has been developed to remove cured resin from fibres for recycling composites.

¹⁵⁹ See Plastics Recyclers Europe <https://www.plasticsrecyclers.eu/chemical-recycling>

¹⁶⁰ See European Coalition for Chemical Recycling <http://www.coalition-chemical-recycling.eu/>

¹⁶¹ ‘Vartega Announces New Facility, Increased Capacity, and Funding’, Vartega 16/8/22 <https://www.vartega.com/news-and-media/2022/8/16/vartega-announces-new-facility-increased-capacity-and-funding>

¹⁶² V Carbon announces joint venture with Voith, V Carbon, 4/5/22 <https://www.v-carbon.com/v-carbon-announces-joint-venture-with-voith-to-deliver-first-circular-economy-for-hydrogen-tanks/>

8.9.1 Fluidised bed for carbon fibre

A fluidised bed process for recovering carbon fibre from CFRP has been developed to pilot scale at the University of Nottingham through a strategic collaboration with Boeing.¹⁶³ Its unique feature, compared to other CFRP recycling routes, is that it is capable of processing contaminated and mixed waste from end-of-life components. It tends to result in more strength loss in the rCF fibres than pyrolysis or solvolysis techniques, though in many applications this not a major factor, as a) stiffness is often the dominant design factor and b) properties of the finished composite may be more dependent on fibre alignment and processing parameters than individual fibre strength.

This process is ready for commercialisation, and may well be commercialised as more end-of-life CFRP material emerges.

8.9.2 Fluidised bed for glass fibre

Fluidised bed can also be used for recovering fibres from GFRP, with similar contamination tolerance. The University of Strathclyde has developed a fluidised bed thermal process to recover fibres, with a patented post-treatment that restores their strength to around 80% of virgin fibres, while stiffness is retained or even improved upon. This shows more promise than other processes for creating virgin-like recycled products, but would need large volumes to scale up economically (e.g. 5,000 t p.a. or more). This process is proven at lab scale and is now being developed at pilot scale in the PProGrESS project, led by Composites UK, with lead industrial partner Aker Offshore Wind.¹⁶⁴

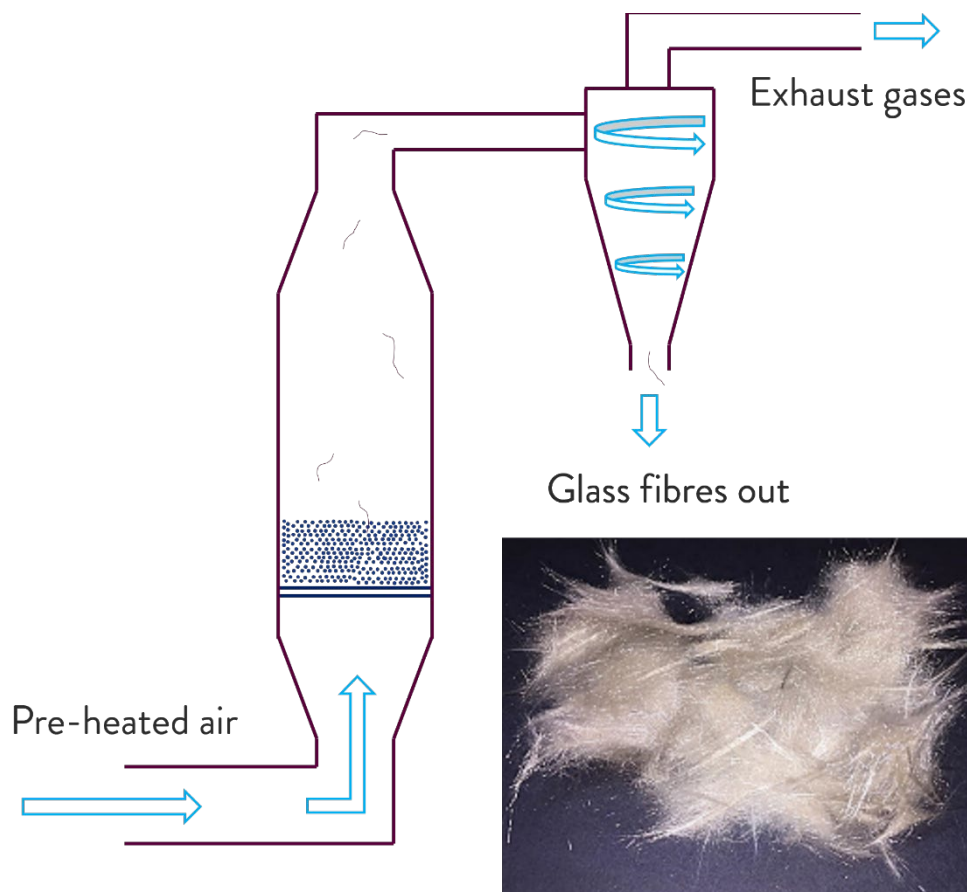


Figure 8.1: Schematic of fluidised bed process for glass fibre. Courtesy of University of Strathclyde.

8.10 Pressolysis

The term “pressolysis” is used for the separation of fibres from polymers using pressure. Recent research has indicated that the DEECOM® process from B&M Longworth Ltd, originally invented to remove polymer from filters and related

¹⁶³ <https://www.nottingham.ac.uk/research/groups/composites-research-group/research/recycling-of-composites/recycling-of-composites.aspx>

¹⁶⁴ ‘Wind Turbine Blade Recycling Project Kicks Off’, Composites UK, 13/5/22 <https://compositesuk.co.uk/wind-turbine-blade-recycling-project-kicks-off/>

production equipment, can also be used to remove polymer matrices from composite fibres.¹⁶⁵ This is being commercialised worldwide by Cygnnet Texkimp.¹⁶⁶

Using a combination of compression and decompression cycles or 'pressure swings', it gently removes a range of organic material from composite fibres, effectively reversing the bond between fibre and matrix. The process takes place in a pressure vessel filled with superheated steam. Depending on the polymer type, temperatures above 200 °C will melt or soften the polymer and a degree of hydrolysis will occur. When at pressure, the steam will penetrate fissures in the polymer where it condenses before, upon decompression, it boils, causing an instant physical fracturing of the polymer chain and carrying away monomers and oligomers along with polymer fragments from the outer faces.

Since the process interacts with the resins rather than the fibre, this has been demonstrated to reclaim format, length and structure of post-industrial or EOL waste composites, whether cured or uncured. Energy use may be high due to long duration, high temperature pressure cycling, though likely to be still much lower than virgin CF manufacturing energy. The benefits of being able to recover long tows intact are very attractive. Research is ongoing to evaluate pressolysis for GFRP.

8.11 Recovered fibre interfacial properties and fibrillation

Different recycling processes have different effects in terms of mechanical damage, surface properties of the recovered fibres and fibrillation of tows. These affects handling properties, mechanical properties and interfacial bonding with resin matrices. How this affects use of recyclate is discussed in chapter 4, but a summary is provided here.

8.11.1 Fibre size and surface properties

The fibre size is a coating which is applied at fibre manufacture to protect the fibre and make it easier to handle as well as providing interfacial adhesion. It will be different if the fibre is intended for thermoplastic or thermoset resins. Any chemical or thermal recycling processes is likely to remove the fibre size.

For carbon fibres, the interfacial properties of the resulting fibres, if left unsized, will depend on the surface reactivity of the fibres. The fluidised bed process takes place in air and there are lots of active oxygen species on the surface of the rCF. This means that the fibre bonds just as well to epoxy resin as a virgin sized fibre.¹⁶⁷ A pyrolysis process, depending on the conditions, may result in lower surface oxygen.¹⁶⁸ Fibres recovered from a chemical process, such as a supercritical fluid, have lower surface oxygen and this may reduce their ability to bond to epoxy.¹⁶⁹ So the surface properties all depend on the conditions during a recycling process. For instance, a pyrolysis process can be operated with different temperature, time and oxygen concentrations histories resulting in different fibre surface properties.

For glass fibres, the loss of size coupled with heat treatment tends to result in rapid loss of mechanical strength, which can be substantially recovered with post-treatment and re-sizing as developed by University of Strathclyde (see 8.9.2).

Mechanical processing leaves the sizing intact, but leaves resin particles attached to the surface. Interfacial bonding then tends to be very good if similar resins are used.¹⁷⁰ If regrind is used with thermoplastics, compatibilisers can be added to improve binding with the matrix.

¹⁶⁵ DEECOM®, <https://www.deecomlite.com/>

¹⁶⁶ 'Waste Recycling', Cygnnet Texkimp <https://cygnnet-texkimp.com/products/recycling-solutions/waste-recycling/>

¹⁶⁷ G. Jiang, et al, 'Surface characterisation of carbon fibre recycled using fluidised bed' Applied Surface Science, Volume 254, Issue 9, 2008, Pages 2588-2593 <https://www.sciencedirect.com/science/article/abs/pii/S0169433207014389>

¹⁶⁸ Jiang, G., Pickering, S.J. 'Structure-property relationship of recycled carbon fibres revealed by pyrolysis recycling process', J Mater Sci 51, 1949-1958, 2016 <https://link.springer.com/article/10.1007/s10853-015-9502-2>

¹⁶⁹ G. Jiang, et al, 'Characterisation of carbon fibres recycled from carbon fibre/epoxy resin composites using supercritical n-propanol', Composites Science and Technology, Volume 69, Issue 2, 2009, Pages 192-198 <https://www.sciencedirect.com/science/article/abs/pii/S0266353808004041>

¹⁷⁰ J. Palmer, et al, 'Successful closed-loop recycling of thermoset composites', Composites Part A: Applied Science and Manufacturing, Volume 40, Issue 4, 2009, Pages 490-498 <https://www.sciencedirect.com/science/article/abs/pii/S1359835X09000335>

8.11.2 Fibrillation and fluffiness

Virgin fibres are supplied as tows which may contain thousands of individual fibres aligned together. Recycling processes tend to split these tows, resulting in “fluffy” fibres which are difficult to process into intermediate products, particularly if the size has been removed, and affect the transfer of resin in infusion. Processes with less mechanical activity, such as pyrolysis, solvolysis and pressolysis, may cause less fibrillation depending on associated handling. This fibre fluffiness has been a major challenge in reuse of recovered fibres, as discussed in section 4.3.

8.12 Consumables

Consumable materials are a significant waste stream in the composites industry, including breather mesh, peel ply, vacuum bagging, backing films, etc. Where significantly contaminated with resin or silicone sealant recycling may not be possible and incineration may be more appropriate. Recycling routes may be available for clean offcuts or film, usually nylon or PET, with similar waste streams.

Silicone release paper can be cleaned and re-used and this is done commercially by Techlan in Wales, presenting an opportunity for composite manufacturers to use low cost and more sustainable release paper, usually from prepreg manufacture.¹⁷¹

8.13 Product marking and digital twins to enable recycling and reuse

Products can be labelled to enable better recovery at EOL, particularly due to the wide variety of material compositions that are possible with composites. Marking is required for some automotive plastic (including composite) products under the ELV directive (see 9.3.4). Standards exist for product marking in several other sectors. Some high value products in aerospace and automotive now have RFID tags inserted in them for the purpose of tracking PLM (product lifecycle management) and securing provenance and traceability. These tags could hold data on the material content to enable higher value recycling, and could link to virtual databases including material provenance, manufacturing and through life usage data. This is discussed further in the context of design for circularity in 2.6.3, and similar concepts may be progressed through the proposed EU ‘Digital Product Passports’ (see 9.5.3).

8.14 Impact of FRP composites in the environment

FRP composites are typically extremely durable, as is seen by numerous boats still on the water after 50 years or more, despite the harsh marine environment. A report was produced by marine ecologist Simon Bray for the International Maritime Organization (IMO), *End-Of-Life Management of Fibre Reinforced Plastic Vessels*.¹⁷² This included looking at the impacts of FRP in the marine environment. The report considered FRP chemical breakdown and risk in landfill and concluded that “degradation is viewed as unlikely with FRP material, showing little change over time”.

In an aquatic environment, particularly once gelcoats have been compromised, degradation will occur. It has been shown that the strength properties of GFRP degrade in seawater, though effect on modulus is small.¹⁷³ Some have suggested that scuttling of boats may be acceptable for forming artificial reefs. Research reviewed by Bray considered this inappropriate as hulls may be moved by currents and damage sensitive habitats (e.g. seagrass or corals), and the FRP “will ultimately break up to potentially become microplastics with, as yet, poorly understood ecological pathways and direct biological effects, though it’s known plastics sorb organic and heavy metal pollutants potentially making them more bioavailable to organisms which may ingest plastics.”

¹⁷¹ <https://www.techlanltd.co.uk/>

¹⁷² Bray, *End-Of-Life Management of Fibre Reinforced Plastic Vessels: Alternatives to At Sea Disposal*, IMO 2019

¹⁷³ José-Trujillo et al, ‘Seawater ageing effect on the mechanical properties of composites with different fiber and matrix types’, *Journal of Composite Materials* 2019, Vol. 53(23) 3229–3241



The sun sets over an old Mersey class lifeboat in Poole. Photo: Stella Job

Researchers at the University of Brighton have observed that glass microfibres have been ingested by oysters in Chichester Harbour, which may adversely affect the digestive system and reproductive cycle of shellfish.¹⁷⁴ Their research shows that if you expose mussels and water fleas to high concentrations of GFRP dust in the laboratory, it has negative effects on them, even leading to high mortalities in water fleas.¹⁷⁵ Work continues in this area to explore where the fibres are coming from – e.g. from old boats or from GFRP dust in run off from boatyards – and better understand the scale of these effects.¹⁷⁶ Given the irritant and respiratory effects of GFRP machining and sanding dust to human health, adverse effects on other creatures may be expected.

A conclusion to draw for the composites industry is that it is important to provide adequate dust extraction, and not to allow wastes, particularly machining dust and loose fibres, to enter the natural environment, especially any watercourses or the sea. In the marine context, the dust from removal of antifouling coatings is especially important to control. The copper found in many antifouling coatings can be toxic to aquatic life in high concentrations, e.g. around marinas, and, much more so, any older tributyltin antifouling coatings (now banned). Clearly end-of-life boats or other composite scrap should not be left to degrade in marine environments and formal removal and recovery systems for end-of-life boats are needed.

¹⁷⁴ Ciocan, 'Nautical not nice: how fibreglass boats have become a global pollution problem', The Guardian, 6/820 <https://www.theguardian.com/environment/2020/aug/06/nautical-not-nice-how-fibreglass-boats-have-become-a-global-pollution-problem>

¹⁷⁵ Ciocan et al, 'Glass reinforced plastic (GRP) a new emerging contaminant - First evidence of GRP impact on aquatic organisms', Marine Pollution Bulletin 160 (2020) 111559

¹⁷⁶ 'Microplastics and Chichester Harbour', University of Brighton, <https://www.brighton.ac.uk/community-partnerships/working-with-you/ignite-partnerships/microplastics-and-chichester-harbour.aspx>

8.15 Summary and overview of recycling and end of life processes

In summary, recycling processes to recover carbon fibres from CFRP by pyrolysis and solvolysis are established, though mostly for process waste rather than end-of-life. New solutions such as fluidised bed, the introduction of pressolysis and improvements to solvolysis processes may soon be commercialised. Markets for rCF are growing, and are likely to be helped by the emergence of commercial short fibre alignment processes.

GFRP can be recycled by co-processing in cement kiln in Germany, though not yet in the UK. Recycling by mechanical grinding uses less energy and has been successful at small scale for several decades, with larger scale commercial operations emerging. Thermal processes for recycling GFRP may become economically viable with economies of scale, leading to recovery of glass fibres close to virgin properties.

Table 8.1 provides an overview of recycling and end-of-life processes, with technology readiness, effect on fibre strength (if applicable) and potential to recover resin chemicals. Estimates of primary energy demand and global warming potential (GWP) are given for the process, per kg FRP composite processed (not per kg recycle product). This does not account for credit / offset from use of recycled products or energy recovered. Values should be seen as indicative as they will vary depending on material constituents and recycling routes.

A rough approximation of the effect on fibre strength is given, however it should be noted that fibre modulus is substantially retained in most recycling processes, and since many applications are stiffness-driven, some loss of strength may not be a problem in those applications. Factors such as fibre alignment and processing methodology for recycled fibres are discussed in Chapter 4. A useful comparison of potential applications of carbon fibre from different recycling routes and using different manufacturing processes can be found in Meng *‘Environmental aspects of use of recycled carbon fibre composites in automotive applications.’*¹⁷⁷

¹⁷⁷ Meng F, McKechnie J, Turner T, Wong KH, Pickering SJ, ‘Environmental aspects of use of recycled carbon fibre composites in automotive applications’, *Environ Sci Technol*. 2017;51(21):12727–36

Table 8.1: Overview of FRP recycling and end-of-life processes. Fibre strength, energy and GWP figures will vary substantially with process parameters, so should be treated as a guide only.

Process	Technology readiness	Fibre strength retention	Suitable for	Recovery of resin chemicals	Primary energy demand (MJ/kg FRP)	GWP (kg CO ₂ e/kg FRP)	Source / notes
Landfill	commercial	n/a	all	none	1.11	0.14	[178]
Incineration	commercial	n/a	GF, NF	energy only	0.15	0.76 – 1.02 (GF)	[179] GWP dep on resin content
Cement kiln recycling	commercial	n/a – recycled into cement	GF	energy only	1.28	0.84 – 1.72	[179] GWP dep on resin content
Pyrolysis CFRP	commercial	95%+ is achievable, but typ. less in commercial processes	CF	possible, limited in practice	37.4	2.90	[178]
Pyrolysis GFRP	pilot scale	significant strength loss (varies)	GF	syngas / oils recovered	not known	not known	
Mechanical grinding	commercial	significant strength loss (varies)	GF, NF, CF	as low value filler	1.20 (CF, to fine) 0.27 (GF, fibre retention)	0.11 (CF)	[178] [180]
Solvolytic CFRP	commercial at small scale	95%+	CF	possible, limited in practice	38.4 but varies by process	1.53 but varies by process	[178] Also chemical disposal
Solvolytic GFRP	lab	loss of strength due to size removed	GF	possible, limited in practice	not known	not known	Also chemical disposal
Fluidised bed CFRP	pilot scale	50-75%	CF	none currently (energy used to power process)	10.4	1.56	[181], [178]
Fluidised bed GFRP with fibre regeneration	moving to pilot scale	approx 80%	GF	none currently (energy used to power process)	13 (for 60% wt fibre content GFRP)	est sim to CFRP fluidised bed	[182]
Pressolysis CFRP	pilot scale	95%+	CF (GF research in progress)	research in progress	not known	not known	[183]

¹⁷⁸ Meng et al. 'Comparing Life Cycle Energy and Global Warming Potential of Carbon Fiber Composite Recycling Technologies and Waste Management Options'. ACS Sustain Chem Eng. 2018; 6:9854-65

¹⁷⁹ 'FRP Circular Economy Study', Composites UK, 2018

¹⁸⁰ Shuaib et al. 'Resource Efficiency and Composite Waste in UK Supply Chain', Procedia CIRP 29 (2015) 662 – 667

¹⁸¹ Meng et al. 'Energy and environmental assessment and reuse of fluidised bed recycled carbon fibres'. Compos Part A-Appl S. 2017; 100:206-14

¹⁸² Pender, Yang, 'Towards a Cost Effective Recycling Process for GRP Waste', presentation from Recomp Conference, 2020

¹⁸³ Hecker, Longana, Thomsen, Hamilton, 'From sail to structure: End-of-life sails as a feedstock for circular manufacturing', ECCM20. 26-30 June, 2022, Lausanne, Switzerland

9. POLICY AND LEGISLATION

Author: Stella Job

9.1 Introduction

Environmental legislation is developing at a remarkable pace. It is important to understand your legal obligations, and those of your clients and suppliers, and to be aware of trends in government policy and what changes are likely to be forthcoming. Many of the changes present opportunities for composite markets, and at the same time, strategic composite technologies can accelerate the path to net zero. It is also important for industry to get involved in consultations to ensure that regulations are appropriate for composites and work towards a solution which does not have unintended consequences and is better for the environment overall.

This chapter addresses policy and legislation in the UK and EU, but companies that export need to be aware of different legislation for countries, regions and sectors around the world.

9.2 Development of UK policy and legislation for sustainability over the last five years

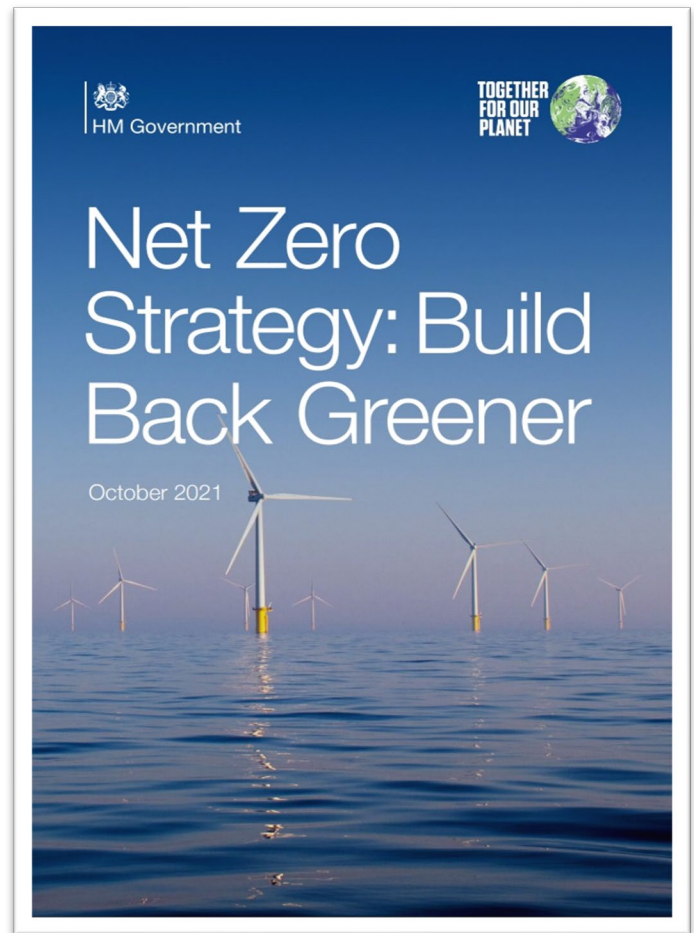
UK government policy is increasingly promoting a circular economy, biodiversity, reduction of greenhouse gas emissions and other harmful emissions to the environment. All research funding applications must demonstrate awareness of the environmental impact of the innovation and it is increasingly driving regulations.

9.2.1 Strategies in 2017 to 2018

2017 and 2018 saw an acceleration of UK government environmental policy with strategies published in areas such as clean growth¹⁸⁴ (also a focus of the 'Industrial Strategy'¹⁸⁵), plastics research, zero emission road vehicles¹⁸⁶, bioeconomy¹⁸⁷, resources and waste¹⁸⁸, and a '25 Year Environment Plan'¹⁸⁹

9.2.2 The Ten Point Plan

In November 2020 the government set out 'The Ten Point Plan for a Green Industrial Revolution' which provides many opportunities for sustainable composite development, with a commitment to £12 billion of government



¹⁸⁴ <https://www.gov.uk/government/publications/clean-growth-strategy>

¹⁸⁵ 'Industrial Strategy: Building a Britain fit for the future' 2017. <https://www.gov.uk/government/publications/industrial-strategy-building-a-britain-fit-for-the-future>

¹⁸⁶ 'Reducing emissions from road transport: Road to Zero Strategy' 2018. <https://www.gov.uk/government/publications/reducing-emissions-from-road-transport-road-to-zero-strategy>

¹⁸⁷ 'Growing the Bioeconomy', 2018. <https://www.gov.uk/government/publications/bioeconomy-strategy-2018-to-2030>

¹⁸⁸ 'Our waste, our resources: a strategy for England' 2018. <https://www.gov.uk/government/publications/resources-and-waste-strategy-for-england>

¹⁸⁹ 'A Green Future: Our 25 Year Plan to Improve the Environment' 2018. <https://www.gov.uk/government/publications/25-year-environment-plan>

investment, and potentially 3 times as much from the private sector, to create and support up to 250,000 green jobs.¹⁹⁰ The “Ten Points” were:

1. Advancing offshore wind
2. Driving the growth of low carbon hydrogen
3. Delivering new and advanced nuclear power
4. Accelerating the shift to zero emission vehicles
5. Green public transport, cycling and walking
6. ‘Jet zero’ and green ships
7. Greener buildings
8. Investing in carbon capture, usage and storage
9. Protecting our natural environment
10. Green finance and innovation



Lentus Composites, the NCC, and Ultima Forma have launched project HYSTOR to develop novel, high pressure hydrogen storage tanks for HGV, bus and off highway applications. Photo courtesy of Lentus Composites.

These support many opportunities for composites.

9.2.3 Path to Net Zero

June 2019 saw the UK become the first country to pass a net zero emissions law, with the amendment to the Climate Change Act 2008 to 100% (rather than 80%) reduction by 2050 from a 1990 baseline. The Climate Change Committee’s (CCC) pivotal ‘Sixth Carbon Budget’ recommended an accelerated approach, and provided a data-driven methodology for scenarios of how net zero 2050 can be achieved.¹⁹¹ Following the CCC’s recommendations, the net zero law was further strengthened, requiring 78% reduction by 2035. For the first time, this includes the UK’s share of international aviation and shipping emissions.¹⁹²

Alongside this, in November 2020 the decision was made to end the sale of new petrol and diesel cars in the UK by 2030.¹⁹³ This was followed in December 2020 by the ‘Energy white paper: Powering our net zero future’ further reinforcing the commitment to grow the offshore wind sector.¹⁹⁴ Following extensive consultation, the ‘Industrial Decarbonisation Strategy’ in March 2021 set out an aggressive plan to incentivise and achieve decarbonisation of heavy industry while remaining competitive and without pushing emissions abroad.¹⁹⁵

The ‘Net Zero Strategy’ was published in October 2021, just in time for COP26.¹⁹⁶ Commitments included:

- Around £1 billion for electric vehicles and charging points
- £180 million in funding to support the development of UK sustainable aviation fuel (SAF) plants

¹⁹⁰ ‘The ten point plan for a green industrial revolution’ BEIS et al, 18/11/20 <https://www.gov.uk/government/publications/the-ten-point-plan-for-a-green-industrial-revolution>

¹⁹¹ ‘Sixth Carbon Budget’ Climate Change Committee, 9/12/20. <https://www.theccc.org.uk/publication/sixth-carbon-budget/>

¹⁹² ‘UK enshrines new target in law to slash emissions by 78% by 2035’, BEIS et al, 20/4/21 <https://www.gov.uk/government/news/uk-enshrines-new-target-in-law-to-slash-emissions-by-78-by-2035>

¹⁹³ ‘Government takes historic step towards net-zero with end of sale of new petrol and diesel cars by 2030’, DfT et al, 18/11/20 <https://www.gov.uk/government/news/government-takes-historic-step-towards-net-zero-with-end-of-sale-of-new-petrol-and-diesel-cars-by-2030>

¹⁹⁴ ‘Energy white paper: Powering our net zero future’ BEIS, 14/12/20. <https://www.gov.uk/government/publications/energy-white-paper-powering-our-net-zero-future>

¹⁹⁵ ‘Industrial Decarbonisation Strategy’ BEIS, 17/3/21. <https://www.gov.uk/government/publications/industrial-decarbonisation-strategy>

¹⁹⁶ ‘Net Zero Strategy: Build Back Greener’, BEIS, 19/10/21 <https://www.gov.uk/government/publications/net-zero-strategy>

- £140 million to accelerate industrial carbon capture and hydrogen
- An extra £500 million for development of green technologies
- £3.9 billion of new funding for decarbonising heat and buildings
- £124 million boost to our Nature for Climate Fund to restore peatland and create woodland.
- £120 million towards the development of nuclear projects

9.2.4 Hydrogen and aviation

August 2021 saw the publication of the UK Hydrogen Strategy, providing further support for hydrogen production and infrastructure, and uses of hydrogen in industry, power, transport and potentially heat.¹⁹⁷ The Jet Zero council produced its first strategy in July 2022, promising funding and policies to support the road to net zero aviation, including sustainable aviation fuels (SAF) and zero-carbon emission electric and hydrogen aircraft.¹⁹⁸ These present huge opportunities for composites in hydrogen storage and infrastructure, as well as in incremental improvements in airframes.

9.2.5 The Environment Act

The much-delayed UK Environment Act was passed in November 2021 and has important implications for composites.¹⁹⁹ This will:

- Set up a new Office for Environmental Protection;
- Require long term (15 years+) environmental targets to be set, for resource efficiency and waste reduction, as well as air quality, water and biodiversity;
- Confer power on devolved administrations to make regulations about producer responsibility obligations and for amendment of REACH regulations.

While the Act itself does not define specific targets and producer responsibilities, it paves the way and formalises the intention to do so, in accordance with the 25 Year Environment Plan. In proposing regulations, it requires consideration of the product's whole life impact, the costs of compliance and whether special provision should be made for smaller businesses. This is important for composites in the following ways:

- **“Recyclable”** - Where composites are technically recyclable but the supply chains do not yet exist, new requirements to separate “recyclable waste” could increase the pressure to make those supply chains work, or declare composite material to be unrecyclable until they do. (The latter being bad for public image.)
- **Life cycle assessment (LCA)** - This could lead to the first regulatory requirements for environmental impact assessments, which lends urgency to the need to develop capability and methodology to undertake LCAs. This could also act in favour of composites as they often save through-life emissions and are more durable and easier to maintain.
- **Producer responsibility** – Minimum levels of re-use / recycling / recovery are likely to increase and manufacturers / suppliers may increasingly be required to meet or contribute to disposal costs. (See section 9.3.7.)
- **Information** - may be required about a product's impact, including expected life, aspects of design, ability to maintain, repair and upgrade the product, how it can be disposed of at end of life, or the extent to which it can be recycled. This may include materials, manufacturing techniques, resources consumed and pollutants released during production, use or disposal. (from ‘Schedule 6 – Resource Efficiency Information’, Part 1, (2))
- **Tracking and labelling** – Requirements on product labelling to inform consumer purchasing and disposal. While most composite products are not consumer facing, the expectation to include tracking data will increase.

¹⁹⁷ ‘UK hydrogen strategy’, BEIS, 17/8/21 <https://www.gov.uk/government/publications/uk-hydrogen-strategy>

¹⁹⁸ ‘Jet Zero strategy: delivering net zero aviation by 2050’, DfT, 19/7/22 <https://www.gov.uk/government/publications/jet-zero-strategy-delivering-net-zero-aviation-by-2050>

¹⁹⁹ ‘Environment Act 2021’, 9/11/21 <https://www.legislation.gov.uk/ukpga/2021/30/contents/enacted>

It is important for the composites industry to engage in consultations to ensure that the subsequent targets and regulations allow for the unique situations which arise with composites.

9.2.6 Critical minerals strategy

The July 2022 UK Critical minerals strategy²⁰⁰ represents increasing concern about minerals for which both economic vulnerability and supply risks are high. Carbon fibre composites can replace some critical minerals such as magnesium (light weight alloys in automotive) and vanadium (in titanium alloys such as Ti-6Al-4V used in aerospace) and ceramic matrix composites are beginning to replace nickel-based superalloys which contain cobalt, niobium and tantalum, for high temperature, high performance applications such as turbine blades. Cobalt is in increasing demand in superalloys and batteries, though work to replace it in batteries is ongoing.

However, cobalt salts are used in unsaturated polyester resins as promoters or accelerators and both supply chain risks and social impacts around cobalt supply are areas the composites industry needs to be involved in. The developing standards landscape around responsible mineral extraction is likely to form the basis of further regulation. The Responsible Minerals Initiative is a useful source of information on this.²⁰¹

9.3 Regulations on disposal and end-of-life

Policy on waste legislation has shifted over the last 20 years from a simple landfill tax which incentivises recycling routes, to more complex legislation, in many cases driven by EU Directives, to introduce a producer responsibility approach which is enacted in diverse ways. (See section 9.3.7 for summary.)

While Brexit has affected how EU regulation affects UK, several directives had already been transposed into UK laws. These have generally set targets and introduced the concept of producer responsibility,²⁰² which may well be extended to other areas. For markets which affect composites, there is legislation covering construction, automotive, electrical and electronic goods and renewables. There is currently no specific legislation to incentivise responsible disposal for aerospace, marine or other sectors.

Across Europe, waste legislation is surprisingly diverse, despite being generally guided by the same EU directives. Details of this are beyond the scope of this guide, but it should be noted that in several cases FRP wastes cannot cross national borders within the EU. Those exporting to regional markets within and outside the EU need to comply with regulations in those regions.

Waste legislation in UK is generally devolved to the administrations of England, Scotland, Wales and Northern Ireland, but at the time of writing, it is generally the same, based on EU directives, and the landfill tax rates are the same. Extensive guidance on waste regulation is available from UK government.²⁰³ Overall in UK, waste to landfill has dropped dramatically in the last 15 years or so, with recycling and energy from waste (EfW) increasing, as illustrated for local authority waste in Figure 9.1. At present there is no tax on incineration, but this may change.²⁰⁴

²⁰⁰ 'Resilience for the Future: The UK's critical minerals strategy', BEIS, 22/7/22 <https://www.gov.uk/government/publications/uk-critical-mineral-strategy>

²⁰¹ Responsible Minerals Initiative <https://www.responsiblemineralsinitiative.org/>

²⁰² See <https://www.gov.uk/government/collections/producer-responsibility-regulations>

²⁰³ See <https://www.gov.uk/topic/environmental-management/waste>

²⁰⁴ 'MPs call for incineration tax in commons debate' 13/2/20 <https://resource.co/article/mps-call-incineration-tax-commons-debate>

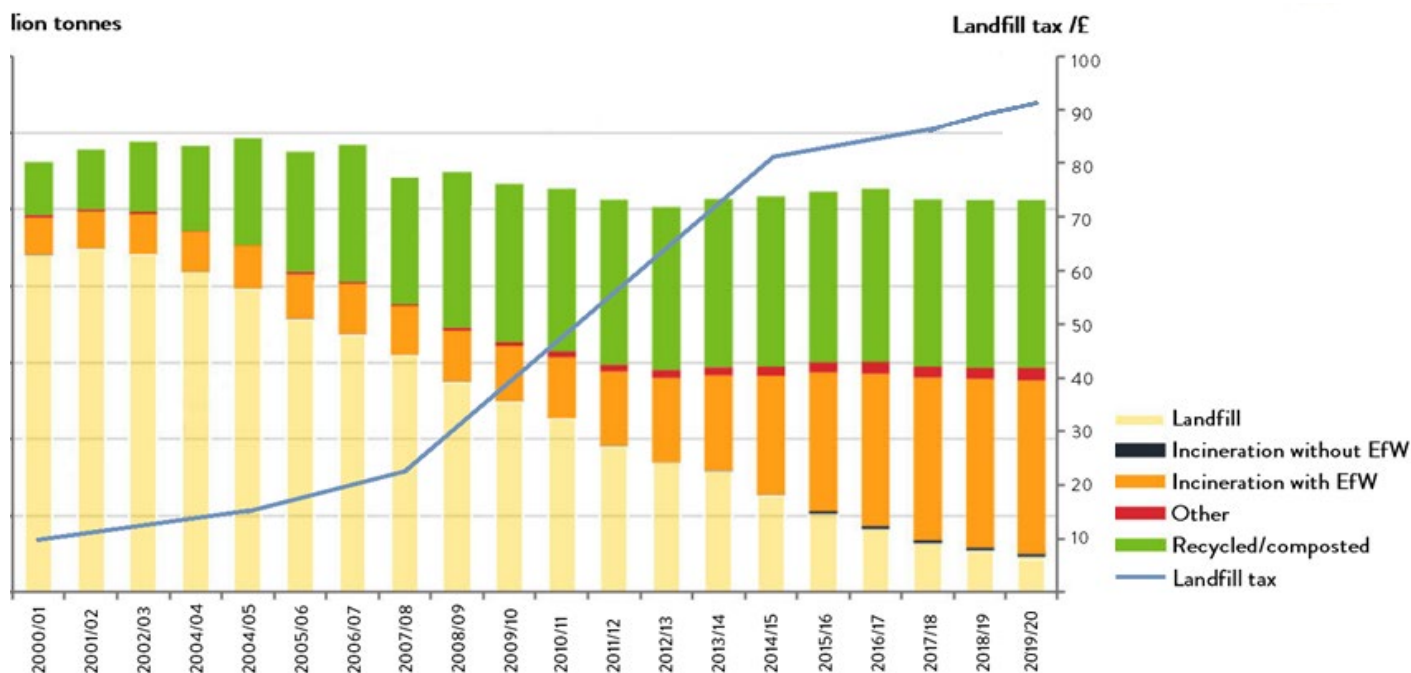


Figure 9.1: Management of local authority collected waste and landfill tax, England 2000/01 - 2019/20. Edited from Defra²⁰⁵

9.3.1 Landfill

The UK has one of the highest landfill taxes in Europe, with standard rate tax at £98.60 per tonne (2022-23). The tax is paid by the landfill site operator, and added to the gate fee charged to the customer. As the UK landfill tax is already high, and rates of disposal to landfill have dropped so much, it is unlikely that it will increase more than the approx. 3% per year that we have seen in the last few years. Instead, we may see more targets to incentivise recyclability and recycled content emerging.

There is a second, lower rate landfill tax for inert or inactive waste, currently £3.15 per tonne (2022-23). Scrap glass fibre (without organic matrix) is covered in this lower rate. A 'small amount' of standard rate material is allowed, as long as it has not been intentionally blended in, could not reasonably have been separated from the qualifying material and is not hazardous. The 'small amount' is not defined, but there is a test for fines to qualify for lower rate which requires the loss on ignition to be less than 10%, so it seems reasonable that fibre sizing and possibly a light binder would not exclude glass fibres from the lower rate.²⁰⁶

At present there is no pending legislation to prohibit landfill of FRP composites in UK, as exists in Germany. (Scotland and Northern Ireland are likely to ban all biodegradable waste to landfill by 2025, so that may follow in England and Wales.) Several other countries in Europe have landfill restrictions for wastes with more than a small amount (varies 3 to 8%) organic content, but in some cases FRP is exempt if there is no recycling / recovery solution.²⁰⁷

9.3.2 Waste Framework Directive 2008/98/EC (WFD)

Incorporated in the 'Waste (England and Wales) Regulations 2011', this requires re-use / recycling of at least 70% of construction waste since 2020 (in addition to household waste recycling targets).

²⁰⁵ 'Statistics on waste managed by local authorities in England in 2019/20' Defra,, March 2021

<https://www.gov.uk/government/statistics/local-authority-collected-waste-management-annual-results>

²⁰⁶ 'Excise notice LFT1: A general guide to landfill tax', April 2020. Section 4.2, groups 2 and 3 apply.

<https://www.gov.uk/government/publications/excise-notice-lft1-a-general-guide-to-landfill-tax>

²⁰⁷ 'Landfill taxes and bans overview' CEWEP,, updated March 2020 <https://www.cewep.eu/wp-content/uploads/2017/12/Landfill-taxes-and-bans-overview.pdf>

The WFD defines the waste hierarchy as illustrated in Figure 9.2. It allows for consideration of other technical, economic and social factors, and to ‘depart from the priority order ... so as to achieve the best overall environmental outcome where this is justified by life-cycle thinking...’

Recycling is defined in the WFD:

‘recycling’ means any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations

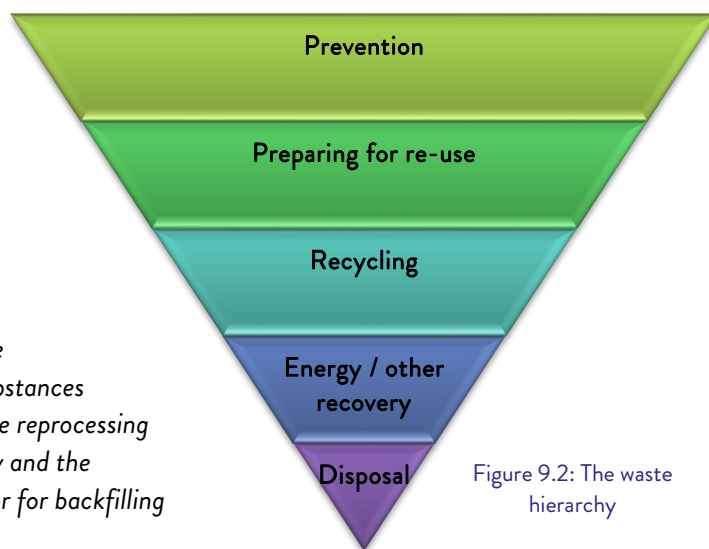


Figure 9.2: The waste hierarchy

This means that the cement kiln route can be identified as ‘recycling’ for GFRP because the mineral content is reprocessed into clinker, but EfW is not, since the incinerator bottom ash (IBA) is either landfilled or reprocessed into aggregate for ‘backfilling operations’. The definition is not the same in the End-of-life Vehicle Directive, see 9.3.4.

9.3.3 Classification of wastes

When waste is moved or disposed of it must be accompanied by a waste transfer note/consignment note. This describes the waste, producer of the waste and the disposal point. European Waste Catalogue codes (EWC codes, or EURAL codes) are used, as defined in the European List of Waste.²⁰⁸ There is no specific EWC code for cured composite waste. Table 9.1 is a non-exhaustive list of codes that could relate to composite industry waste of different kinds. ‘Technical Guidance WM3’, Appendix A gives guidance on how to use the List of Waste.²⁰⁹

Hazardous wastes are considered to present a particularly high risk to health or the environment and require special handling and treatment. The co-disposal of hazardous waste with non-hazardous waste at the same landfill site has been prohibited since 2004. WM3 also provides guidance on hazardous waste identification and classification. In the composites industry this mainly applies to liquid chemicals and uncured resins and preregs, and any packaging (e.g. drums, IBCs) or process consumables (e.g. breather mesh, vacuum bagging) which have residues of uncured resin.

²⁰⁸ European List of Waste <https://ec.europa.eu/environment/waste/framework/list.htm>

²⁰⁹ ‘Technical Guidance WM3: Waste Classification - Guidance on the classification and assessment of waste’ 2015 <https://www.gov.uk/government/publications/waste-classification-technical-guidance>

Table 9.1: European Waste Catalogue codes which may be used for wastes from the composites industry (not exclusive – others may also apply). As composite waste is not clearly defined, it may be categorised (whether correctly or not) as those starred * GFRP, ** any composite. Red is hazardous.

EWC Code	Description in List of Waste	Comments
04 02	textile industry	relates to manufacturing waste from the textile industry
04 02 09	wastes from composite materials (impregnated textile, elastomer, plastomer)	e.g. cured prepreg scrap (uncured prepreg scrap would be considered hazardous) **other if manufacturing waste, not end of life
04 02 21	wastes from unprocessed textile fibres	e.g. end of reel scrap
04 02 22	wastes from processed textile fibres	e.g. selvedges, trim / offcuts of dry fibre
07 02	manufacture - formulation - supply and use (MFSU) of plastics - synthetic rubber and man-made fibres	
07 02 13	waste plastic	e.g. cured polymer manufacturing waste**
08 04	wastes from MFSU of adhesives and sealants (including waterproofing products)	
08 04 09	waste adhesives and sealants containing organic solvents or other hazardous substances	e.g. uncured adhesive waste. 08 04 10, 11, 12 may also apply
10 11	wastes from manufacture of glass and glass products	
10 11 03	waste glass-based fibrous materials	*e.g. waste from glass fibre manufacture, also recommended for GFRP by SEPA ²¹⁰ (for manufacturing waste)
15 01	packaging	several other sub-categories apply to regular packaging materials, e.g. paper and cardboard, plastic
15 01 10	packaging containing residues of or contaminated by hazardous substances	e.g. drums / IBCs with residues of resin / chemicals
16 01	end-of-life vehicles from different means of transport (including off road machinery) and wastes from dismantling... and vehicle maintenance	This includes end-of-life boats, ships, aircraft, caravans and trailers as well as road vehicles and off-road vehicles. Not including liquid wastes, batteries, spent catalysts
16 01 19	plastic	*i.e. polymer composite waste from vehicles
16 01 20	glass	* recommended for GFRP by SEPA (for vehicle wastes)
16 02	wastes from electrical and electronic equipment	
16 02 16	components removed from discarded equipment other than those mentioned in 16 02 15	** (16 02 15 contains hazardous substances)
16 03	off-specification batches and unused products	
16 03 05	organic wastes containing hazardous substances	off spec / unused liquid resin
16 03 06	organic wastes other than those mentioned in 16 03 05	off spec / unused solid / cured resin
17 02	construction and demolition wastes: wood, glass and plastic	i.e. could include “virgin” offcuts from the construction process or EOL waste
17 02 02	glass	* recommended for GFRP by SEPA (for construction wastes)
17 02 03	plastic	** i.e. polymer composite waste from construction
19 12	wastes from the mechanical treatment of waste (for example sorting, crushing, compacting, pelletising)	
19 12 04	plastic and rubber	**
19 12 08	textiles	
19 12 10	combustible waste (refuse derived fuel)	**
19 12 12	other wastes (including mixtures of materials) from mechanical treatment of wastes other than those mentioned in 19 12 11	** (19 12 11 contains hazardous substances)

²¹⁰ ‘Waste Thesaurus: SEPA guidance for coding waste’, June 2015 <https://www.sepa.org.uk/environment/waste/waste-data/guidance-and-forms-for-operators/licensed-and-permitted-sites/>

9.3.4 End-of-life Vehicle Directive 2000/53/EC (ELV)

This covers cars (up to 9 seats) and small vans (up to 3.5 tonnes), including components made for them. The End-of-life Vehicles Regulations 2003 (as amended) and the End-of-life Vehicles (Producer Responsibility) Regulations 2005 (as amended) enforce the provisions of the ELV Directive in UK. Requirements relevant to composites include:

- Producers to provide authorised treatment facilities offering free take-back to meet targets of at least 95% recovery and 85% reuse and recycling by weight.
- Public information required on materials, together with guidance on how its components can be dismantled, reused or recovered ²¹¹
- Marking ('coding') of plastic (including composite) parts over 100g, according to ISO 1043 and 11469, to promote recovery ²¹²
- Removal of large plastic (including composite) components if these materials are not segregated in the shredding process in such a way that they can be effectively recycled ²¹³



Figure 9.3: Automotive scrap. Photo: Stella Job

This can disincentivise composites because:

- a) Composite recycling supply chains are still limited, and some OEMs are particularly keen to see a closed loop recycling solution;
- b) Where the overall weight of the vehicle is reduced by using composites, even though they are recyclable, the weight % of non-recyclable parts is then greater, so the vehicle may not achieve the recyclability targets.

Following a major consultation in 2019, a review of the ELV Directive was completed in 2020. The EC expects to present a legislative proposal in 2022, following public consultation in 2nd quarter 2021. This gives consideration to the feasibility of setting targets for specific materials contained in the relevant waste streams, so may affect the use of composites. It may also be extended to include other vehicle types, and may review the definition of recycling which is currently wider than that in the WFD in that it allows backfilling / aggregate to count as recycling. ²¹⁴

9.3.5 Waste Electrical and Electronic Equipment Directive 2012/19/EU

This affects composites increasingly as they are used in more areas, such as large household appliances, medical devices, telecommunications equipment, etc. Implemented in UK as Waste Electric and Electronic Equipment (WEEE) Regulations 2013, the overall aim is for the EU to recycle at least 85% of WEEE by 2016. This requires producers or importers of WEEE (who place more than 5 tonnes of EEE on the UK market) to:

- provide free take-back through producer compliance schemes for recovery and environmentally sound disposal, aiming for 85% recycling;
- mark products with the crossed-out wheeled-bin symbol and provide information on reuse and treatment of the products and components (including materials);
- aim to improve product design to facilitate recycling and reuse of components and materials. ²¹⁵

²¹¹ <https://www.gov.uk/guidance/elv>

²¹² ISO 1043-1 'Plastics — symbols and abbreviated terms' Parts 1-4; ISO 11469:2016 'Plastics — Generic identification and marking of plastic products'. See https://www.legislation.gov.uk/eudn/2003/138/pdfs/eudn_20030138_adopted_en.pdf

²¹³ See Annex 1, item 4 at <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02000L0053-20200306>

²¹⁴ The latest on the ELV review can be found at https://ec.europa.eu/environment/topics/waste-and-recycling/end-life-vehicles_en

²¹⁵ <https://www.gov.uk/guidance/electrical-and-electronic-equipment-eee-producer-responsibility>

9.3.6 Wind energy decommissioning

Offshore renewable energy installations (OREIs) must be decommissioned in accordance with Sections 105 to 114 of the Energy Act 2004 (as amended by the Energy Act 2008 and the Scotland Act 2016). This has its origins in the UN Convention on the Law of the Sea (UNCLOS), 1982 which requires disused installations to be removed for safe navigation. The operator is responsible for ensuring financial security is in place at the time of construction for the OREI to be decommissioned at the end of its useful life, so limiting the risk of the taxpayer having to cover the cost. The financial security is based on a costed decommissioning plan and may be upfront cash paid or bonds which cannot be withdrawn until needed for decommissioning. There is no requirement for recycling.²¹⁶

A similar approach is usually taken for larger onshore wind farms, enacted through planning policy, requiring sites to be restored at end of life. This varies on a case-by-case basis and is at the discretion of the individual planning authority.

9.3.7 Summary of producer responsibility regulations

It is helpful to summarise the various ways the “polluter pays” principle has been and is being enacted, to illustrate the diversity. See Table 9.2. Undoubtedly there will be more such requirements in future, particularly with the advent of the Environment Act, and it is important for industry to be involved in consultations to ensure that regulations are appropriate and work towards a solution which is better for the environment overall.

Table 9.2: Summary of producer responsibility regulations for end-of-life treatment

Application	Year	Reference	Key requirements
End of life vehicles	2003	ELV Directive 2000/53/EC UK End-of-life Vehicles Regulations	requires free take-back; manufacturer / importer must register; marking and information required on dismantling, materials, recovery; must meet 95% recovery, 85% of recycling (soon to be revised)
Offshore wind farms	2004	Energy Act 2004	upfront cash / bonds required to ensure appropriate decommissioning of windfarms
Onshore wind farms	n/a	Planning policy - varies	upfront cash / bonds required to ensure appropriate decommissioning of windfarms
Potentially harmful chemicals (REACH)	from 2006	EC Regulation No 1907/2006 The REACH etc. (Amendment etc.) (EU Exit) Regulations 2020	increasing list of chemicals banned or required to be registered
Waste electrical and electronic equipment (similar for batteries)	2013	WEEE Directive 2012/19/EU UK WEEE Regulations	requires free takeback through producer compliance schemes for recovery and disposal; improve design; marking and information on treatment; aim for 85% recycling
Construction waste	2020	WFD 2008/98/EC Waste (England and Wales) Regulations (similar Scotland / NI)	recycling of at least 70% of construction waste (already being met)
SCIP	2021	WFD 2008/98/EC (2018 amendment)	reporting of Substances of Very High Concern in articles to reduce EOL impacts
Packaging	2022	Plastic Packaging Tax ²¹⁷	tax on packaging with less than 30% recycled plastic – this is the first regulation to require recycled content, and may set a precedent.

²¹⁶ See ‘Decommissioning offshore renewable energy installations’, <https://www.gov.uk/government/publications/decommissioning-offshore-renewable-energy-installations>

²¹⁷ See <https://www.gov.uk/government/publications/introduction-of-plastic-packaging-tax/plastic-packaging-tax>

9.4 Regulations on chemical content

The main regulation of relevance to chemical content and environmental sustainability in the UK is REACH, which exists to protect human health and the environment. In Europe SCIP also applies, which is primarily to limit hazardous content which may affect end-of-life processing. These are in addition to regulations such as COSHH (Control of substances hazardous to health) which relate only to human health. Many lists of restricted substances exist and vary by countries, regions and sectors. For hazardous waste see 9.3.3 'Classification of wastes'. The implications of these regulations for design are discussed in section 2.3.

9.4.1 REACH

The 'Registration, Evaluation, Authorisation and Restriction of Chemicals' (REACH) Regulation No 1907/2006 is operated by the European Chemicals Agency (ECHA), agency of the European Union. It requires the registration and risk management of chemicals used within the EU to protect human health and the environment and removes particularly harmful chemicals. Epoxy is on the REACH list, along with many additives, teflons, etc. Currently most polymers do not have to be registered, but ongoing discussions about how to include polymers in REACH may result in changes in 2022-23.²¹⁸ This will have an impact on the matrix materials used in composites.

UK government has put in place a separate 'UK REACH' regime since Brexit, with the Health and Safety Executive (HSE) established as the UK Chemicals Authority, taking over the functions of the ECHA. If you manufacture chemical substances or import them from outside Europe above one tonne per year, you may have registration obligations under REACH.²¹⁹

9.4.2 Substances of Concern in Products (SCIP)

Following the EU action plan for the circular economy adopted in 2015, the 2018 amendment to the Waste Framework Directive gave ECHA the task to develop a database with information on articles / products containing substances of very high concern (SVHCs²²⁰) on the 'Candidate List'.²²¹ This ensures that the information on articles containing SVHCs is available to waste operators and consumers throughout the whole lifecycle of products and materials.²²²

The SCIP database has three main objectives:

- Decrease the generation of waste containing hazardous substances
- Make information available to further improve waste treatment operations
- Allow authorities to monitor the use of substances of concern in articles and initiate appropriate actions

Companies that produce, import or supply articles containing Candidate List substances in a concentration above 0.1% by weight have to submit information on these articles placed on the EU market to the SCIP database, since January 2021. SCIP has not been transposed into UK law, so is only relevant to products exported to the EU, but a forthcoming DEFRA Chemicals Strategy (expected 2022 or 23) is likely to address this area.

²¹⁸ See 'Commission sets goal for polymer REACH registration proposal by 2022' <https://chemicalwatch.com/85658/commission-sets-goal-for-polymer-reach-registration-proposal-by-2022>. See also EU Competent Authorities for REACH and CLP (CARACAL) subgroup <https://circabc.europa.eu/ui/group/a0b483a2-4c05-4058-addf-2a4de71b9a98/library/806e87e4-1236-4b2b-a768-de1ac2ba15c4>

²¹⁹ For further information see <https://www.hse.gov.uk/reach/> and <https://www.gov.uk/guidance/how-to-comply-with-reach-chemical-regulations>. Composites UK members are kept up to date by email and can access the latest guidance in the Members Area of the website <https://compositesuk.co.uk/member-resources/business-development/material-supply-information/>

²²⁰ SVHCs are listed at <https://echa.europa.eu/candidate-list-table>

²²¹ 'Understanding WFD', ECHA <https://echa.europa.eu/understanding-wfd>

²²² <https://echa.europa.eu/scip-database>. Also see article and "Who needs to Notify?" video at <https://echa.europa.eu/-/substances-of-concern-in-products-database-try-out-the-prototy-1>

9.5 Regulations on environmental impact and ecodesign

9.5.1 Energy and carbon reporting for organisations

Large companies in UK are required to report under ESOS, SECR and TCFD, and some may also report voluntarily through CCAs. TCFD is likely to be mandatory for all companies by 2025. For details, see section 7.8 ‘Sustainability reporting’.

9.5.2 Environmental impact of products

Ideally, environmental legislation for materials and products would be based on the whole life environmental impact, to avoid an intention to improve one area causing an incentive to make another area worse. (e.g. concerns about marine toxicity of plastic packaging leading to regulation which incentivises higher carbon footprint and less recyclable materials.) However, regulation based on LCA is very difficult to achieve as methodology can vary widely and data is expensive to produce. Currently life cycle impact assessment for products is not a regulatory requirement, though it may be required by clients.

As emissions and energy use from transport and buildings reduce, the impact of the materials in the vehicle / building become a higher proportion of the whole life impact. Hence material decisions and trade-offs considering the entire life cycle become increasingly important and are likely to be more scrutinised from a standards and regulation perspective.

Standardised approaches have been developed which could form a basis for regulation. These are well established in the construction industry with EPDs, with associated PCRs, and the BRE’s BREEAM for buildings and CEEQUAL for civil engineering and infrastructure (or LEED in the USA). BIM provides a framework for integrating environmental data into building models. The European Commission’s PEFCR methods are intended to be used as a common way of measuring environmental performance for diverse products, for companies to substantiate their environmental claims.

These are described further, with explanation of the acronyms, in section 3.5. However, the proposal to revise the ‘EU Construction Products Regulation’ may influence how information is conveyed for construction products, to address sustainability performance as well as properties such as reaction to fire and insulation.²²³

9.5.3 EC Ecodesign for Sustainable Products Regulation

In March 2022 the EC presented a package of proposals “to make sustainable products the norm in the EU, boost circular business models and empower consumers for the green transition”.²²⁴ This is another initiative of the EU Circular Economy Action Plan, which is one of the building blocks of the European Green Deal.²²⁵ An overview of the initiatives is shown in Figure 9.4.

A key part of this is a proposal for an ‘Ecodesign for Sustainable Products Regulation’ (ESPR) to address product design, which determines up to 80% of a product’s lifecycle environmental impact. It will set new requirements to make products more durable, reliable, reusable, upgradable, repairable, easier to maintain, refurbish and recycle, and energy and resource efficient. This will cover almost all physical good placed on the EU market, except food and feed, and will lead to considerably more labelling requirements and ‘Digital Product Passports’ (DPP). DPPs will hold data on materials (including SCIP, critical / scarce materials, etc), information on repair, etc. This will be shared across entire value chains so all actors, including consumers, have a better understanding of the materials and products used and their environmental impact, making it easier to repair or recycle products.

Information on environmental impacts for consumers is important, and the initiative cracks down on greenwashing. It also includes welcome measures to end the destruction of unsold consumer goods and expansion of green public procurement

²²³ ‘Questions & Answers: Revision of the Construction Products Regulation’, European Commission, 30/3/22 https://ec.europa.eu/commission/presscorner/detail/en/QANDA_22_2121

²²⁴ ‘Green Deal: New proposals to make sustainable products the norm and boost Europe’s resource independence’, European Commission, 30/3/22 https://ec.europa.eu/commission/presscorner/detail/en/ip_22_2013

²²⁵ ‘Circular economy action plan’, European Commission https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en

and incentives for sustainable products. However, the balance between data sharing and data protection must be ensured, and there is concern that DPPs should not put an unnecessary administrative burden on businesses regarding data disclosure and reporting.²²⁶

Making sustainable products the norm in a more resilient Single Market



Figure 9.4 Overview of initiatives in the EU Circular Economy package. Source: [COM/2022/140 final](#)

9.6 Bio-based and biodegradable materials

While the Bioeconomy Strategy supports development of bio-based plastics and composites, there is no UK legislation or procurement policy to incentivise the use of bio-based materials. The US Department of Agriculture BioPreferred® Program designates categories for federal purchasing, including minimum bio-based content in numerous product categories.²²⁷ A generalised policy to support bio-based content has inherent risks, as while some bio-based materials are excellent, others may be more energy intensive than the oil-based alternative, or may have toxicity or sustainable sourcing issues such as land use change. However, it is essential that we move to bio-based materials in the longer term where 100% circularity cannot be achieved, so policies to support development of sustainable bio-based materials need to be developed.

Several standards exist to define terminology, test methods and communication methods for bio-based content, biodegradability and compostability. BS EN 17228:2019 specifies the vocabulary, methods for characterization, and

²²⁶ 'Digital product passports: What does the Sustainable Products Initiative bring?', European Policy Centre, 11/5/22 <https://www.epc.eu/en/publications/Digital-product-passports-What-does-the-Sustainable-Products-Initiative-484018>

²²⁷ See <https://www.gsa.gov/governmentwide-initiatives/sustainability/buy-green-products-services-and-vehicles/buy-green-products/biobased-and-biopreferred-products>

templates for reporting about bio-based polymers, plastics, and plastics products (including semi-finished plastics products and composites). In particular this document covers: terminology, bio-based content, bio-based carbon content, life cycle assessment, sustainability aspects, and declaration tools.²²⁸

9.7 Emissions regulations and targets for transport

Emissions regulations are important for composites as they tend to incentivise weight reduction.

9.7.1 Road vehicles

There will be a two-step approach to end the sale of new petrol and diesel cars and vans in the UK:²²⁹

1. Sale of new fully petrol and diesel cars and vans phased out by 2030.
2. Sale of all new cars and vans must be fully zero emission at the tailpipe from 2035. Between 2030 and 2035, new cars and vans can be sold if they have the 'significant zero emission capability' (not yet defined), for example, plug-in hybrids or full hybrids.



Electric vehicle. Stock image.

Regulation (EU) 2019/631 (which replaced (EC) 443/2009 for cars and (EC) 510/2011 for vans) sets the EU fleet-wide average emission target for new cars at 95 gCO₂/km and for new vans at 147 gCO₂/km. Targets are applied to manufacturers, or manufacturing groups, by a formula. Smaller manufacturers are eligible for derogations (relaxations). In 2020, the 95 g CO₂/km target applied for each manufacturer's 95% least emitting new cars. From 2021, it applies to all new cars and vans.

'Super-credits' also apply for the registration of zero or low emission vehicles (ZLEVs), i.e. vehicles emitting less than 50 gCO₂/km 2020-23. A ZLEV will be counted as 2 vehicles in 2020; 1.67 vehicles in 2021; 1.33 vehicles in 2022. There is also an incentive mechanism for ZLEVs from 2025. Fines are issued to any manufacturer that exceeds their emissions target by way of an 'excess emissions premium.' This premium is €95 per gram of exceedance per vehicle registered by that manufacturer.

Following consultation, this has been substantially maintained in UK law post-Brexit.²³⁰ Further CO₂ reduction targets were set to apply from 2030, however, these will now be superseded in the UK by the requirement to end sale of petrol and diesel cars and vans.

9.7.2 Aviation

Environmental policy in aviation is rapidly changing as 'flight-shaming' and the COVID-19 pandemic has brought home the need to change. Several organisations have produced "route to net zero" plans, but it is clear that net zero CO₂ by 2050 is a huge challenge. The non-CO₂ climate impacts are also still very uncertain but are probably significantly greater than the CO₂ impacts.

²²⁸ BS EN 17228:2019 'Plastics. Bio-based polymers, plastics, and plastics products. Terminology, characteristics and communication' <https://knowledge.bsigroup.com/products/plastics-bio-based-polymers-plastics-and-plastics-products-terminology-characteristics-and-communication/standard>

²²⁹ Transitioning to zero emission cars and vans: 2035 delivery plan, DfT / OLEV, 14/7/21 <https://www.gov.uk/government/publications/transitioning-to-zero-emission-cars-and-vans-2035-delivery-plan>

²³⁰ 'Regulating CO₂ emission standards for new cars and vans after transition', DfT, 10/7/20 <https://www.gov.uk/government/consultations/regulating-co2-emission-standards-for-new-cars-and-vans-after-transition>

The International Civil Aviation Organization (ICAO) is the United Nations agency developing policy and standards, for member nations to apply as regulation, for aviation. The ICAO approach for global aviation includes: ²³¹

- An aspirational, non-obligatory target for global aviation fleet fuel efficiency improvement of 2% p.a. from 2021 to 2050 (fuel used per revenue tonne km)
- A commitment to carbon neutral growth from 2020
- Implementing the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) – see below
- A collective long-term global aspirational goal (LTAG) of net-zero carbon emissions by 2050.²³²

Flights within the European Economic Area, Switzerland and UK are subject to the EU Emissions Trading Scheme (EU ETS), with free allowances reduced progressively to 2027. Flights from the EU ETS region to other ICAO members are subject to CORSIA.²³³

CORSIA has been developed as part of achieving the ICAO commitment to stabilise CO₂ emissions at 2020 levels.²³⁴ Emissions are monitored and carbon offsets are purchased to compensate for growth above 2019 levels. (The 2020 baseline year was revised to 2019 due to the effects of the COVID-19 pandemic on aviation in 2020.) This is initially optional, becoming mandatory for ICAO member states from 2027, with exemption for states with small aviation contribution and “least developed countries”. Achieving these goals requires technological step changes in areas such as sustainable aviation fuels, new propulsion systems and new airframe design concepts. However, the goals are weak compared with the UN goal for zero carbon emissions by 2050. They simply stabilise emissions rather than reducing them, and only address CO₂, not other non-CO₂ warming effects of aviation. There is increasing pressure for global aviation to accelerate progress to achieve net zero emissions by 2050.

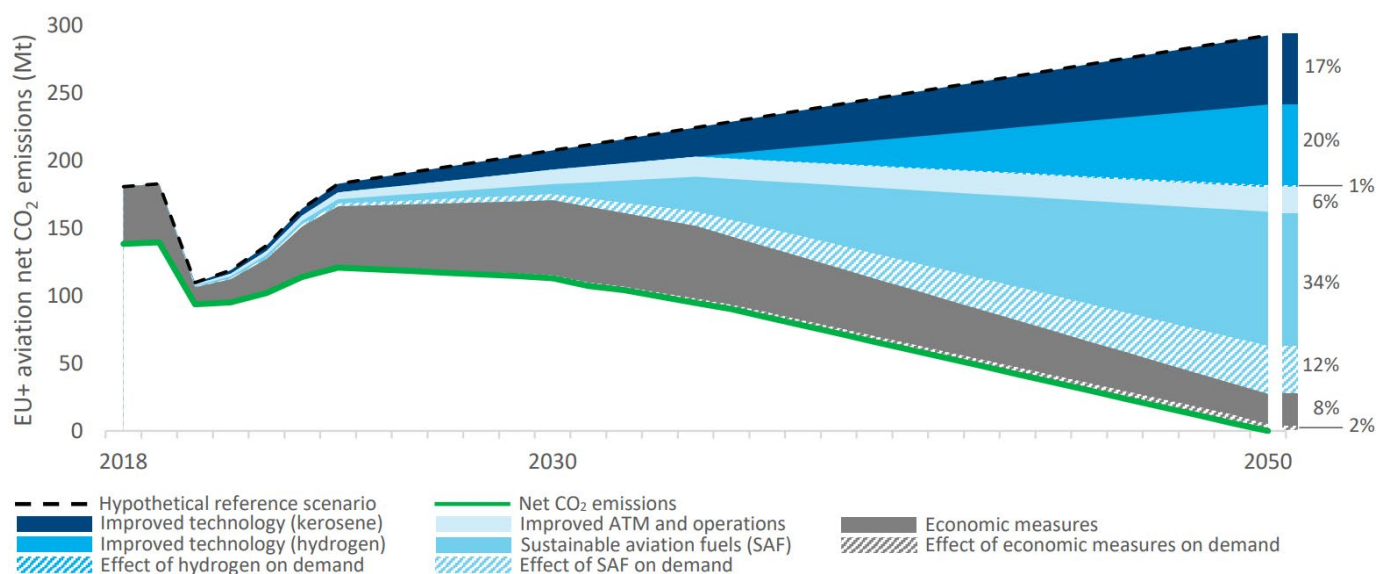


Figure 9.5: Decarbonisation Roadmap for European Aviation. Image: Destination 2050 ²³⁵

Results are presented for all flights within and departing from the EU region (EU, UK and EFTA). Improving aircraft and engine technology, ATM and aircraft operations, SAF and economic measures all hold decarbonisation potential. Modelled for 2030 and 2050, the impacts are linearly interpolated. The base year for this study is 2018.

²³¹ ICAO Resolution A40-18: ‘Consolidated statement of continuing ICAO policies and practices related to environmental protection - Climate change’ <https://www.icao.int/environmental-protection/pages/climate-change.aspx>

²³² ‘States adopt net-zero 2050 global aspirational goal for international flight operations’, ICAO 7/10/22 <https://www.icao.int/Newsroom/Pages/States-adopts-netzero-2050-aspirational-goal-for-international-flight-operations.aspx>

²³³ ‘Aviation and the EU ETS’, EC, https://ec.europa.eu/clima/eu-action/european-green-deal/delivering-european-green-deal/aviation-and-eu-ets_en

²³⁴ See https://www.iata.org/en/about/worldwide/asia_pacific/What-is-CORSIA/

Other aviation organisations have taken a similar approach:

- Europe's aviation sector has launched 'Destination 2050', a plan to reach net zero European aviation CO₂ emissions by 2050.²³⁵
- The UK's aviation sector, represented by Sustainable Aviation, a UK industry membership body, has launched interim decarbonisation targets of at least 15% by 2030 and 40% by 2040, having reaffirmed their commitment to net-zero by 2050.²³⁶
- Members of the International Air Transport Association (IATA) agreed to commit to net zero by 2050 at their annual general meeting in 2021.²³⁷

The UK Climate Change Committee has now included aviation and shipping in the Sixth Carbon Budget requirement, now incorporated into UK law, to achieve 78% reduction in emissions between 1990 and 2035.²³⁸ The Jet Zero Council was launched by government in 2020 "with the aim of delivering zero-emission transatlantic flight within a generation, driving the ambitious delivery of new technologies and innovative ways to cut aviation emissions".²³⁹ This is much more ambitious, seeking to eliminate the problem rather than offset it.

Aviation (together with international shipping) is not included within the UNFCCC and so not covered by the Paris Agreement, because it has been difficult to apportion international travel to individual countries.²⁴⁰ Where emissions are attributed, typically the emissions of each flight leaving a country are attributed to that country.

The UK composites sector has a unique opportunity to support the route to zero carbon aviation through structural weight reduction and provision of safe, durable and lightweight hydrogen storage.

9.8 Summary

Policy and legislation in the UK and Europe is developing rapidly in all areas related to sustainability. In many cases, this provides opportunities for composites, such as materials for hydrogen storage and renewable energy and lighter weight materials for transport.

While regulations are not yet in place to provide LCA assessments for products, the frameworks now exist for those to be implemented, and requirements for reporting company GHGs will soon be extended to smaller companies as well as larger ones. Regulations on chemical content are well-developed, and require compliance, especially in the area of resin chemicals and constituents. EOL regulations are steadily moving in the "polluter pays" direction, putting pressure on the composites industry to scale up EOL solutions.

Emissions regulation for road vehicles in the UK is well developed, with new cars and vans using petrol or diesel to be phased out by 2035. While global aspirational goals exist, the pathway to net zero for aviation is much more challenging, though the UK has now adopted aviation and shipping in the Sixth Carbon Budget.

²³⁵ Destination 2050: – A route to net zero European aviation', February 2021 <https://www.destination2050.eu>

²³⁶ 'UK aviation industry strengthens commitment to achieving net zero and launches first interim decarbonisation targets' June 2021 <https://www.sustainableaviation.co.uk/news/uk-aviation-industry-strengthens-commitment-to-achieving-net-zero-and-launches-first-interim-decarbonisation-targets/>

²³⁷ 'Our Commitment to Fly Net Zero by 2050', IATA, 2021 <https://www.iata.org/en/programs/environment/flynetzero/>

²³⁸ 'UK enshrines new target in law to slash emissions by 78% by 2035' April 2021 <https://www.gov.uk/government/news/uk-enshrines-new-target-in-law-to-slash-emissions-by-78-by-2035>

²³⁹ Jet Zero Council <https://www.gov.uk/government/groups/jet-zero-council>

²⁴⁰ 'Aviation & carbon emissions: pressure grows for net zero', CAPA, June 2019 <https://centreforaviation.com/analysis/reports/aviation--carbon-emissions-pressure-grows-for-net-zero-475985>

10. NEXT STEPS AND FUTURE DEVELOPMENTS

Author: Stella Job

The state of our planet and its capacity to remain stable under the increasing pressure of human civilisation has become a matter of urgent attention. We are in a period of rapid change in relation to all aspects of sustainability good practice, and despite the authors' best efforts, this guide will almost certainly be out of date before it is published. The challenge for composites companies is, and will remain, to keep up with this rapid rate of change and contribute positively towards it.

10.1 Short-, medium- and long-term vision

Each organisation needs a vision of a sustainable future with composites and an action plan to accelerate progress towards that in the areas they control (internal) and to seek ways to inspire and bring change in the areas they can influence (external), especially areas that constrain or enable sustainable development. We need both vision and action and also perspective for different timescales. It is important to keep the long-term vision in view as we plan for the short and medium term.

*Composite materials
have a strategic part to
play in reaching net zero.*

Short term: What can my organisation do within the next 12 months to actively reduce impact?

The primary short-term needs are for knowledge sharing of good practice, understanding the impact of products we make now and designing for more circular products. Manufacturers can adopt recycled or bio-based materials that are already available, supporting the growth of sustainable material supply chains, and can implement practical ways to reduce waste and energy use. Work could also begin on an environmental management system or a sustainability certification.

Medium term: What can be done in the next two to five years to make more significant progress?

This is likely to include significant research and development, adopting new processes, working with clients to make a part more recyclable or lighter, helping them understand what is possible and using sustainability metrics that incentivise the best solutions. There may be a standards committee that is appropriate for your organisation to join, to ensure that new and revised standards allow for innovation, or consultations on pending regulations your company can contribute to, so they do not have unintended negative consequences. It could also require working with other areas of industry, such as waste management companies who can enable large scale recycling routes, or developing new business models that stimulate adoption of cleaner or more circular technology. At every level significant progress will involve collaboration.

Long term: What can be done for the long-term future of our planet, thinking five or more years ahead?

Accelerating these short- and medium-term changes will reduce the damage done to our environment for the longer term and keeping a long-term perspective is vital so we do not over-focus on a quick win which limits the opportunity to move to a better future solution. The composites industry needs to understand the disruptive emerging technologies which will create a better future for everyone and step in quickly to provide the material solutions to accelerate their uptake. Moving to bio-based materials and achieving much more efficient recycling of materials that can't be bio-based, to create a much more circular composites value chain, are ultimately essential, as mineral and fossil resources will otherwise run out.

10.2 Technical solutions

The most significant area for composites to make a contribution is enabling the technologies for sustainable long term future solutions. Composites have already provided the only viable solutions for blades for large scale wind turbines. They are

critical to lightweight structures for transport and pressure vessels for a hydrogen economy. They also provide parts for cryogenic applications in fusion reactors. But we still need to keep working on the challenges of reducing the impact of our own material sources and manufacturing, and making our composite products more circular. These challenges include:

- **Zero-carbon carbon fibre:** Using bio-based PAN precursor chemicals, lower processing energy and renewable energy sourcing, carbon fibre could become a completely renewable high-performance material.
- **Bio-based resins:** As we increasingly source our resin chemicals from bio-feedstocks, we will avoid fossil fuel-based emissions when materials are combusted at EOL as well as decoupling material prices from oil prices and availability.
- **Design for sustainability:** Good design practice needs to take into account sustainable material sourcing, efficient manufacturability, repair, refurbishment and EOL considerations, as well as incentivising more sustainable business models.
- **Resource and energy efficient manufacturing:** Low or no waste, net shape manufacturing and efficient processes powered by low or fully renewable energy will move us significantly closer to a net zero position.
- **High value recovery of resin chemicals:** The value of chemicals will be maintained in the economy as much as possible, as well as reducing CO₂ emissions, as we improve recovery techniques rather than combusting resins at EOL.
- **Raising the value of recovered fibres:** We have processes today to recover fibres from manufacturing or EOL scrap, but we need to improve these further so that we make intermediate materials that industry can easily use in appropriate markets and that are price competitive with virgin fibres.

10.3 Communication, coordination, collaboration

Sustainable development is heavily influenced by external factors. The economic situation, public opinion and market pull, and government policy and legislation may seem the most difficult to change. The availability and relevance of standards and data, supply chain factors and financing and business models are closer, but are often still difficult to impact. Any of these can make or break a potential sustainable innovation.

In each case there are actions the composites industry can take to influence these macro-factors, and so more effectively accelerate sustainable development while maximising the opportunities that arise.

To support this influencing and acceleration of sustainable developments, Composites UK is committed to continue, and increasingly invest more in, their role to:

- **Communicate** with members and the wider industry about new developments, opportunities to contribute to standards and policy, sharing good practice and providing platforms to educate and inspire one another.
- **Coordinate** strategic activities through its subgroups and the Composites Leadership Forum, where it provides the secretariat and plays a major role in decarbonisation and circularity initiatives, including workshops and focused studies which identify gaps and strategic areas to progress, help build collaborations and find funding.
- **Collaborate** with members, other trade associations, funding bodies, government, academia, Catapult centres and hundreds of organisations across the world to accelerate the contribution of composites to sustainable growth.



Figure 10.1: Influencing the macro-factors.
Image: Stella Job

10.4 Join us in shaping the change

Change on a scale that is hard to imagine is not only possible, but will happen. Our opportunity is to shape the direction in which this change happens. You are therefore warmly encouraged and invited to join the Composites UK Sustainability Subgroup, the NCC and the Composites Leadership Forum in working towards their vision of:

“a future where ultra-light weight, high performance composite products and durable, repairable composite structures contribute to a sustainable environment, sustainable society and sustainable economy. Zero or negative CO₂ composite manufacturing will no longer use virgin petrochemicals, will turn waste back into raw materials and will have predominantly local material supply chains, reducing our impact on the planet for our generation and all future generations.” ²⁴¹

Thank you for reading this far and good luck in your future sustainability journey!

²⁴¹ ‘A Vision and Roadmap for Sustainable Composites’, Composites UK, 2019 <https://compositesuk.co.uk/industry-support/environmental/sustainable-composites-roadmap/>

APPENDIX 1: GLOSSARY & TERMINOLOGY

In alphabetical order by term, so acronyms are not all in order. Abbreviations for chemicals have generally not been included but are explained in the text.

Acronym	Term ^	Definition
APCr	Air pollution control residue	Contaminants which are removed as a solid ash from combustion exhaust, e.g. in an energy from waste facility
	B Corp	B Corp Certification is a designation that a business is meeting high standards of verified performance, accountability, and transparency on factors from employee benefits and charitable giving to supply chain practices and input materials
BREEAM	BRE Environmental Assessment Method	International sustainability assessment, rating and certification scheme for buildings
BIM	Building Information Modelling	System for tracking information for buildings and infrastructure assets from design stage, through construction management and facility operation.
BRE	Building Research Establishment	A former UK government national laboratory for building science that was privatised in 1997 and provides research, advice, training, testing, certification and standards for both public and private sector organisations
BMC	Bulk moulding compound	Intermediate material consisting of fibres, resin and fillers, mixed and supplied ready for use in compression or injection moulding. Sometimes also referred to as dough moulding compound (DMC)
CV	Calorific value	i.e. the energy contained in a material, or heat produced by the complete combustion of a specified quantity of it, usually measured in MJ/kg
CO ₂	Carbon dioxide	A gas which used to be in Earth's atmosphere at a concentration of 180 to 300 ppm for 800,000 years, but over the last 100 years has increased to around 420 ppm, primarily due to humans burning fossil fuels. It is a greenhouse gas.
CO ₂ e	Carbon dioxide equivalent	Often used in climate metrics where greenhouse gases other than carbon dioxide contribute to the impact, but their impact is normalised to the impact of the same mass of carbon dioxide.
CFRP	Carbon fibre reinforced polymer	
	Carbon offset	A reduction in CO ₂ (or other GHG) emissions or removal of CO ₂ from the atmosphere in order to compensate for CO ₂ (or other GHG) emissions elsewhere
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation	A scheme developed as part of achieving the ICAO commitment to stabilise CO ₂ emissions. Emissions are monitored and carbon offsets are purchased to compensate for growth above 2019 levels.
	Chemical recycling	A term used in the plastics industry for processes which “convert polymeric waste by changing its chemical structure to produce substances that are used as products or as raw materials for the manufacturing of products. Products exclude those used as fuels or means to generate energy.” This may include pyrolysis and solvent based processes. [more info]
CE	Circular Economy	“an alternative to a traditional linear economy (make, use, dispose) in which we keep resources in use for as long as possible, extract the maximum value for them while in use, then recover and regenerate products and materials at the end of each service life” (WRAP) or A model of production and consumption, which involves sharing, leasing, reusing, repairing, refurbishing and recycling existing materials and products as long as possible. In practice, it implies reducing waste to a minimum. (European Parliament)

Acronym	Term ^	Definition
CEEQUAL	Civil Engineering Environmental Quality Assessment and Award Scheme	International sustainability assessment, rating and awards scheme for civil engineering, infrastructure, landscaping and works in public spaces
CCA	Climate Change Agreement	Voluntary agreement made between UK industry and the Environment Agency to reduce energy use and carbon dioxide emissions. In return, operators receive a discount on the Climate Change Levy (CCL) energy tax.
CCC	Climate Change Committee	An independent non-departmental public body, formed under the Climate Change Act to advise the United Kingdom and devolved Governments and Parliaments on tackling and preparing for climate change.
CCL	Climate Change Levy	A tax added to electricity and fuel bills for businesses
	Composite material	Material composed of at least two materials, which combine to give properties superior to those of the individual components. This Guide refers mainly to fibre reinforced polymer composites.
CLF	Composites Leadership Forum	A forum supported by BEIS, chaired by industry with members drawn from industry sector groups, government, funding bodies and other stakeholders to bring together support for composites and ensure growth and industrial success for the UK
COBie	Construction Operations Building Information Exchange	A non-proprietary data format for the publication of a subset of building information models (BIM) focused on delivering asset data as distinct from geometric information.
COSHH	Control of substances hazardous to health	UK regulation that requires employers to control substances that are hazardous to health
CSR	Corporate Social Responsibility	A management concept whereby companies integrate social and environmental concerns in their business operations and interactions with their stakeholders
Defra / DEFRA	Department for Environment, Food and Rural Affairs	UK government department
BEIS	Department for Business, Energy and Industrial Strategy	UK government department
DfT	Department for Transport	UK government department
D4S	Design for sustainability	
DPP	Digital Product Passport	Proposed as part of ESPR to hold data on materials, information on repair, etc. to be shared across entire value chains so all actors, including consumers, have a better understanding of the materials and products used and their environmental impact, making it easier to repair or recycle products.
EMAS	Eco-Management and Audit Scheme	A voluntary environmental management tool for companies and other organisations to evaluate, report and improve their environmental performance [more info]
ESPR	Ecodesign for Sustainable Products Regulation	Proposed EC regulation to address product design, to make products more durable, reliable, reusable, upgradable, repairable, easier to maintain, refurbish and recycle, and energy and resource efficient.
EOL	End of life (n.) or end-of-life (adj.)	(At) the point at which a substance or object is classed as waste, i.e. the holder discards or intends or is required to discard it
ELV	End-of-life Vehicle	Also referring to the EU Directive 2000/53/EC to prevent and limit waste from end-of-life vehicles (ELVs) and their components by ensuring their reuse, recycling and recovery [more info]
EFW	Energy from waste	Referring to incineration plants which take various wastes, often processed and referred to as RDF, and convert them into energy – electricity and/or heat). By-products are IBA and APCr.

Acronym	Term ^	Definition
ESOS	Energy Savings Opportunity Scheme	Every four years audits are required of the energy used by buildings, industrial processes and transport to identify cost-effective energy saving measures.
EMS	Environmental management system	A set of processes and practices that enable an organization to reduce its environmental impacts and increase its operating efficiency [more info]
EPD	Environmental Product Declaration	A short document that describes how a product impacts the environment, that can be used as proof of a products' environmental credentials, a form of Type III Environmental Declaration according to ISO 14025
ESG	Environmental, Social and Governance	Referring to rating systems for these factors to identify investment risks
ECHA	European Chemicals Agency	The agency of the EU which regulates the safe use of chemicals [more info]
EC	European Commission	
EU	European Union	
EU ETS	EU Emissions Trading Scheme	A "cap and trade" scheme where a limit is placed on the right to emit specified pollutants over an area and companies can trade emission rights within that area. [more info]
EuCIA	European Composites Industry Association	Trade association headquartered in Brussels which represents European national composite associations as well as industry-specific sector groups at EU level [more info]
FRP	Fibre reinforced polymer	
FVF	Fibre volume fraction	Proportion of fibres in a composite, which can be much higher if the fibres are well aligned, resulting in a composite with better mechanical properties
FST	Fire, smoke and toxicity	Referring to a range of properties / tests to define a material's reaction to fire. (Fire resistance refers to a different group of properties.)
	Fluidised bed	A process where a fluid, typically a gas, is passed through a bed of solid particles, e.g. sand, causing the particles to behave like a fluid. It is used in chemical processes and in the efficient burning of coal or wastes for power generation.
GFRP or GRP	Glass fibre reinforced polymer	
GRI	Global Reporting Initiative	The most-used standards for sustainability reporting, freely available, divided into four groups: Universal, Economic, Environmental and Social.
GWP	Global warming potential	A metric used to quantify climate warming impact, it is the radiative forcing (energy flux per unit area into earth's atmosphere) integrated (summed up) over a defined timescale (100 years for GWP ₁₀₀). GWP is typically measured in kg or t CO ₂ e.
GHG	Greenhouse gas	A gas that absorbs and emits radiant energy within the thermal infrared range, causing the greenhouse effect, trapping heat in the earth's atmosphere. The primary greenhouse gases in Earth's atmosphere are water vapour (H ₂ O), carbon dioxide (CO ₂), methane (CH ₄), nitrous oxide (N ₂ O), and ozone (O ₃).
HVMC	High Value Manufacturing Catapult	A group of seven manufacturing research centres across the UK, part of the wider Catapult network set up by the UK government research agency, Innovate UK.
IBA	Incinerator bottom ash	Ash resulting from incineration, e.g. in EfW plants. May contain concrete, ceramics, glass, brick, clinker, some metals and fused material particles, and is often recycled into aggregate.
IRF	Integrated Reporting Framework	Sustainability reporting standards which recognize that organisations draw on different resources which are referred to as the Capitals: Financial, Manufactured, Natural, Human, Social, Intellectual.
ICVCM	Integrity Council for the Voluntary Carbon Market (Integrity Council)	Independent governance body for the voluntary carbon market, setting and enforcing definitive global threshold standards for high-quality carbon credits.

Acronym	Term ^	Definition
IP	Intellectual property	Property which is created by the human mind and may include inventions, brands, written work or designs, often protected through patents, trademarks, copyright, registered design.
IPCC	Intergovernmental Panel on Climate Change	The UN body responsible for advancing knowledge on human-induced climate change.
IATA	International Air Transport Association	Trade association of the world's airlines
ICAO	International Civil Aviation Organization	The United Nations agency developing policy and standards, for member nations to apply as regulation, for aviation.
IMO	International Maritime Organization	The United Nations agency developing policy and standards, for member nations to apply as regulation, for shipping.
ISSB	International Sustainability Standards Board	Set up in November 2021 as part of International Financial Reporting Standards to deliver a comprehensive global baseline of sustainability-related disclosure standards that provide investors and other capital market participants with information about companies' sustainability-related risks and opportunities to help them make informed decisions. Several other reporting standards have been consolidated into ISSB, including IRF, CDSB and SASB.
LEED	Leadership in Energy and Environmental Design	A green building certification program developed by the U.S. Green Building Council
LCA	Life cycle assessment	A methodology for assessing environmental impacts associated with all the stages of the life cycle of a commercial product, process, or service, or a clearly defined subset of these stages.
LCC	Life cycle costing	Assessment of all the costs that will be incurred throughout the life cycle of a product, process, or service
LCIA	Life cycle impact assessment	Stage in LCA where the inputs and outputs from the LCI are grouped into respective categories, and their environmental effects are quantified
LCI	Life cycle inventory	In LCA, this is the list of all inputs and outputs to / from the system, related to environmental impact
LCSA	Life cycle sustainability assessment	The evaluation of all environmental, social and economic impacts throughout the life cycle of a product, process, or service
MSW	Municipal solid waste	Waste consisting of everyday items that are discarded by the public and may be collected from homes, schools, businesses, hospitals, etc.
NCC	National Composites Centre	An independent, open-access technology centre delivering world-class research and development of composites, part of the HVMC
NNS	Near net shape	Referring to processes that aim for the initial fabrication of a component to be close in size and shape to the finished product, thus minimising waste
	Net Zero	A target (for an organisation, region or country) of completely negating the amount of greenhouse gases produced by human activity, to be achieved by reducing emissions and implementing methods of absorbing carbon dioxide from the atmosphere.
NFRD	Non-Financial Reporting Directive	Directive covering reporting of non-financial details, including climate risk and mitigation, social responsibility, etc, in annual reports
OLEV	Office for Low Emission Vehicles	A team working across UK government to support development of low emission vehicles
OEFCRs	Organisation Environmental Footprint Category Rules	A harmonised methodology for the calculation of the environmental footprint of organisations as part of the EC's Circular Economy Action Plan
OEM	Original equipment manufacturer	Technically a company that produces parts and equipment, but use may be ambiguous, often referring to an end-product producer or prime.

Acronym	Term ^	Definition
	Paris Agreement	An international treaty on climate change, adopted at the 2015 United Nations Climate Change Conference (COP21) in Paris, with a key element being the long-term temperature goal to keep the rise in mean global temperature to well below 2 °C (3.6 °F) above pre-industrial levels, and preferably limit the increase to 1.5 °C (2.7 °F). As of November 2021, The EU and 192 states, totalling over 98% of anthropogenic emissions, have ratified or acceded to the Agreement.
PAN	Polyacrylonitrile	Polymer which is used, in fibre form, as the precursor for most carbon fibre manufacturing. (Also used in clothing textiles)
PCR	Product category rules	Rules to enable comparative LCA for a specific category of products
PEFCRs	Product Environmental Footprint Category Rules	A harmonised methodology for the calculation of the environmental footprint of products as part of the EC's Circular Economy Action Plan
PLM	Product lifecycle management	The process of managing manufactured products from design through manufacture, operation and disposal. Often referring to software to manage this
RFID	Radio frequency identification	System using electromagnetic fields to automatically identify and track tags attached to objects
rCF	Recycled (or recovered) carbon fibre	
rGF	Recycled (or recovered) glass fibre	
RDF	Refuse derived fuel	Fuel from waste sources, typically less refined and not as efficient as a fuel compared to SRF.
REACH	Registration, Evaluation, Authorisation and restriction of Chemicals	Regulations for monitoring chemicals, operated by ECHA [more info]
ROI	Return on investment	
SBTi	Science Based Targets initiative	A collaboration between CDP, the United Nations Global Compact, World Resources Institute (WRI) and the World Wide Fund for Nature (WWF) to help companies to set emission reduction targets in line with climate science and Paris Agreement goals
	Scope 1, 2, 3 emissions	Scope 1 GHG emissions are direct emissions from owned or controlled sources. Scope 2 GHG emissions are indirect emissions from the generation of purchased energy. Scope 3 GHG emissions are all indirect emissions (not included in Scope 2) that occur in the value chain of the reporting company, including both upstream and downstream emissions. "
SMC	Sheet moulding compound	Intermediate material where fibres are chopped onto a resin/ filler paste on a carrier film, and another layer of resin/filler paste is extruded over the fibres. It is supplied in sheet form ready for compression moulding.
SME	Small to medium sized enterprise	An SME is any organisation that has fewer than 250 employees and a turnover of less than €50 million or a balance sheet total less than €43 million. [more info]
S-LCA	Social life cycle assessment	Assessment of social impacts, for example, working conditions, human rights, local communities, health and safety, etc.
SRF	Solid recovered fuel	Fuel from waste sources, shredded typically to around 25 to 50 mm pieces, used to replace fossil fuels at large industrial installations such as cement kilns, power stations or blast furnaces. Specifications are tightly controlled and covered by a range of BS/EN standards.
SECR	Streamlined Energy and Carbon Reporting	Requirement to report UK energy use and associated greenhouse gas emissions as a minimum relating to gas, electricity and transport fuel, as well as an intensity ratio and information relating to energy efficiency action, through company annual reports. (For quoted and large companies)

Acronym	Term ^	Definition
SVHC	Substance of very high concern	According to the ECHA Candidate List [more info]
SASB	Sustainability Accounting Standards Board	Sustainability reporting standards which focus on information impacting financial performance and feature multiple standards for different industries.
SCIP	Substances of Concern In Products	The database for information on Substances of Concern In articles as such or in complex objects (Products) established under the WFD [more info]
	Sustainable	There are many definitions. For example: Working in balance with natural systems so that there is not a systematic degradation of these systems which are essential to the continuation of all life on Earth or Meeting the needs of the present without compromising the ability of future generations to meet their own needs
SAF	Sustainable aviation fuel	A common term for synthetic aviation fuels derived from waste, crops or captured carbon dioxide, combined with green hydrogen.
SDGs	Sustainable Development Goals	17 goals, targets and indicators set up in 2015 by the UN, that UN member states are expected to use to frame their agendas and political policies over the 15 years to 2030. They follow the 8 Millennium Development Goals from 2000 to 2015. [more info]
TCFD	Taskforce on Climate-related Financial Disclosures	TCFD is a taskforce set up by the G20 Financial Stability Board, and also refers to the TCFD's globally recognised framework for disclosing exposure to transition and physical climate risks as well as strategy to both mitigate these risks and harness opportunities to decarbonise. Since April 2022 TCFD disclosures are required for very large companies in the UK and are expected to be required for all companies by 2025.
TIMWOODS	Transportation, Inventory, Motion, Waiting, Over-production, Over-processing, Defects, Skills	An acronym for “the 8 wastes of lean”, which summarize how value can be lost in any manufacturing process through a variety of different inefficiencies or wastes
UD	Unidirectional	Referring to aligned fibre nonwoven fabrics
UN	United Nations	The United Nations is an intergovernmental organization whose purposes are to maintain international peace and security, develop friendly relations among nations, achieve international cooperation, and be a centre for harmonizing the actions of nations.
UNFCCC	United Nations Framework Convention on Climate Change	“The parent treaty of the 1997 Kyoto Protocol and the 2015 Paris agreement, now with near universal membership (197 Parties)
UPR	Unsaturated polyester resin	Polymer commonly used in GFRP products
VSM	Value Stream Mapping	A lean-management method for analysing the current state and designing a future state for the series of events that take a product or service from the beginning of the specific process until it reaches the customer.
WEEE	Waste Electrical and Electronic Equipment	Also referring to the EU Directive 2012/19/EU which set collection, recycling and recovery targets for all types of electrical goods [more info]
WFD	Waste Framework Directive	EU Directive 2008/98/EC concerned with “measures to protect the environment and human health by preventing or reducing the adverse impacts of the generation and management of waste and by reducing overall impacts of resource use and improving the efficiency of such use” [more info]

Acronym	Term ^	Definition
ZLEV	Zero or low emission vehicles	

APPENDIX 2: STANDARDS

This table lists standards and guidance documents which are referenced in this good practice guide or relevant to the content. These are constantly being updated so it is important to check that the most recent version is being used. The list is not exhaustive.

Reference	Description
Circular Economy	
BS 8001:2017	Framework for implementing the principles of the circular economy in organizations. Guide
Technical Committee ISO/TC 323	A range of international standards on circular economy are under development [more info]
Design for manufacture, assembly, disassembly and end-of-life processing (MADE)	
BS 8887-1:2006 (also ISO 8887-1:2017)	Design for MADE: General concepts, process and requirements
BS 8887-2:2009	Design for MADE: Terms and definitions
BS 8887-3:2018	Design for MADE: Guide to choosing an appropriate end-of-life design strategy
BS 8887-220:2010	Design for MADE: The process of remanufacture. Specification
BS 8887-240:2011	Design for MADE: Reconditioning
Quality management systems	
ISO 9001:2015	Quality management systems — Requirements <i>[Advice and resources from BSI]</i>
Environmental management systems	
ISO 14001:2015	Environmental management systems. Requirements with guidance for use. <i>[Advice and resources from BSI]</i>
ISO 14004:2016	Environmental management systems. General guidelines on implementation
ISO 14005:2019	Environmental management systems — Guidelines for a flexible approach to phased implementation <i>For SMEs, to meet the requirements for an EMS in a phased, flexible way</i>
ISO 14006:2020	Environmental management systems — Guidelines for incorporating ecodesign
ISO 14009:2020	Environmental management systems — Guidelines for incorporating material circulation in design and development <i>For all ISO standards in this category see ISO/TC 207/SC 1</i>
Environmental labelling	
ISO 14020:2000	Environmental labels and declarations — General principles
ISO 14021:2016	Environmental labels and declarations — Self-declared environmental claims (Type II environmental labelling) <i>Type II is self-declared</i>
ISO 14024:2018	Environmental labels and declarations — Type I environmental labelling — Principles and procedures <i>Type I relates to programmes which award a licence</i>
ISO 14025:2006	Environmental labels and declarations — Type III environmental declarations — Principles and procedures <i>Type III is externally qualified data, categorised for products</i>
ISO 14026:2017	Environmental labels and declarations — Principles, requirements and guidelines for communication of footprint information
ISO/TS 14027:2017	Environmental labels and declarations — Development of product category rules <i>For all ISO standards in this category see ISO/TC 207/SC 3</i>
Life cycle assessment	
ISO 14040:2006 AMD 1:2020	Environmental management — Life cycle assessment — Principles and framework
ISO 14044:2006 AMD 1:2017 , AMD 2:2020	Environmental management — Life cycle assessment — Requirements and guidelines <i>For all ISO standards in this category see ISO/TC 207/SC 5</i>
BS EN 15804:2012+A2:2019	Sustainability of construction works. Environmental product declarations. Core rules for the product category of construction products

Reference	Description
BS EN 15942:2021	Sustainability of construction works - Environmental product declarations - Communication format business-to-business
PEFCR Guidance Version 6.3 – May 2018	Product Environmental Footprint Category Rules Guidance
Social value and social life cycle assessment	
BS 8950:2020	Social value. Understanding and enhancing. Guide
ISO/AWI 14075 (under development)	Principles and framework for social life cycle assessment
Greenhouse gas emissions	
ISO 14064 Part 1:2018 Part 2:2019 Part 3:2019	Greenhouse gases Part 1: Specification with guidance at the organization level for quantification and reporting of greenhouse gas emissions and removals Part 2: Specification with guidance at the project level for quantification, monitoring and reporting of greenhouse gas emission reductions or removal enhancements Part 3: Specification with guidance for the verification and validation of greenhouse gas statements
	<i>For all ISO standards in this category, relating to greenhouse gas emissions, reductions, removals, verification, see ISO/TC 207/SC 7</i>
Greenhouse Gas Protocol standards	Product life cycle accounting and reporting standard Corporate accounting and reporting standard Corporate value chain (scope 3) accounting and reporting standard
PAS 2050:2011	Specification for the assessment of the life cycle greenhouse gas emissions of goods and services <i>PAS2050 and GHG Protocol Product Standard are generally aligned. PAS 2050 includes requirements for recording while the GHG Protocol standard includes requirements for public reporting. The minor differences are listed here.</i>
PAS 2060:2014	Specification for the demonstration of carbon neutrality
IAEG guidance and tool	GHG Reporting Guidance for the Aerospace Industry – A Supplemental to the GHG Protocol Accounting and Reporting Standard
Product marking	
ISO 1043 Part 1:2011 Part 2:2011 Part 3:2016 Part 4:2021	Plastics — symbols and abbreviated terms. Part 1: Basic polymers and their special characteristics Part 2: Fillers and reinforcing materials Part 3: Plasticizers Part 4: Flame retardants
ISO 11469:2016	Plastics — Generic identification and marking of plastic products
Bio-based products, compostability and biodegradability	
PAS 600:2013	Bio-based products. Guide to standards and claims
ISO 16620 Part 1:2015 Part 2:2019 Part 3:2015 Part 4:2016 Part 5:2017	Plastics — Biobased content Part 1: General principles Part 2: Determination of biobased carbon content Part 3: Determination of biobased synthetic polymer content Part 4: Determination of biobased mass content Part 5: Declaration of biobased carbon content, biobased synthetic polymer content and biobased mass content
BS EN 16575:2014	Bio-based products. Vocabulary
BS EN 16785-2:2018	Bio-based products. Bio-based content - Determination of the bio-based content using the material balance method
BS EN 17228:2019	Plastics. Bio-based polymers, plastics, and plastics products. Terminology, characteristics and communication
	<i>See CEN/TC 411 for more on determination and declaration of bio content</i>
	<i>See ISO/TC 61/SC 14 for more on compostability and biodegradability</i>
Recycled content and traceability	
BS EN 15343:2007	Plastics. Recycled plastics. Plastics recycling traceability and assessment of conformity and recycled content
Building information modelling	

Reference	Description
<u>ISO 19650</u> (Parts 1, 2, 3, 5)	Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM). Information management using building information modelling
<u>BS 1192-4:2014</u>	Collaborative production of information - Fulfilling employer's information exchange requirements using COBie. Code of practice <i>Likely to be replaced soon by <u>ISO 19650-4</u></i>
Energy management systems	
<u>ISO 50001:2018</u>	Energy management systems. Requirements with guidance for use [Free BSI guide]
End-of-life treatment	
<u>AFRA BMP Guide 5.0</u>	AFRA Best Management Practice for Management of Used Aircraft Parts and Assemblies and for Recycling of Aircraft Materials (BMP)
<u>IMI NOS for EOL vehicle recycling</u> April 2022	National Occupational Standards (NOS) for End-of-Life Vehicle Recycling

APPENDIX 3: D4S METHODOLOGY & CHECKLIST

Below is a non-exclusive checklist of things to consider in the early stages of design, and a suggested Design for Sustainability (D4S) methodology for using the checklist. The checklist is intended to stimulate thought on whether design could enhance sustainability in each category area. These are high level, but can be developed for an individual organisation's context. Ideally the D4S methodology will be integrated with open innovation methods and procedures for design for safety, cost and manufacture (D4X) which may already be in place.

Aspects of the checklist draw from [Ellen MacArthur Foundation's 'Building blocks of a circular economy'](#). Acknowledgements to Naresh Kumar for his "Check-a-tool" concept and to Bethany Hall, Rolls-Royce for developing a version of this tool with Stella Job in the Aerospace Technology Institute's [FlyZero](#) project.

D4S Checklist

Category	Consider	Notes
Efficient design	Material efficiency	Saves material impact, weight and cost
	Multi-functional materials	But multi-material solutions may be negative for recyclability
	Use of standardised components where appropriate	Usually lower impact due to economy of scale, easier to replace and potentially re-use
	Modularity and flexibility	Varies with context. Composites can enable part consolidation - how will this affect disassembly / recycling?
	Features which promote or enable sustainable use behaviours	Such as automatic control systems to reduce energy use
Raw materials	Embodied energy from extraction and processing	LCA models will inform this and highlight hotspots in upstream supply chains
	Potential to include recycled or bio-based content	Not always lower impact, consider trade-offs, e.g. with weight
	Security of supply or unethical sourcing	
	Hazardous / toxic materials, subject to REACH, etc.	
Efficient manufacture	Understand manufacturing processes to inform efficient design	

Category	Consider	Notes
	Material efficient processes, including (near) net shape processing	
	Low energy processing	
	Minimise supply chain steps where possible / beneficial	Each step in the supply chain adds energy, waste and transport
	Potential for use of by-products (scrap)	Ideally in-house, or business to business
Use phase	Lifetime of component and durability / reliability	Long life typically means lower impact
	Potential for refurbishing / re-use of parts	If applicable, design to enable re-use; in-use monitoring may support this
	Ability to be easily maintained and repaired	Consider joining / disassembly and access
	Minimise spread of disease	e.g. anti-microbial materials
End of life	Understand how a part will be recycled / disposed of at end of life (EOL)	Important to understand and inform design
	Joining, etc to allow easier disassembly	
	Use of hybrid materials	Could reduce recyclability
	Effect of manufacturing processes, paints & coatings, etc	Could reduce recyclability
	Toxicity of materials released at EOL (SCIP)	Consider what happens to nano-material additives, fire retardants, etc
	If organics will be combusted at EOL, could they be bio-sourced?	
	Tagging to enable sorting, disassembly info and higher value recycling	RFID or other marking, could be integrated with digital twin.
Business models	Consider emerging business models which lend themselves to more circular or sustainable solutions	New business models can inspire and incentivise a sustainable approach. How can the product allow for and enable these?
Enablers and favourable system conditions	Influence of government policy (UK and international)	Engage in policy consultations which will effectively incentivise the most sustainable solutions.
	Identify standards and data sources needed to enable more sustainable solutions	

Category	Consider	Notes
	Feed into roadmaps to inform government funding priorities and accelerate development	Especially where novel technologies could improve solutions
	Understand and working with supply chains to enable rapid development of sustainable solutions	

D4S methodology

A suggested methodology for using the checklist is presented here, to be adapted for use in a specific design application. This could be accompanied by wider training in design for sustainability, circular economy and life cycle assessment as appropriate.

Initial workshop:

1. Set a date for an initial workshop, or workshops if the product is complex and merits breaking into smaller groups. Involve key designers and other stakeholders if appropriate.
2. In advance of the workshop:
 - a. Sustainability leader edits the checklist categories to be appropriate for the application.
 - b. Introduce the concept and circulate the checklist, requesting attendees to spend 30 minutes considering topics where design could have positive or negative effects as they look through the checklist.
3. During the workshop, discuss pre-work and identify topics as you work through checklist – some categories may have several topics, some may have none, some topics may fit more than one category. For each topic:
 - a. Record a title and short description.
 - b. Assign an owner and accountability – very important!
 - c. Identify next steps, e.g. studies / data collection / simplified LCA. This may require external advice.

D4S value assessment:

4. Using a risk assessment type approach, scores can be given for each topic. This could be done within the workshop or separately by topic owners, e.g.
 - a. How much impact would addressing this have on sustainability improvement? (1=low impact; 5=high impact)
 - b. How difficult is it to address this? (may include design effort, cost, technology readiness) (1=very difficult; 5=very easy)
 - c. Multiply (a) and (b) to get a D4S score from 1 to 25. Use these scores to aid decision making on which topics to prioritise.

Follow-up work and workshop:

5. For the prioritised topics, owners / teams progress next steps work on integrating the D4S topic into the design.
6. After a suitable period, hold a follow-up workshop to review the D4S checklist with feedback from the outcomes of studies, etc.
7. Revise D4S scores as appropriate and make design decisions to carry into detailed design stage.
8. If appropriate, discuss with client / other stakeholders to align priorities, e.g. they may be willing to pay more for a significant sustainability improvement.

APPENDIX 4: LCA SOFTWARE PACKAGES

This list includes professional software for detailed LCA (e.g. GaBi, SimaPro, OpenLCA) as well as several simplified LCA tools for specific applications. Different software packages currently have differing levels of composites related data sets. It is therefore important to understand the data sets that are provided within the software to understand whether it will meet the project requirements.

Tool Name	Supplier	Main Database	Speciality?	Free?	Free trial
Athena EcoCalculator v3.71	Athena Sustainable Materials Institute	Environmental Impact Estimator	Construction - specifically commercial assemblies	Yes	N/A
Athena Pavement LCA	Athena Sustainable Materials Institute	Environmental Impact Estimator	Roadway designs	Yes	N/A
BEES v4.0	National Institute of Standards and technology	Bees	Construction	Yes	N/A
Brightway2	Ecological Systems Design	ecoinvent	No	Yes	N/A
CCaLC Tool	The University of Manchester	Multiple, including ecoinvent	No	Yes	N/A
CMLCA v5.2	Leiden University	No Database - have to download add-ins	No	Yes	N/A
Eco Audit	Ansys	Material Universe™ (includes LCA data) and ecoinvent	Integrates with material properties, cost and risk and with engineering tools	No	Yes
Eco-Bat v2.1	Haute Ecole D'Ingenierie et de Gestion du Canton de Vaud	Eco-Bat	Construction	No	No
Eco Impact Calculator	EuCIA	From SimaPro, therefore same as	Composites	Yes	N/A
ecoinvent Waste Disposal	Doka Life Cycle Assessments	ecoinvent	Waste management	No	Yes
EIME v3.0	CODDE	EIME	Electrical, mechanical and electronic products	No	Yes
EIO-LCA	Carnegie Mellon University	Unknown	Input-output LCA technique	No	Yes

Tool Name	Supplier	Main Database	Speciality?	Free?	Free trial
Environmental Impact Estimator	Athena Sustainable Materials Institute	Environmental Impact Estimator	Construction - specifically buildings	Yes	N/A
eVerdEE v2.0	ENEA	ENEA	No	Yes	N/A
eToolLCD	eTool	Life Cycle Strategies	Whole building LCA	No	Yes
GaBi v4	PE International GmbH University of Stuttgart	GaBi	No	No	Yes
GEMIS v4.4	Oeko-Institut	Unknown	Energy, transport, recycling and waste management	No	No
KCL-ECO v4.1	VTT	Unknown	No	No	No
LEGEP v1.2	LEGEP Software GmbH	LEGEP	Construction	No	Yes
LTE OGIP v5.0	t.h.e. Software GmbH	Unknown	Construction	No	No
One Click LCA	Bionova Ltd	Revit, IFC (BIM), Excel, gbXML etc	Construction	No	Yes
OpenLCA	GreenDeltaTC GmbH	Unknown	No	Yes	N/A
Qantis Suite v2.0	Qantis	Qantis	No	No	Yes
REGIS v2.3	Sinum AG	ecoinvent	No	No	Yes
SankeyEditor v3.0	STENUM GmbH	Unknown	No	No	Yes
SimaPro 7	Pre Consultants B.V.	Multiple, largest being ecoinvent	No	No	Yes
TEAM 4.5	Ecobilan	Unknown	No	Some	Yes
The Boustead Model v5.0.12	Boustead Consulting Ltd	The Boustead Model	No	No	Yes
The LCA Calculator	idc Naked Creativity	ecoinvent	No	No	Yes
Umberto 5.5	ifu Hamburg GmbH	Umberto Library	No	No	Yes

Tool Name	Supplier	Main Database	Speciality?	Free?	Free trial
USES-LCA	Radboud University Nijmegen	Unknown	Toxic impacts between substances	Yes	N/A
WRATE	UK Environment Agency	Unknown	Municipal waste management systems	No	Yes