New Materials &
Circular Economy Accelerator

Composite Materials: A Hidden Opportunity for the Circular Economy

CSR EUROPE

LEONARDO

BAX & COMPANY
VALUE FROM SCIENCE AND TECHNOLOGY

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1. Introduction

Russia's war on Ukraine has shed light on the **urgency for the European Union to become independent from external resources and accelerate the green transition**. In this context, the Commission has set a clear, transformational strategy for sustainable growth with the European Green Deal and the Circular Economy Packages, aimed at reaching **climate neutrality by 2050**.

The EU's transition to a Circular Economy will reduce pressure on natural resources, eliminate waste and pollution, and create jobs. However, **not all materials are equal when it comes to recycling**, and some, like composite materials, are still landfilled or incinerated, losing all functionality and value. **Developing sustainable circular approaches for composite materials remains challenging**.

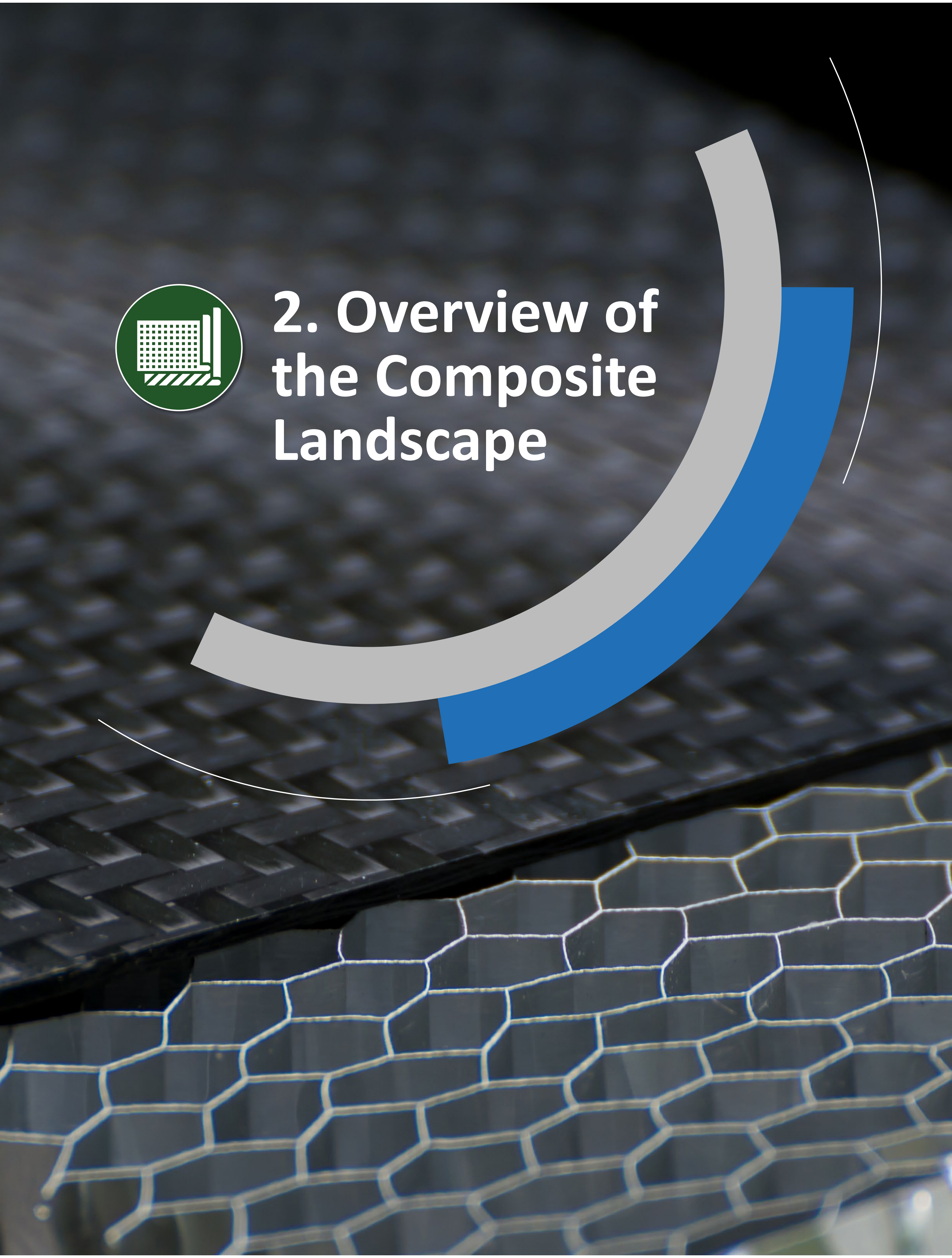
Fibre-reinforced composite materials (FRP) - used in the aerospace, automotive, wind energy, construction, and marine sectors – have a **low environmental impact in the use phase** due to their lightweight structures and energy savings properties. However, these advantages are **not yet matched throughout the lifecycle**.

Lifetime extension and product recovery are key elements in the Circular Economy of composite materials. It is estimated that product design determines up to **80% of the product's environmental impact over its lifecycle**. Yet, sustainable strategies at the design phase remain often undeveloped and undiscovered. Prejudices related to the circularity of composites materials still exist and make the current **technical, market, and regulatory barriers** even more difficult to overcome. Downgrading the material, the high costs associated with recycling processes, infrastructure scaling-up and virgin materials, as well as the lack of Life Cycle Assessments and product-related information are just some examples of this **fragmented ecosystem**.

This is why CSR Europe - the European leading network for Corporate Sustainability and Responsibility – launched the **"New Materials and Circular Economy Accelerator"** Think Tank in collaboration with **Leonardo**. This temporary Think Thank involved a wide range of stakeholders that collaborated between April and September 2022 to take stock of the challenges, opportunities, and key learnings to **increase the circularity of composite materials**. The learnings of the Think Tank's Working Group have been collected in this Blueprint.

The Blueprint is aimed at supporting companies and stakeholders in their efforts to **advance the circularity of composite materials and turning sustainability into a competitive advantage**. The document provides first a brief **overview of the composites sector** – types of materials, manufacturing technologies, application sectors, and state-of-play on circularity. Then, it delves into the **current challenges hindering the circularity of composites and identifies opportunities to address them**.

The input presented in this document was collected through the New Materials & Circular Economy Accelerator, literature research, as well as the network of knowledge partner **Bax & Company**.



2. Overview of the Composite Landscape

2.1 Introduction to Composites

Composites are materials that are composed of two or more constituent materials, which are dissimilar in their chemical and physical properties. The constituent materials are combined to form a material that can achieve properties that are different from those of each component. Within the wide field of composite materials, polymer composites are typically defined by the combination of a **polymer matrix**, either **thermoset** (TS) or **thermoplastic** (TP), and a reinforcing agent forming Fibre-Reinforced Polymers (FRP). This **reinforcing agent** is typically a filament or fibre made of either **carbon**, **glass**, **aramid**, or a **biobased** source like e.g. wood pulp or flax. Longer fibres or textile structures (2D or 3D) provide high-performance properties for large structural parts. Multiple layers with varying fibre orientations can be “stacked” together to increase properties in all directions. In smaller parts with lower mechanical requirements, short fibres can be dispersed in the resin matrix.

Thermoplastic or thermoset resins differ in their chemical structure and thus their mechanical, chemical, and thermal properties.

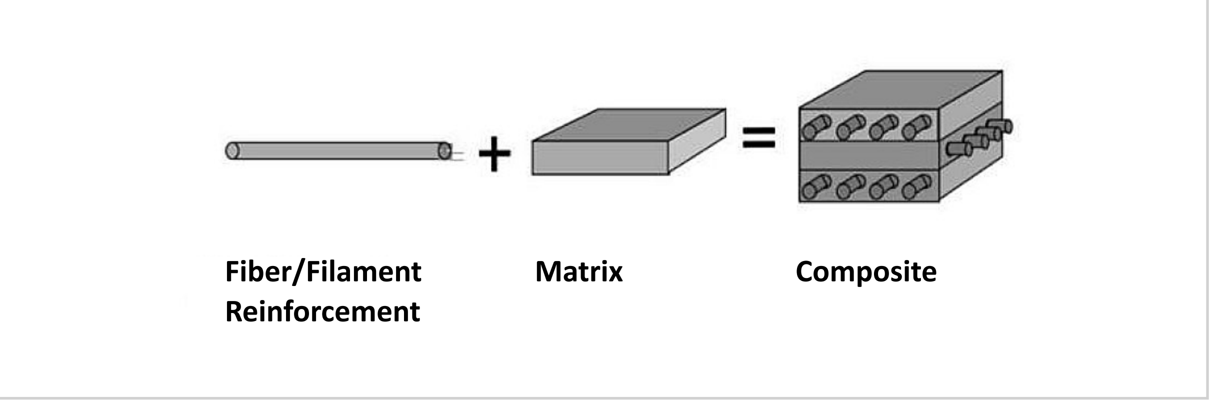
Thermosets cannot be remoulded due to the irreversible cross-linking of polymer chains during the curing process. **Thermoplastics**, however, can (theoretically) be infinitely melted, and remoulded into different structures. In addition, composites may contain fillers, modifiers, and additives that adjust the material’s properties and improve the performance of the composite material and final structure.

FRP composites allow for an efficient structural design due to their **unique and customisable physical and chemical properties**. They offer a **high strength-to-weight ratio**, **corrosion resistance**, **long-term durability**, **low maintenance,** and **dimensional stability – properties sought for in many high-performance applications.**

Their exact composition can be customised to fulfil the needs of the intended use according to several criteria. Both the type and quantity of the constituent materials (e.g. type, length and orientation of fibre, type of matrix, the ratio of fibre to matrix) will affect the properties of the final component.

Figure 1:

FRP constituents (source: Kumar et al).[1]



1 Y.K. Kumar et al. (2016). Influence of Aviation Fuel on Mechanical properties of Glass-Fiber-Reinforced Plastic Composite, International Advanced Research Journal in Science, Engineering and Technology, 3.

Manufacturing processes

The selection of the manufacturing process is another factor that influences the **components' properties**. A variety of manufacturing processes can be employed, depending on the needs of the application (durability, volume, rate, geometry, size, etc.). Due to the possibility to use composites from very small to very large structures, the manufacturing processes **vary significantly in cost, production volume, and degree of automation**.

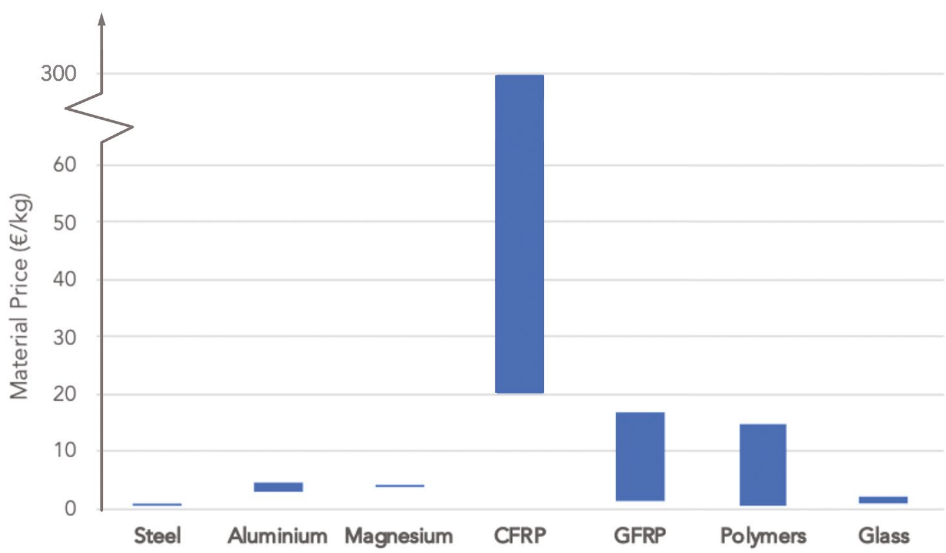
Today, *open moulding* is the most common and widely used method due to its flexibility in size and design options. Open moulding processes are labour intensive and, therefore, used for low-volume components. *Closed moulding* techniques such as injection moulding or Vacuum Assisted Resin Transfer Moulding (VARTM) can consistently produce superior parts and are used for higher volumes as those justify the higher mould costs of these automated processes.

In addition to the abovementioned manufacturing technologies, **additive manufacturing** (AM) use in FRP is seeing increasing adoption in various application sectors, mainly due to the ability to manufacture parts with complex geometry, and lower cost per component for low production volumes.

Comparison of lightweight materials

The cost of FRP per kilogram varies a lot and can be multiple times higher than that of other lightweight materials[2]. Glass fibre-reinforced polymers (GFRP) are cheaper compared to carbon fibres (CFRP). However, the higher lightweighting potential of CRFP leads to less material needed to achieve the same mechanical properties compared to other materials. The cost of CFRP can vary greatly depending on the mechanical performance and length of the fibres. In aerostructures, this can reach up to €300 per kilogram for virgin material. The cost of components using bio-based reinforcements varies greatly depending on the requirements of the end-user, and the fibre source (e.g. natural fibres such as sisal, or man-made fibres e.g. made from wood processing waste). However, these are typically not suited for all applications due to their low impact resistance and moisture degradation, which makes them less resistant to extreme conditions. Yet, additional treatment (sizing) applied on the bio-based fibres already allows widening the field of application for those materials.

Figure 2:
Cost ranges (€/kg) for different types of lightweight materials (source: EMIRI, Bax & Company).[3]



2 The University of Utah (2012). Composites in Cars: making Vehicles Lighter, Safer and More Fuel-Efficient.
3 Bax & Company, EMIRI, Sustesco (2019). Advanced Materials for Clean and Sustainable Energy and Mobility.

2.2 Application Sectors

Owing to their lightweighting potential, mechanical properties, and customization potential – among others – FRP have seen increasing adoption in multiple sectors. The main markets for composites currently are **aviation/aerospace**, **automotive** and **wind energy**.

Aerostructures

Composites used in aircraft have generated a weight saving of 20% over traditional aluminium alloys. A weight reduction of 580 kilograms per aircraft translates to fuel savings of about 10-15% compared to a traditional aircraft i.e. 5,700 tons per year, and consequently in about 20% greenhouse gas emissions (ca. 12 tons of CO_{2e} per year). Today, FRP already make up for more than 50% of the materials used in an aircraft by weight[4].

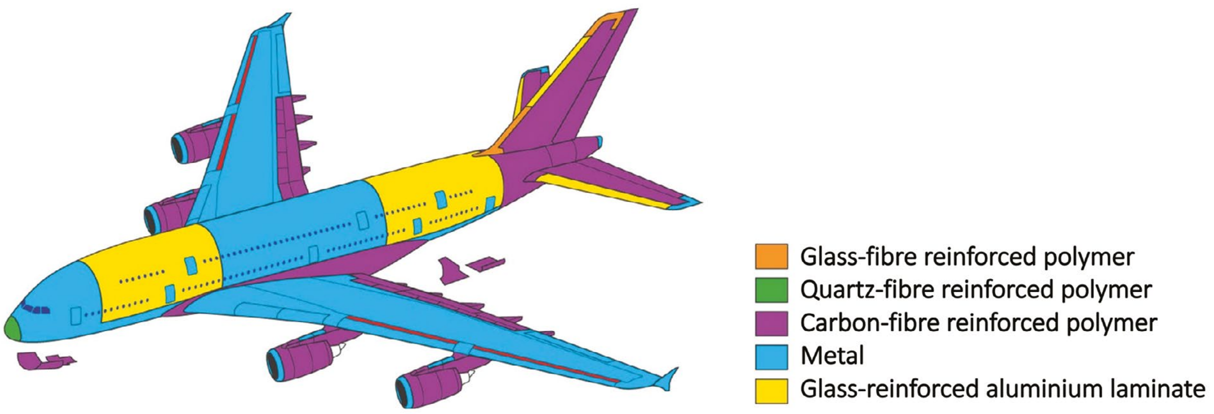
The global aviation composites market was €13.45 billion in 2018 and is projected to reach €27.30 billion by 2026, exhibiting a CAGR of 9.3% [5]. Aircraft have a longer lifecycle compared to for example automotive vehicles and have higher mechanical requirements (due to higher loads, extreme conditions, stringent requirements, etc.). As such, the material utilized is more expensive expressed in a higher share of CFRP compared to GFRP.

Wind energy

The need to harvest higher amounts of wind energy, typically in harsher weather conditions (e.g. off-shore vs. on-shore installations) has driven the growth of FRP in the wind sector. Roughly 2.5 million tons of composite materials are currently used in 70,000 wind turbines in Europe, with a combined capacity of 189 GW[6]. Composites can be found in blade reinforcements, blade laminates, spar caps, blade root joints, spacers, and carrots. Additionally, composites are used in access structures (such as ladders and platforms), as well cable management systems, and even in the generator itself as insulation solutions. However, to improve the output power of wind power generation, the key lies in the wind turbine blades that form the rotor, whose design directly relates to the performance of the wind turbine. With constantly increasing rotor diameters and as such higher loads on the blades, the wind sector is evolving from traditionally focusing on glass fibres to expanding to more carbon fibre use.

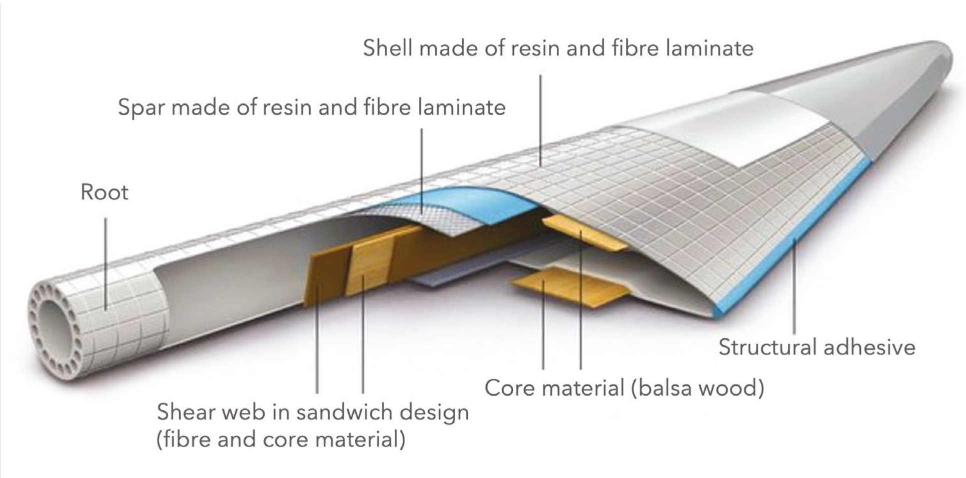
Figure 3:

Materials used in a passenger aircraft (source: Opdenakker).[7]



4 B. Kadir et al. (2018). Chapter XI: Application of Glass fibers in 3D preform composites.
5 Fortune Business Insights (2019). Advanced Materials / Aerospace Composites Market.
6 M. Ierides, J. Reiland (2019) Wind turbine blade circularity.
7 R. Opdenakker (2020-2021). Glare: Open innovation gets wings.

Figure 4:
Typical structure of a wind turbine blade (source: Bank et al.).[8]



Automotive

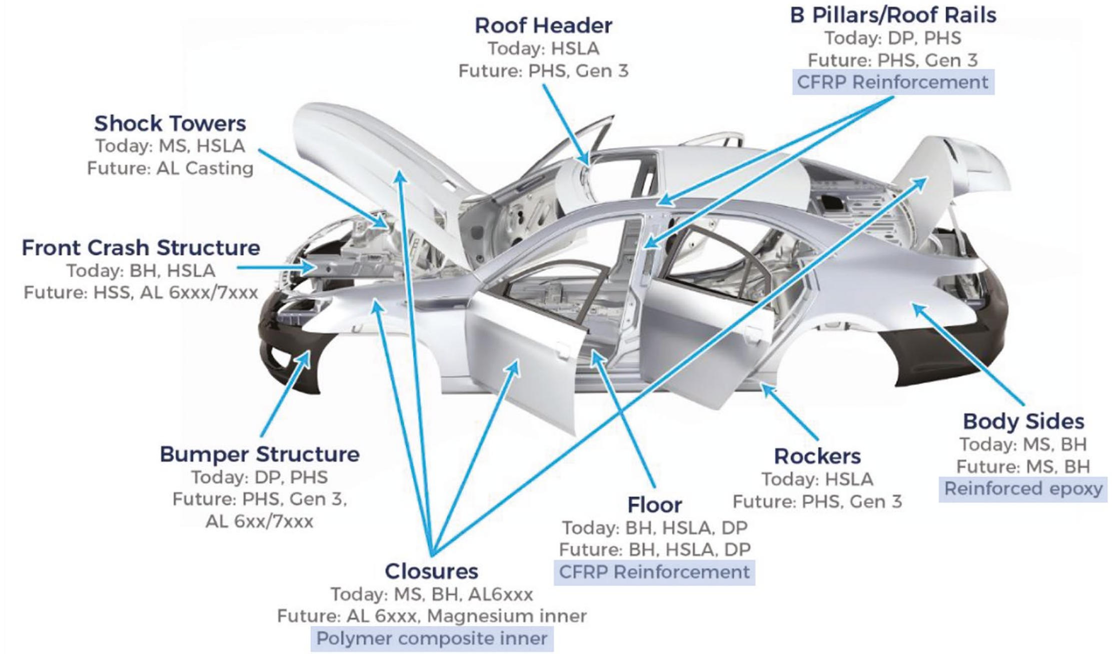
The main drivers for the adoption of FRP in the automotive sector are fuel savings and consequently emissions reduction. Today, in the fast-growing field of **e-mobility**, composites contribute to extending the driving range of Electric Vehicles (EV) and provide **key properties to battery housing cases**. As for hydrogen-fuelled vehicles, composites are pivotal for storing hydrogen in high-pressure tanks that are both lightweight and safe.

Composites can offer a **reduction in weight** of up to 25% for GFRP, and up to 40% for CFRP, compared to conventional materials such as high-strength steel (HSS) and aluminium. Assuming a theoretical 33% weight reduction on a 10% volume of the entire EU fleet, FRP can potentially achieve a reduction in CO_{2e} emissions from road transportation of up to 8 million tons.

The market for global automotive composite materials is forecasted to reach €12.5 billion by 2026, up from €7.1 billion in 2018, representing a compound annual growth rate (CAGR) of about 7%.[5] However, the current composites share of the average automotive bill of materials for an automotive body (body-in-white and closures) stands at 6% of the weight with competing materials such as steel and aluminium still dominating.[9] **Composite materials can be used in a wide range of applications in cars**.

8 L.C: Bank, F.R. Arias (2016) Assessment of Present/Future Decommissioned Wind Blade Fiber-Reinforced Composite Material in the United States.
9 S. Modi, A. Vadhavkar (2019). Technology Roadmap: Intelligent Mobility Technologies, Center for Automotive Research.

Figure 5: **Materials used for key vehicle components (source: Centre for Automotive Research).**[9]



Metals					
HSLA	High-strength low-alloy steel	**DP**	Dual-phase steel	**Gen 3**	Generation three steel
BH	Bake-Hardenable Steel	**PHS**	Press Hardenable Steel	**MS**	Mild Steel
Plastics and Polymer Composites					
ABS	Acrylonitrile Butadiene Styrene	**PET**	Polyethylene terephthalate	**PUR**	Polyurethane
HDPE	High-density polyethylene	**POM**	Polyoxymethylene	**PVB**	polyvinyl butyral
PA	Polyamide	**PP**	Polypropylene	**PVC**	Polyvinyl Chloride
PBT	polybutylene terephthalate	**PPE**	Polyphenylene Ether	**CFRP**	Carbon Fiber Reinforced Composite
PC	Polycarbonate	**PPO**	Polyphenylene Oxide		

2.3 Circular Economy in Composites

The inherent properties of composite materials make them suitable for a range of **medium- to high-value applications**. This has contributed to their widespread adoption in various sectors over the past few decades and has generated several benefits (e.g. the ability to manufacture larger wind turbine blades that can harvest more wind energy). At the same time, the increasing number of composite applications has raised the big question of **how to make sure composites are a sustainable source throughout their entire life**.

The very same properties that make composites ideal for many applications make their End of Life (EoL) treatment challenging and costly. Separating the reinforcement and the matrix is difficult, especially in the case of thermoset matrices (the majority of installed applications) due to the covalent bonds in the chemical structure. Fillers and additives that provide additional properties increase this difficulty even more.

In Europe, it is estimated that **683,000 tons of composite waste will be generated in 2025** not counting the already accumulated untreated waste.[10]

10 ETIP Wind (2020). How Wind is going Circular.

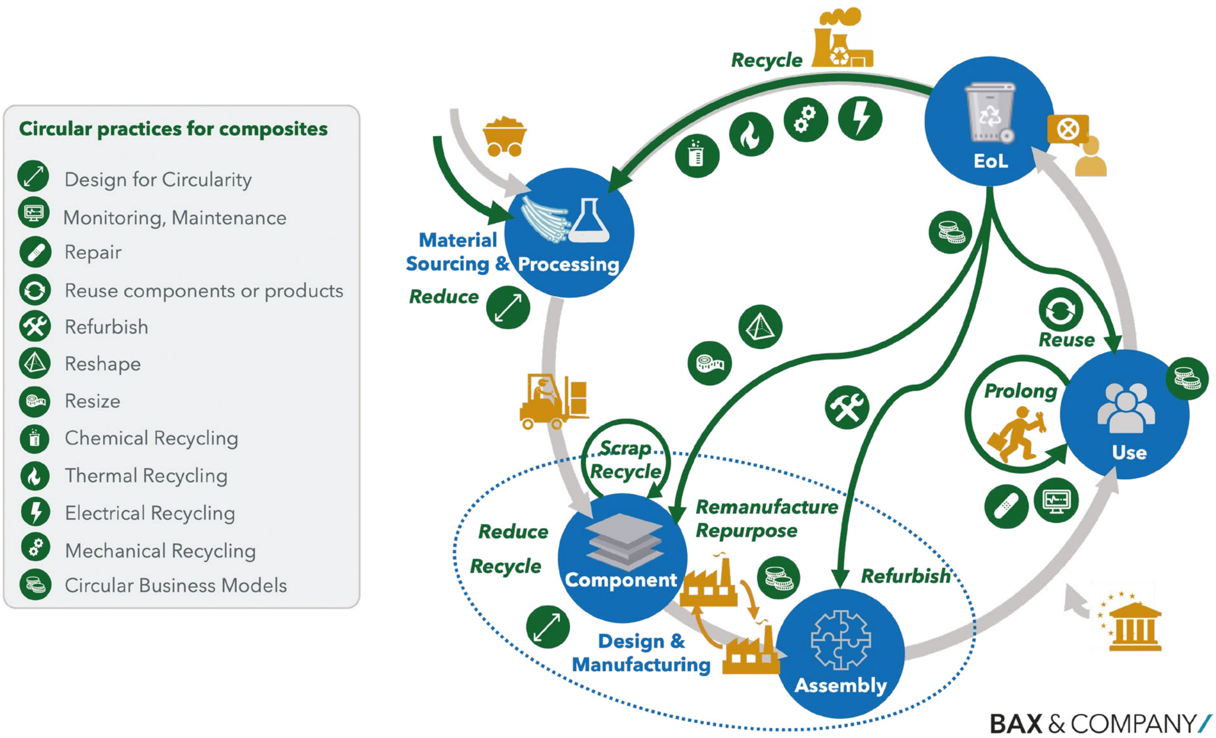
At the same time, the **global annual FRP recycling capacity is estimated to be less than 100,000 tons.**[11] While this is a big challenge to be addressed, it also presents a significant business opportunity for several stakeholders including FRP end-users, remanufacturers, and recyclers. Growth scenarios in the European wind sector from WindEurope estimate some 23 GW of new installations per year until 2026[12].

Considering that up to 15 tons of FRP are used for each MW installed[13], this translates to a **yearly demand for new FRP material of 345,000 tons from the European wind sector** alone. In addition, the aviation industry is expected to resume growth, with an estimated 39,000 small, medium, and large passenger aircraft to be delivered globally over the next 20 years[14]. Assuming 20 tons of FRP per aircraft on average, the **global demand for FRP material for aviation would reach around 39,000 tons per year.**

A part of that demand for new materials could be covered by secondary (reused, remanufactured, recycled) components and materials. Developing and implementing practices that enable this, can create value for stakeholders involved, and society as a whole. The overarching aim of circularity in the context of composites is to minimise the extraction and use of virgin raw materials and energy resources. **Figure 6** illustrates the Circular Economy principles and their corresponding practices related to FRP.

Reducing waste is the highest priority in the Circular Economy and aims at minimizing the extraction and use of material in several phases of the product's lifecycles. This can be achieved manifold, e.g. through *low scrap rate manufacturing technologies*, *virtual* instead of physical *testing* of products, or simply by not producing parts in the first place (e.g. through optimised design).

Figure 6:
Circular Economy principles in the FRP sector (source: Bax & Company).



11 Mordor Intelligence (2021). Fiber-Reinforced Plastic (FRP) Recycling Market.
12 Wind Europe (2021). Wind Energy on Europe: 2021 Statistics and the outlook for 2022-2026.
13 Wind Europe (2017). Discussion paper on managing composite blade waste.
14 Airbus (2022). Global Market Forecast 2022-2041.

Lifetime prolongation through maintenance and repair refers to preventive measures that in turn minimize the use of (virgin) material and energy. Examples include *design for circularity practices* that can be employed to *reduce the chance of early onset damage*, or *ease of repairing activities*.

Reuse/Refurbishing aims at extending the lifetime of an article or its components through use in the same function. Examples are *refurbishment* or *disassembly* and *reuse* of individual components of a given product, a common practice in the automotive industry.

Remanufacturing/Repurposing instead aims at extending the lifetime of the article or its components, but for a different application, typically of lower value. Examples are *resizing* or *reshaping* the original article, e.g. parts of wind turbine blades used as covers for bus stops or bridge structures. These actions discard the original product's function but maintain the unique structural properties, defined by the combination of material composition and structural design.

Recycling aims at preserving material integrity by returning material that can be reused as secondary raw materials in the manufacturing of new FRP components.[15]

It is important to mention that **technologies that contribute to the Circular Economy of composites are vastly available**, regardless of the inherent difficult-to-recycle nature of composites. There are many misconceptions about the circularity of composites that need to be tackled. Nowadays, the main focus of the industry's ¨Circular Economy strategy¨ is on recycling material. However, a clear distinction in the industry must be made between Circular Economy as a whole and ¨recycling¨ as a Circular Economy practice.

Due to the **different technology or market readiness** of several circularity practices as well as already accumulated waste a critical view of the hierarchy is required. The urgency to treat current and future waste streams in the short term to prevent landfilling makes it inevitable to also consider and upscale the treatment through less favourable routes. These include for example the cement kiln route for low value or heavily damaged components, or recycling practices for a higher value. Yet, the developments need to go hand-in-hand with the circularity practices in higher steps of the hierarchy to secure that mid- to long-term material streams are retaining value for as long as possible pushing recycling or recovery activities after a multiple-lives-scenario.

The demand for new FRP material and the expansion to new application markets opens **new opportunities for a front-to-back circular business model** that incorporates practices on all levels of the value chain. For this new demand, it is important to address the hierarchy of circularity practices. But also a review of existing linear business models and a transformation towards circular models promise new ways of value capture for multiple stakeholders e.g. through industrial symbiosis, and servitisation models, among others.

The complex nature of the Circular Economy calls for an **integrative problem-solving strategy**. In every step of the value chain, there are opportunities that will often have an impact on other parts of the value chain as well. With these improvements, the technologies available today can thrive and new innovative technologies can be developed and integrated to enable the circularity of composites.

15 Joustra, J., & Bessai, R. (n.d.). *Circular Composites A design guide for products containing composite materials in a Circular Economy*.

3. Challenges to Circularity

The section below presents the main challenges hindering a higher degree of circularity in the composite sector. These are listed per lifecycle phase, defined as follows:

[3.1 Raw material sourcing and processing](#)
[3.2 Design and manufacturing](#)
[3.3 Use](#)
[3.4 End of Life](#)

3.1 Raw Material Sourcing and Processing

The composites value chain starts with the sourcing of the primary or pre-cursor materials, e.g. Polyacrylonitrile (PAN) for carbon fibre (CF) and hydrocarbons for the matrix, and their processing and transformation into raw materials to be used for the production of FRP components. **Reducing or avoiding the extraction and use of raw materials** is the highest priority of the circularity hierarchy, and therefore actions in this step of the value chain are of great importance for the circularity of composites.

Challenge 1.

Energy and emission intensity for raw material processing

Processing of precursors into raw materials for composite production requires multiple steps under high process temperatures, thus being highly energy-intensive. Especially in (CF) processing, high temperatures needed for the carbonisation of PAN (up to 1600 °C) contribute to the high energy intensity of the whole process. Production of CF can reach 200-315 kWh/kg and that of epoxy resin 25 kWh/kg [16], [17] resulting in an embodied energy of 113-170 kWh/kg for the materials of a 50% CF-epoxy FRP. As a comparison, the energy needed to produce one kilogram of steel and aluminium is four and 22 kWh/kg respectively.

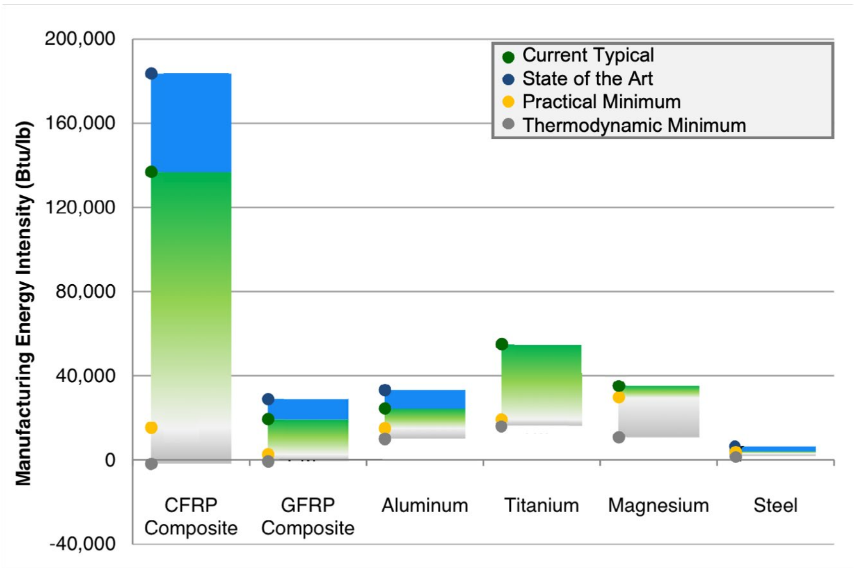
Challenge 2.

Use of finite (petrochemical) raw materials

Raw materials for composites are today mostly based on **finite fossil fuels**. Most CFs are made of PAN (some small percentage is made of rayon or the petroleum pitch process), while about 80% of the polymers used to fabricate composites are obtained from non-renewable sources.[18]

Figure 7:

Comparison of on-site energy intensities for different material types (adapted from Liddell et al.)[16]



16 Liddell, H., et. al. (2016). Manufacturing Energy Intensity and Opportunity Analysis for Fiber-Reinforced Polymer Composites and Other Lightweight Materials. ACS2016.
17 Sunter, D., et. al. (2015). The Manufacturing Energy Intensity Of Carbon Fiber Reinforced Polymer Composites And Its Effect On Life Cycle Energy Use For Vehicle Door Lightweigting. ECCM20.
18 J. J. Andrew et al. (2022). Sustainable bio-based composites for advanced applications: recent trends and future opportunities – A critical review. Composites Part C, 7.

At the same time, deposits are unequally distributed and Europe strongly depends on imports for most of the domestic production, posing material shortage risks in addition to circularity risks. With the increasing demand for composite materials, it is crucial to find ways to **decrease the dependency on fossil-based materials**.

Challenge 3.
Inconsistent quality of recycled material

Currently, there is a **general belief that recycled material is inferior to virgin material**. Indeed, some recycling technologies reduce the tensile strength of fibres (e.g. ~50% retained strength compared to virgin carbon fibre for mechanical recycling), others, however, provide nearly full purity and retained strength (~95% retained strength compared to virgin carbon fibre for chemical recycling).[19] Nevertheless, the main issue when it comes to recycled material is ensuring **consistency between recycling plants**, and even between batches of the same recycling plant, within an acceptable confidence level, comparable to virgin material. This is particularly relevant for the aerostructures sector where new material needs to undergo strict certification processes. To achieve this, a testing campaign on a sufficiently large portion of the secondary material is needed, which is resource-intensive (time and cost). To date, **there are no standards on recycled fibres from EoL applications**. This deters suppliers and manufacturers from using secondary raw materials.

3.2 Design and Manufacturing

The design of the material structure as well as composite components, and their manufacturing into products has the biggest influence on the circularity of composites, and as such the biggest potential for increasing it.

Challenge 4.
Lack of knowledge and/or prioritization of design for circularity

Designers and engineers are often still **not familiar with circular design practices** or do not consider it a priority of design. End-use requirements and cost are usually the driving forces in the design phase. Where circularity is considered, usually fundamental aspects of circular design are missing, and manufacturers tend to focus on only one part of the circularity hierarchy (if any) while disregarding others. **A clear set of priorities for circular design has to be established** and should pay attention to the hierarchy of actions.[20]

Challenge 5.
Insufficient information on use and EoL of components

To increase - by design - the potential for reuse, repair and recycling of the material, component and product as a whole is a complex undertaking. Designers and engineers face many challenges when aiming to address Circular Economy principles and **anticipate recovery practices** in their designs. To be able to make truly circular design choices, vast knowledge of the use and available circular pathways during the use and EoL phases is required. Without adding these very uncertain requirements it is difficult to anticipate the residual quality and potential recovery routes. Especially for products with long lifespans the availability of certain routes considered during the design phase may no longer be valid once the product reaches its EoL.[15]

Challenge 6.
High scrap rates

Conventional manufacturing technologies typically have high scrap rates, and in addition, make use of a significant amount of consumables (e.g. vacuum bags, fabrics, tapes). Scrap rates for established manufacturing technologies range from **7% up to 46% of the initial material**. In many cases, the scraps are incinerated or sent to landfills.[21] In addition, consumables that are used during manufacturing are single-use and get disposed of after the process.[22]

19 A. E. Krauklis et al. (2021). Composite material recycling technology—state-of-the-art and sustainable development for the 2020s. Journal of Composites Science, 5 (1).
20 General opinion from the webinar of CSRE and Leonardo.
21 J. Rybicka et al. (2015). Capturing composites manufacturing waste flows through process mapping. Journal of Cleaner Production.
22 R. Kupfer et al. (2022). Neutral lightweight engineering: a holistic approach towards sustainability driven engineering. Discover Sustainability.

Challenge 7.

Increasing complexity of materials and components

The often very large dimensions and increasing complexity of FRP parts due to increasing functional demands, together with the lack of consideration for dismantling and separation during the design phase, increase the challenges of retrieving material without incurring major downgrading. The current trend is to make parts more complex and with an increasing number of materials, which will only further compromise dismantling and finally recycling quality. Also, old product models that are reaching their EoL often do not have the same features as new product models. Due to missing considerations for **interchangeability and modularity** during the design phase, their parts are not necessarily usable in new models. The increasing diversity of material combinations also hinders the upscaling of recycling and reusing strategies and technologies. Examples are the use of wood or foam glue to connect parts, which are difficult to recycle, or the use of adhesives that are difficult to disassemble.[23]

3.3 Use

This is the phase where the composite product enters the use phase and undergoes **degradation** due to various mechanisms. The main objective in this phase is to **increase the lifetime of the component**.

Challenge 8.

Lacking in-use assessment of structural integrity

Microcracks or other micro-damages on fibres, matrix, or the interfaces between them can be deteriorating towards the performance of the component. Such damages are often not visible to the naked eye. To reduce risks and avoid accidents, components are replaced periodically (either based on usage cycles or time in use) preventatively, using high safety factors. As a result, components that might still be fit for use end up being replaced and sent to landfill or other EoL routes.

Challenge 9.

Value discarded before components reach their EoL

Connected to the above challenge, the lifetime of composite components often exceeds **the lifetime of the application assembly**. As an example, wind turbine blades have a longer lifetime than the turbines that they are used in, either because the tower or generator degrades, or because it is more efficient to install a larger wind turbine at the same location. The same applies to the aerospace sector where composite parts (specifically those made of CFRP) usually exceed the average lifetime of the aircraft (ca. 25 years). Reuse is not always an option, since aircraft components require highly regulated airworthiness tags.

3.4 End of Life

This is the last phase of a FRP product's lifetime, and it occurs when **the product is no longer fit for the purpose it has been originally used for**. The most established circular practice for such products is **recycling**, although other practices exist.

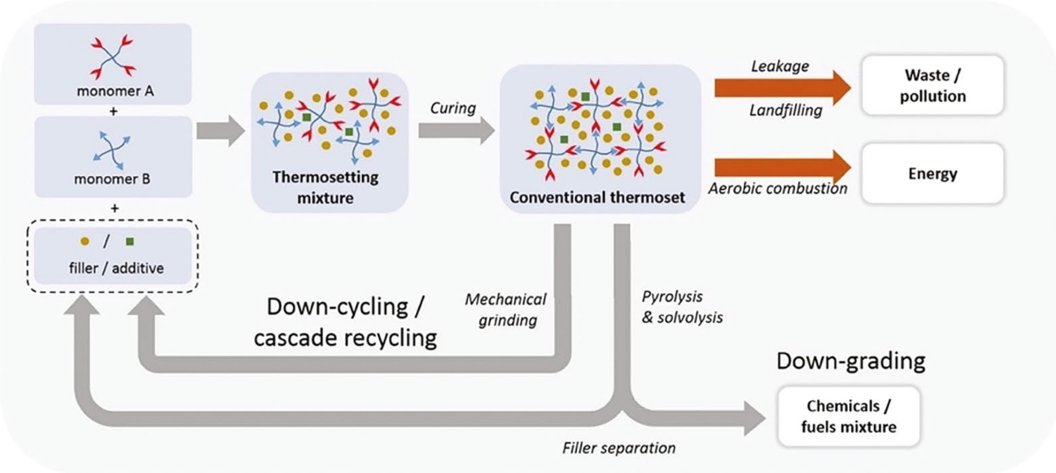
Challenge 10.

Poor recyclability of conventional composite materials

Manufacturers often choose to work with materials they are familiar with. However, these materials may not be the best option regarding recyclability. Thermosets are resistant to high temperatures and have a clear advantage in terms of strength and resistance. However, a direct consequence of this high thermal and mechanical stability is that thermosets are hard to recycle and **most available processes downcycle or downgrade the constituents**. Thermosets still hold the highest market share of composite matrix materials.

23 A. Romain (n.d.). Guide Du Recyclage Et De L'ecoconception Des Composites Rapport Technique.

Figure 8: **Schematic overview of conventional thermoset composite waste processing (source: Post et al.).**[24]



Challenge 11.

Fragmented regulatory framework (on waste)

Barriers that arise from the scattered and fragmented policy landscape in Europe can create a mismatch between the potential of current circularity practices and regulatory requirements, and therefore end up impeding and/or not supporting the implementation of the complex nature of a Circular Economy. This is mainly due to a **lack of understanding of the value of composite waste and recycled materials**. In addition, a lack of policy harmonisation across European countries hinders investments that could increase recycling capacities.

3.5 Information and Data

While this is not a distinct lifecycle stage, challenges related to information and data stretch across **the whole lifecycle of composite material** and can hinder their circularity. The main such challenges are identified below.

Challenge 12.

Incomplete information about material composition

When materials reach the EoL stage, very often the information on their composition is lost or incomplete. The European Commission has been working on implementing a passport that documents and communicates information related to the materialcomposition throughout all stages.[25]

Repair and recycling technologies perform best when they are customised to the material composition of a component. Similarly, refurbishment and repurposing activities benefit from such information. So far, implementation of such an information exchange system on an industry-wide scale has been challenging partly due to **confidentiality**. As a result, recyclers adapt technologies to treat a variety of material compositions in the same process resulting in lower quality of the recyclate than what possibly could have been achieved. This is particularly true for recycling plants that treat material streams from multiple applications and/or manufacturers.

Challenge 13.

Lacking impact data on circular practices

Most stakeholders in the value chain still lack a clear understanding and the relevant data on how certain practices impact the overall circularity of the composite components or the entire product. **The determination of impacts in each value chain step is highly complex**. Additionally, certain practices that tackle one aspect of circularity can negatively impact the circularity of the component in other steps of the value chain. An example of such is the addition of additives for increased durability or sensing materials that may pose a challenge for recycling. Carrying out extensive LCAs for any design or manufacturing choice, or circularity practices in later stages considering various scenarios will allow for making composites more circular. Nevertheless, they are time- and resource-intensive.

24 W. Post et al. (2020). A Review on the Potential and Limitations of Recyclable Thermosets for Structural Applications, Polymer Reviews, 60:2.
25 European Commission (2022). Ecodesign and Energy Labelling Working Program 2022-2024.

4. Opportunities for Stakeholders

The challenges mentioned above can be tackled from several perspectives creating opportunities for a variety of stakeholders that may be involved in addressing them. The opportunities presented here are clustered into the fields **1) Technology 2) Market and 3) Policy** depending on **the type of stakeholder** that would be expected to drive their implementation. Realisation of these opportunities can present additional challenges which require the involvement of several stakeholders to be addressed. As such this section aims at encouraging all stakeholders to **collaboratively seize the opportunities presented**.

4.1 Technology

Technological advancements in materials, their processing, and use can provide solutions that increase the circularity of composite applications. The opportunities listed below require further advancements through applied research and development to increase their Technology Readiness Level (TRL) and reach market maturity. Therefore, academic and research institutions, as well as R&D centres of companies in the FRP field are expected to lead them.

Opportunity 1.
Further advancement of bio-based materials

Bio-based feedstocks are a renewable alternative that can be used to **reduce the dependency on finite fossil-based materials**. It is estimated that between 2016 and 2024, the global bio-composites market will grow at a CAGR of 11.8%, from around €4.5 billion in 2016 to €10.9 billion in 2024.[26]

Bio-based composites have several advantages in comparison to fossil-based materials in terms of **density, cost, recyclability, and sustainability**. However, most current bio-based composites underperform compared to fossil-based alternatives when it comes to long-term durability.

Drawbacks of bio-composites include: high water absorption and hygrothermal ageing, susceptibility to UV degradation, higher fatigue and creep, and thermal instability at higher temperatures.[27] Additionally, the processing of bio-based materials is challenging due to variations in the properties of the feedstock, and incompatibility with established manufacturing processes. Finally, the scaling-up of bio-based technologies is challenged by **longer processing time and higher costs**.[18]

These challenges can be overcome with **additional research on the quality improvement of bio-based composites.** For example, research is being done on the incorporation of nano-fillers or fibres into polymers to increase performance in aspects such as stability, mechanical strength, and thermal properties. Also, the incorporation of bio-fillers such as bamboo charcoal in bio-composites has proven to increase mechanical performance.[18] Biological methods such as the use of fungi and enzymes have also been shown to enhance adhesion and eradicate impurities. However, investments must be made to upscale these technologies and bring them to market level.[19]

Opportunity 2.
Inherently recyclable materials and improvement of the recyclability of existing materials

Decisions at early stages can influence the recyclability of components at the EoL, e.g. by making use of materials that are easier to recycle, such as thermoplastic matrices which can theoretically undergo multiple recycling loops with minimal property degradation. In addition, thermoplastic-based composites can be reshaped, opening up new remanufacturing and repurposing routes, e.g. resizing and thermoforming into new shapes. Another advantage of thermoplastics over conventional thermosets is the **lower processing times**, as the matrix does not need to be cured. Despite their advantages, the overall performance of thermoplastics is inferior to thermosets which makes their use prohibitive for highly demanding applications (e.g. in harsh conditions).

26 T. Gurunathan et al. (2015). A review of the recent developments in biocomposites based on natural fibres and their application perspectives, Composites Part A: Applied Science and Manufacturing, 77.
27 B. P. Chang, et al. (2020). Studies on durability of sustainable bio-based composites: a review. RSC Advances, 10 (31).

Therefore, **further development is needed to bring the material on par with thermoset matrices**.

While the market share of thermoplastics is increasing (from 2% in 1980 to 39% in 2020[23]), thermosets are still dominating, and with increasing use of composite materials, thermoset use in absolute terms is increasing as well. Hence, another approach to increasing circularity is **the development of innovative technologies for energy-efficient recycling of thermosets**. Both biodegradable and dynamic covalent systems are being developed and some are already approaching the market. Vitrimers are a class of polymers that show both thermoplastic- and thermoset-like behaviour that have arisen as a new method to contribute to the circularity of composite materials and were first introduced in 2011. Due to their dynamic covalent bonds, they can retain mechanical stability while also flowing when heated, allowing for properties such as self-healing, recyclability, and weldability. Vitrimers can keep thermoset material in the loop by contributing to the materials' improved lifespan, sustainability, and overall enhanced functionality and versatility. Currently, even biodegradable vitrimers are being reported in literature. [19,24]

Opportunity 3.
Improvement of self-healing and health monitoring technologies

While optically stimulated thermographic methods can assess the structural health of products rapidly, contactless, and at a relatively low cost, their performance is limited to material defects in coatings and fatigue damage. Deeper damage and microcracks stay undetected.[28] New technologies focusing on **health monitoring technologies** e.g. embroidered sensors show great promise and can recognise delamination, fibre fractures, pull-out, macroscopic damages, overload, rigidity, resistance, and weight changes while being in use. Those sensors can be directly embedded in the structure of the plies of the composites. First examples like optic fibres or different stress gauge measuring systems embedded in the composite wing spars of aircraft show already great results.[29]

Another way to increase the lifetime of composite parts is **the use of smart self-healing systems**. Micro- and nano-crack damage as a result of exposure to extreme conditions can be repaired without the need for external intervention. These smart healing systems can be implemented through microcapsules that are directly introduced into the polymer matrix. Healing agents can repair the damaged bonds through bond reformation by crack-filling adhesion.[22] However, there are still limitations such as the stability of the microcapsules and the compatibility of their compatibility with the substrates.[30]

Opportunity 4.
Further development of on-site repair technologies

On-site repairs allow extending **the useful lifetime of components** while reducing transportation costs and downtime. Conventional repair methods include wet lay-up, infusion, and pre-preg repairs, as well as restitution of gel coats and surface finishes.[22] These are successful circular practices because often the pre-pregs used for repair are obtained from scraps from the manufacturing phase, or recycled materials obtained from EoL products.

Challenges that occur with repair include a **lack of compatibility of the material or the susceptibility of the repair to human error**. However, there are several **automated repair technologies in development**. For all these systems, automated functions include the creation of 3D digitized images of the repair surface, non-destructive inspection and evaluation of damage, removal of damaged material and preparation of the repair area, development of the repair materials, as well as assessment of the completed repair.[31] 3D printing has been identified to offer a solution to implement battlefield repairs of helicopters.

28 F. Ciampa et al.(2018). Recent advances in active infrared thermography for non-destructive testing of aerospace components. In Sensors, 18 (2).
29 Patent US5399854A: Embedded optical sensor capable of strain and temperature measurement using a single diffraction grating
30 P. Li et al. (2018). Research progress of self-healing intelligent composite materials. IOP Conference Series: Materials Science and Engineering, 292(1).
31 Composites World (2014). Composites repair.

These printers can use carbon-reinforced thermoplastic filaments to repair damages with a relatively straightforward manufacturing process[32] - a solution viable for a variety of applications.

Opportunity 5.
Adoption of closed system recycling of manufacturing waste

Already in many manufacturing operations a reality today, **a closed system recycling can help address the issues of high scrap rate productions.** Due to the closed system, the manufacturer has **full control and full knowledge of the input materials**, leading to a high consistency of the quantity and quality of the recyclate. Additionally, (small mobile or stationary) recycling plants on or next to manufacturing sites, have the potential of **reducing emissions from transportation** of both the waste material (to the recycling plant) and the raw material to the manufacturing site. Closed system recycling starting from production scraps instead of EoL materials is a great opportunity for manufacturers to reduce costs. An example of successful implementation is included in the achievement section of this blueprint.

4.2 Market

This section discusses opportunities that are already at market maturity. As such, their implementation requires **initiative from commercial/industrial organisations**.

Opportunity 6.
Adopting design for circularity as an industry standard

Design for circularity is a broad term that refers to practices that are employed during **the design of products, materials, or even business practices**. Joustra et al. provide a clear overview of design practices for composites summarised below. [21]

Design for repairability/refurbishment aims at improving the ease of repairability or refurbishment of products. This can be achieved through several practices such as increasing accessibility to ensure reparation and replacements of components. Practices include grouping parts and materials in modules, designs that allow access from a single side with a single tool, and selecting fasteners that are easily removable.

Design for dis-/re-assembly contributes to improved repairability and separation at EoL. Practices include using reversible connections (e.g. screws or thermoplastic adhesives) and avoiding in-moulded inserts, mechanical assembly systems (e.g., form fits), use of accessible tools, and standard connections.

Design for reuse aims to allow the reuse of whole products or their components. Examples are creating a multifunctional design that allows for adaptation to a variety of users, customizable layouts of product components, transformable systems, and reversible assembly.

The *ergonomics of a product* refers to designing products to be used, maintained, reworked, and reprocessed safely and efficiently. The design should consider human actions for lifetime extension and product recovery.

Currently, the biggest challenge in realising this opportunity the lack of awareness of such practices within design, engineering, and decision-making departments in companies. That is why awareness campaigns that educate on the advantages of implementing design for circularity practices, as well as top-down adoption and promotion in companies, are of great importance. Initiatives such as the New Material & Circular Economy Accelerator contribute to this by sharing best practices amongst stakeholders. Beyond that, Circular Product Design frameworks like the one proposed by Den Hollander enable designers to make choices that better anticipate the lifecycle stages. [33]

32 M.W. Joosten et al. (2022). 3D printed continuous fibre composite repair of sandwich structures, Composite Structures, 290.
33 Den Hollander, M. (2018). Design for Managing Obsolescence.

Opportunity 7.

Open-access impact calculators for data-backed decision making

Having a better picture of the material and energy flows can help identify resource-intensive processes and find alternatives. The European Composites Industry Association (EuCIA) has developed **the Eco Impact Calculator** that enables manufacturers to assess the environmental impact of their processes and products. Today, it already includes a variety of established manufacturing processes of the composite value chain. It also draws from a **database of materials and coatings**. While the tool still lacks certain stages in the value chain and doesn't include newer technologies, it allows designers and manufacturers to **easily identify and assess the best (common) manufacturing processes for their application**. Its open-access character reduces the barrier of having to invest in or perform extensive LCA.[34] Increased industry participation in the future could reduce data gaps and increase accuracy.

Opportunity 8.

Implementation of material passports

In March 2022, the EC proposed an Ecodesign for Sustainable Products Regulation (ESPR) in the European Green Deal that stated that **the Digital Product Passports (DPP)** will be the norm for textiles, construction, electric vehicle batteries. Products will be tagged, identified, and linked to data relevant to their circularity and sustainability.[35] This will become a relevant opportunity for composite materials since it will allow for **tracking of data on material composition, environmental impact, and circularity**. Consequently, it will also allow **optimised value retention** through effective reuse, remanufacturing and recycling. Creating the passport will call for the whole supply chain to cooperate and define the necessary information needed to be included in the passport to increase circularity potential, while not hindering competitiveness. This will be exceptionally challenging for composite materials due to the complexity of the materials and the value chain. Another concern often raised when discussing the DPP is the protection of data. However, with data protection software that encrypts sensitive data, e.g. using RSA (Rivest-Shamir-Adleman), end-to-end, or with zero-knowledge proofs, the main challenge is the definition and standardisation of relevant data to be shared across stakeholders.

Opportunity 9.

Digital support tools and Industry 4.0 to streamline production

Using AI, the Industrial Internet of Things (IIoT) as well as other digital support tools in the manufacturing process, allows for generating and analysing data in real-time and obtaining **smart insights and predictions to optimize the factory floor operator**.[36] Tools can be used manifold aiming at:

1. Better understanding the material flows and stocks.
2. Optimising energy and resource usage to avoid wasting resources.
3. Identifying scrap and closed system recycling opportunities.

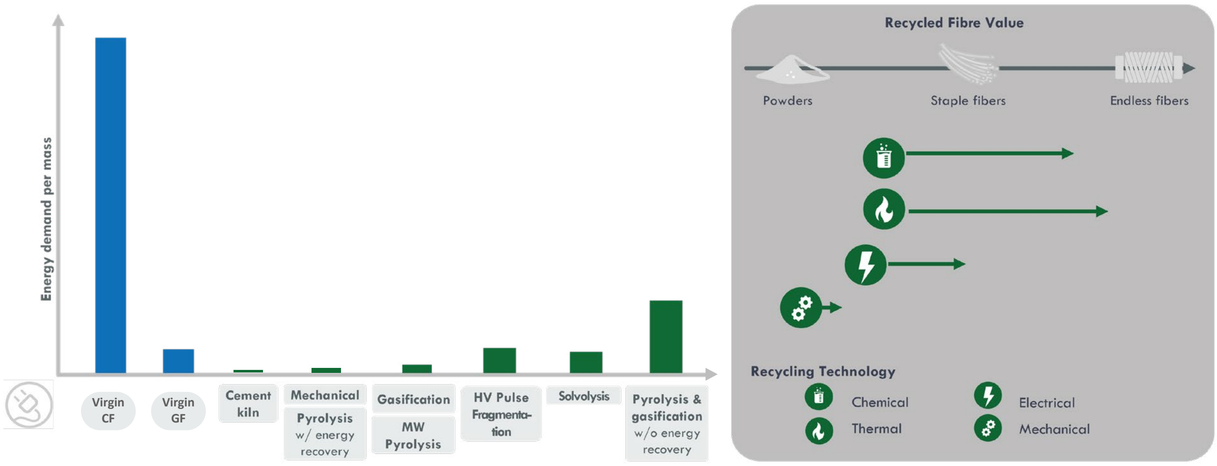
One such example is a tool developed by Plataine® that can aid better Manufacturing Operations Management (MOM), currently in use by Siemens. With a similar approach, the Leonardo Helicopter Division was able to optimise the yield of GFRP in the production flow by achieving a 30% saving in the volume of scraps. Such data-driven decisions can even be used across factories, which would help predict and address supply chain disruptions but also allow for industrial symbiosis in which materials are exchanged between two or more organisations.

As part of the innovation push of the Industry 4.0, advanced production processes such as **additive manufacturing** were scaled. These processes can **drastically reduce scrap rates**, while at the same time making use of waste powder or cropped fibres originating from other processes. As such, combinations of those processes in the same manufacturing site are very beneficial. Additive manufacturing is being use dincreasingly due to its **design freedom, automation, speed of production, and lower scrap rates**.[37]

34 EuCIA (2020). EuCIA Eco Impact Calculator: Background report, Version 1.4.
35 European Commission (2022). On making sustainable products the norm.
36 Plataine (2021). Flawless decision making, from planning to execution.
37 W. Liu et al. (2021). Integrating carbon fiber reclamation and additive manufacturing for recycling CFRP waste, Composites Part B: Engineering, 215.

Figure 9:

Energy demand of various recycling processes and virgin material production (source: Bax & Company).[7]



While additive manufacturing has many advantages regarding circularity due to localized and optimized material placement, its use is focused on specific applications and tooling for composite manufacturing, rather than for mass fabrication.

Opportunity 10.
Upscaling of efficient recycling technologies

While recycling is not the most preferred Circular Economy practice, it is a **prominent solution for conventional materials currently in use reaching their EoL in the next 5-10 years**. The various recycling technologies that are commercially available or under development are introduced below.

Thermal recycling such as *pyrolysis* involves a heat source to burn the matrix and recover fibres (with different degrees of degradation) that are typically used in injection moulding processes. By-products like pyrolysis gas oil can be used as an energy source, making it a self-sustaining process and wax recyclate and gases can be used as intermediates for the production of chemicals. Pyrolysis is already operating at a commercial scale.

Chemical recycling such as *solvolysis* (currently at TRL 6-7) involves a chemical reactor where heat and solvents are applied to the EoL component to separate fibres and matrix. The advantages include the lower degradation of fibres due to lower temperature requirements and the recovery of higher-value oligomers and polymers that are usable in resin production. Process limitations are the high use of solvents which can be highly toxic.

Mechanical recycling approaches involve *grinding* components into fibre- or resin-rich powders of varying particle sizes (significant downcycling), that can be used as fillers in composite or concrete structures with little energy input. While mechanical grinding produces the lowest value recyclate, it is the most established method due to its early commercial maturity and high throughput rates and shows still a large LCA gain.

Electrical recycling such as *high voltage pulse fragmentation* (TRL 6) involves the use of high voltages to recover fibres in near full length - a process easy to scale (no reactor needed) to larger components yet the degradation of fibres (especially glass) due to the high voltages is a clear limitation.

Figure 10: **Process-related costs and material value of recyclate (source: Bax & Company).**[7]

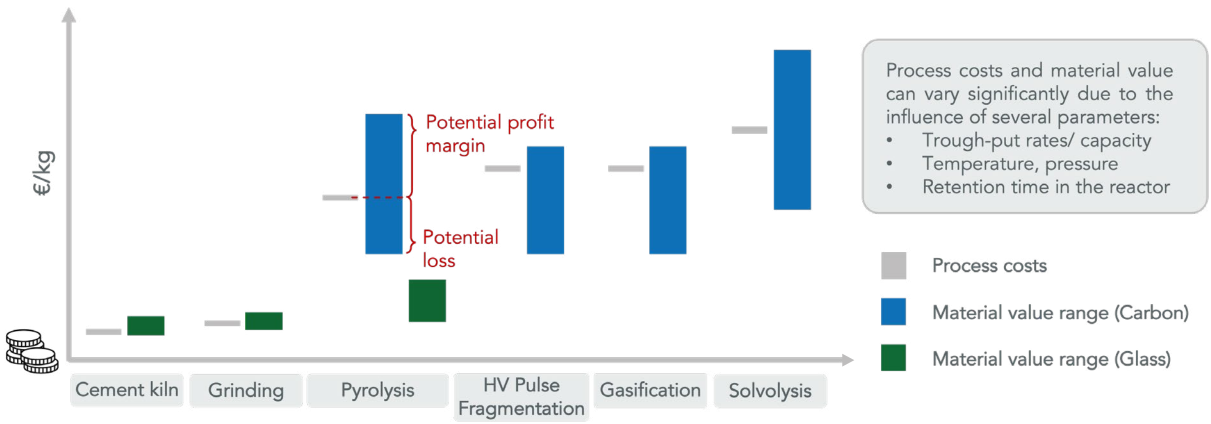


Figure 9 presents a comparison of different recycling technologies according to energy use. For comparison, energy demand for the production of virgin CF is reported to be from 198 to 595 MJ/kg of fibre[38]. Furthermore, the value of the recycled fibres retrieved from each type of technology is depicted.

The process costs, and the range of value of the recyclate are depicted in **Figure 10**. For simplicity, the costs of acquiring manufacturing scrap or EoL parts are omitted. **The value of the recyclate varies greatly** depending on parameters such as the configuration of the recycling technology, the structure, and type of the FRP input material. As such the profitability of recycling processes is a clear challenge. As an example, pyrolysis can be profitable for CFRP under certain circumstances, but is not profitable under any circumstances (considering the present parameters) for GFRP due to the degradation of GFs and the low cost of virgin GFs. This could change in the future if conditions change, e.g. if process become more efficient and throughput rates increase. A tax on virgin fibres, or minimum recycled content requirements would create a business case. For reference, the price of virgin GFs is around 1-2€/kg, while for virgin CFs it starts from 18€/kg and can go up to a few hundred euros per kg for high-quality CFs.

While the figures above attempt to make a comparison, one must consider that several variations of each technology and an endless combination of materials in FRP components (type and volume of reinforcement, type of matrix, additives, …) exist. This makes it practically impossible to quantitatively compare all technology-material configurations. Instead, the reader should see the comparison in a rather qualitative way.

Overcoming the challenges of recyclate quality **pre- and post-processing** can be applied. Common techniques are; improving the bonding between recyclate and matrix in the secondary application, recycled fibre surface treatment (e.g. oxygen plasma), fibre sizing, and fibre alignment along a single axis (e.g. hydrodynamic alignment method). It has been shown that retaining the architecture of carbon fibres during the recycling process through those techniques leads to a 26% reduction in cradle-to-gate primary energy demand compared to unprocessed recycled fibres.[39]

The implementation and scaling of recycling technologies is in many ways not a technical issue but rather a **market issue**. Recyclers face challenges related to waste regulation, lacking markets for secondary materials and a lack of steady waste material streams. The first joint ventures between recyclers and operators or manufacturers are setting a precedent for successful composite recycling in Europe.

38 F. Meng et al. (2017). Energy and environmental assessment and reuse of fluidized bed recycled carbon fibres, Composites Part A: Applied Science and Manufacturing, 100.
39 D. He et al. (2020). Comparative life cycle energy analysis of carbon fibre pre-processing, processing and post-processing recycling methods. Resources, Conservation and Recycling, 158.

Opportunity 11.
Implementation of recycled material class labelling

The high energy investment and associated cost for the production of virgin raw materials, in particular carbon fibres, opens up opportunities for substitutions with reprocessed materials. Depending on the application, these may present a more **attractive quality-to-price ratio**. To enable this, **classifying and labelling secondary materials according to their quality** could increase confidence among manufacturers and therefore their adoption. Currently, there are many different types of classification systems for the quality of recycled materials. The challenge lies in finding the **correct classification or combination of classifications for composite materials**. Tonini et al. attempted to conceptualize the criteria that should be a part of a framework for the definition of recycling quality based on the approaches available in literature. Concepts included in the integrative models are functionality, substitutability, suitability in the Circular Economy, and technical characteristics such as impurities and technical properties.[40] Such a framework can be developed for recyclate from composites giving both recyclers and secondary material suppliers more transactional trust and supporting material pricing structures for the secondary materials market.

Opportunity 12.
Implementation of a secondary marketplace

A secondary marketplace can be applicable at various steps in the value chain, and at different stages in a product's lifetime. For manufacturers, it offers an opportunity to get value for materials they can't or do not know how to use anymore. This can be on the level of pre-preg scraps and unused wheel stocks of pre-preg tape, but also on the level of an entire aircraft wing. In the case of scraps or manufactured parts, the material can be reinjected in the market following the by-product market rules.

Big suppliers of raw materials often request a **large Minimum Order Quantity** for the purchase of the CFRP raw material. Thus, for SMEs and academia, it is very expensive to access small quantities of material for research and prototyping purposes. The secondary marketplace can take up scraps and residual unused materials from different steps of the value chain, and simultaneously make small quantities of composites available for research and development purposes.

Opportunity 13.
Identification of new markets for downgraded secondary materials

Since downgrading of secondary material especially from recycling of EoL parts is still the standard**, new applications of secondary materials** can allow them to remain in the loop for longer, substituting virgin material. At the first webinar of the New Materials & Circular Economy Accelerator organized by CSRE and Leonardo, large corporations, institutions, and SMEs had the opportunity to discuss the options for degraded secondary materials. For example, the FiberEUse project has presented demo cases of recycled materials that could maintain enough properties to be included in products in other sectors, such as sporting goods. Another demo case showed that recovered fibres and resins could be used in the building industry. Lastly, the company Miljøskærm showed that recyclate from mechanical grinding of wind turbine blades is used in the manufacturing of acoustic and thermal applications. However, **there is still a need for the identification of markets that could take up large quantities of secondary material** and a better material classification (see O.11) to identify further opportunities.

40 D. Tonini et al. (2022). Quality of recycling: Urgent and undefined. Waste Management, 146.

4.3 Policy

National, regional, and EU-wide regulations that aim at accelerating the transition to a Circular Economy have been already showing stimulation of the market and a boost in innovation and development. **Further political action and guidance are required** to successfully support the stakeholders of the composite landscape.

Opportunity 14.
Implementation of an (extended) carbon tax

Carbon taxation, or lower taxation for materials with lower embodied energy presents an **opportunity to incentivise companies to switch to lower energy-intensive processes and materials**, such as recycled or bio-based materials with lower embodied energy. Variations of a carbon tax have been implemented around the globe. The EU Emissions Trading Scheme (ETS) – the largest carbon market globally – covers a multitude of sectors and gases from electricity and heat generation: energy-intensive sectors, commercial aviation, aluminium, and some acids production. In the current state, just 1 in 7 molecularly equivalent greenhouse gases are priced – except for specific sectors where N_2O and PFCs are priced as well – with just 1 in 14 prices at above €15 per ton of CO_{2e}, and just 1 in 200 emission units priced above €50 per ton. **Figure 11** shows the World Bank's 2020 state and trend report summary of existing, emerging, and potential regional, national and subnational carbon pricing initiatives. Europe looks well represented when it comes to carbon taxes implemented or scheduled, however, compared to the Swedish and Swiss carbon tax (€99-199 per ton of CO_{2e}), **most European countries are still underperforming**, with France, Finland, and Norway being the most costly at €49-68 per ton of CO_{2e}, and the rest of Europe lagging at with prices as low as €0.07 in Poland.[41] In parallel, this would require the completion of LCA and LCC databases so that carbon taxation can be integrated into the design stage and financial decision-making. It is also worth mentioning that given the already high energy prices due to the gas shortage, a carbon tax should be implemented carefully, in order not to reduce the competitiveness of European companies.

Opportunity 15.
Standardisation and common component interfaces

Standardisation has in the past been successful in supporting market-based competition while reducing costs and improving safety. Setting long-term trends that allow for the **interoperability of products and services** creates resilience and trust in and across industries as well as among users, although for interoperability to properly be implemented across industry, agreements between competitors will need to be reached. From a technical perspective, standards for common component interfaces, interchangeability of parts, components, and products, and simplification **improve repairability, reuse, separation, and recovery of materials at the EoL**. Furthermore, introducing standards on testing regimens for the quality assurance of used parts and components will allow the set-up of secondary markets. Above all, standardisation particularly on recycled composite materials from EoL applications would be an enormous **push for the use of recycled materials in the design and manufacturing of new components** and would support creating much-needed trust in the value chain.

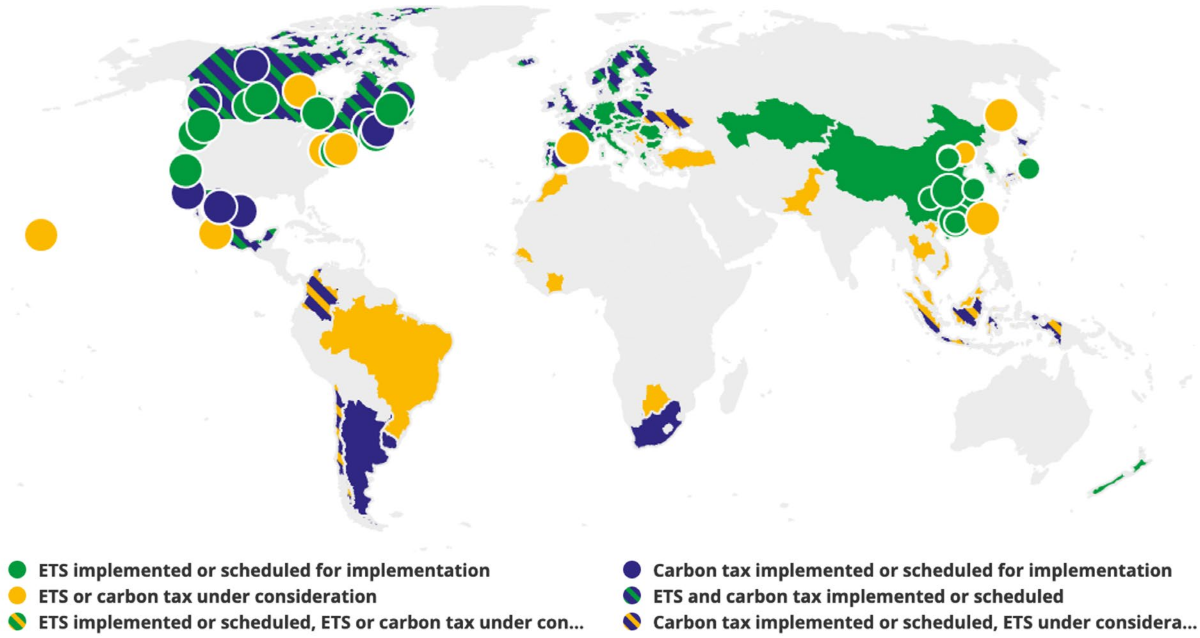
Opportunity 16.
Implementation of a repairability index

France is the first country to implement a repairability index for electronics in Europe. It provides a score giving a clear indication to what level the product can be repaired. This new legislation has already in its first year of implementation **proven to be effective** and has raised high hopes for **more sustainable consumption and better eco-design practices in the electronics sector**.[42] Such an initiative is currently under development also in the automotive sector.[43] While replicability is not straightforward, the expansion of such indices to markets that use/consume composites will doubtlessly trigger transformative action in several value chain stages.

41 Carbon Tax Center (2020). Where Carbon Is Taxed (Overview).
42 Right to Repair (2022). One year on, has the French repair index kept its promise?.
43 World Business Council for Sustainable Development (2022). Paving the Way: EU Policy Action for Automotive Circularity

Figure 11:

Summary map of regional, national, and subnational carbon pricing initiatives (source: The World Bank).[44]



Opportunity 17.

Harmonizing policies for efficient reverse logistics

Reverse logistics all the steps taking place from the point a component has reached its EoL until its further "fate" is decided. **Most European composite markets don't have an established logistics network for products and components that reach their EoL**. As a result, products have to be transported across great distances to be reused, refurbished or recycled. Also, lack of knowledge of the product's compositions and hence adequate options, as well as complicated waste regulations, often result in opting for landfilling or incineration. Therefore, it is integral that policies across borders and between industries are aligned.

Eliminating regulatory barriers such as the cumbersome transportation of FRP waste across borders or variations in regulations for landfilling and incineration (e.g. gate fees) would allow stakeholders to better collaborate on the set-up of a reverse logistics network. Furthermore, an implementation of regulations such as Extended Producer Responsibility (EPR) schemes could accelerate the adoption of recycled material and create more **security for reverse logistics stakeholders**.

44 The World Bank (2022). Carbon Pricing Dashboard.

4.4 Challenges-Opportunities-Matrix

The matrix below displays the challenges and opportunities discussed. It shows which opportunities address those challenges and by doing so it highlights the **complex interlinkages in a circular system** but also the great incentive to push those developments with great impact across the value chain and for multiple stakeholders.

Figure 12:
Challenges and the opportunities that address them.

		MATERIALS			DESIGN/ MANUFACTURING				USE		EoL		DATA	
		Energy and emission intensity of raw material processing	Use of finite (petrochemical) raw materials	Inconsistent quality of recycled material	Knowledge/prioritization of design for circularity	Insufficient information on use and EoL	High scrap rates	Increasing complexity of materials and components	Assessment of structural integrity	Value discarded before components reach their EoL	Poor recyclability of conventional materials	Fragmented regulatory framework	Incomplete information on the material composition	Lacking impact data on circular practices
		C.1	C.2	C.3	C.4	C.5	C.6	C.7	C.8	C.9	C.10	C.11	C.12	C.13
TECH	**O.1** Advancements of bio-based materials		x											
TECH	**O.2** Inherently recyclable materials	x		x							x			
TECH	**O.3** Self-healing and health monitoring technologies				x				x	x				
TECH	**O.4** Development of on-site repair technologies								x	x				
TECH	**O.5** Closed system recycling of manufacturing waste			x	x	x					x			
MARKET	**O.6** Design for circularity as an industry standard				x	x	x	x					x	
MARKET	**O.7** Open-access impact calculators													x
MARKET	**O.8** Implementation of material passports			x	x					x			x	x
MARKET	**O.9** Digital support tools and Industry 4.0	x					x							
MARKET	**O.10** Upscaling of efficient recycling technologies	x		x							x			x
MARKET	**O.11** Recycled material class labelling	x		x		x					x			
MARKET	**O.12** Secondary marketplace	x								x				
MARKET	**O.13** New markets for downgraded secondary materials	x									x			
POLICY	**O.14** Implementation of an (extended) carbon tax	x	x									x		
POLICY	**O.15** Standardisation and common component interfaces					x				x		x	x	
POLICY	**O.16** Repairability index					x				x				
POLICY	**O.17** Harmonizing policies for efficient reverse logistics	x								x		x		

5. Achievements of the Composite Landscape

This section presents state-of-the-art achievements that have increased circularity in the composites sector.

ECOBULK

Designing circular composites

The H2020-project ECOBULK demonstrated circular applications of composites in the furniture, automotive and construction industries. A guide on **design-for-circularity** for composite materials has been developed to support designers in the circular transition achieving longer product lifetimes, and easier remanufacturing and recycling. The project aimed to offer a rethinking of product design to shift towards a Circular Design Framework, validation of material and manufacturing technologies to ensure technical and economic feasibility, new reverse logistics for the recovery of products and parts from users and into the supply chain, implementation of innovative business models, and knowledge sharing on Circular Economy solutions.[45]

ZEBRA

A recyclable wind turbine blade

The H2020 project ZEBRA (Zero wastE Blade ReseArch) has developed a fully recyclable 62-meter wind turbine blade. The thermoplastic liquid resin developed by Arkema showed exceptional physical and mechanical properties. Initial tests have already demonstrated that a part made of the Elium® resin offers greater resistance over time than thermoset composite parts, with 10 times greater fatigue resistance. The blade can be recycled using an advanced chemical recycling method that fully depolymerizes the resin, separating it from the reinforcement, and recovering a new virgin resin and high-performance glass fibres ready for reuse.[46] The project gives a positive outlook, by preventing waste through innovative technologies, and closing the material recycling loop by rethinking the material design.

BMW

Efficient recycling of CFRP production scrap

The automotive industry is taking steps toward closing the loop of composite materials. BMW has successfully recycled CFRP production scraps and used them for the manufacturing of the roof and rear seat structures in their i8 and i3 models. Weaving and preform-kitting scraps from production are collected and cut into chips before being processed to open the constituent fibres. Through a mechanical carding process, the fibres are aligned before being layered and stitched to form nonwovens (mats or fleece) e.g. used in compression-moulded roof structures. This strategy allows reducing costs, by making use of the scraps and reducing the waste linked to the manufacturing phase.[47]

Constrictor©

Reducing transport emissions from large EoL components

Reciclalia, a Spanish composite recycler, has developed an innovative technology to facilitate the dismantling of wind farms, aircraft wings, and large aeronautical structures reaching their EoL – easing the reverse logistics process. This patented technology has been specifically designed for chopping the parts on-site, avoiding the complicated transport of large structures over long distances. The Constrictor© can be mounted on a truck, is 100% automated and allows minimal particle dispersion to the atmosphere. Parts can be cut rapidly at the desired length and then sent to a recycling facility, reducing emissions and costs considerably.[48]

45 ECOBULK project (2021). Circular Composites: a design guide for products containing composite materials in a Circular Economy.
46 Arkema (2020). Arkema supports the wind power industry in its transition towards sustainable energy.
47 TerraTechMedia (2016). Boom time for carbon fibre recycling.
48 Reciclalia (2022). Constrictor: The best shredding technology ever.

6. Outlook

To give recommendations on the implementation of proposed circular opportunities to stakeholders from policy and industry alike, a prioritisation of said opportunities is proposed.

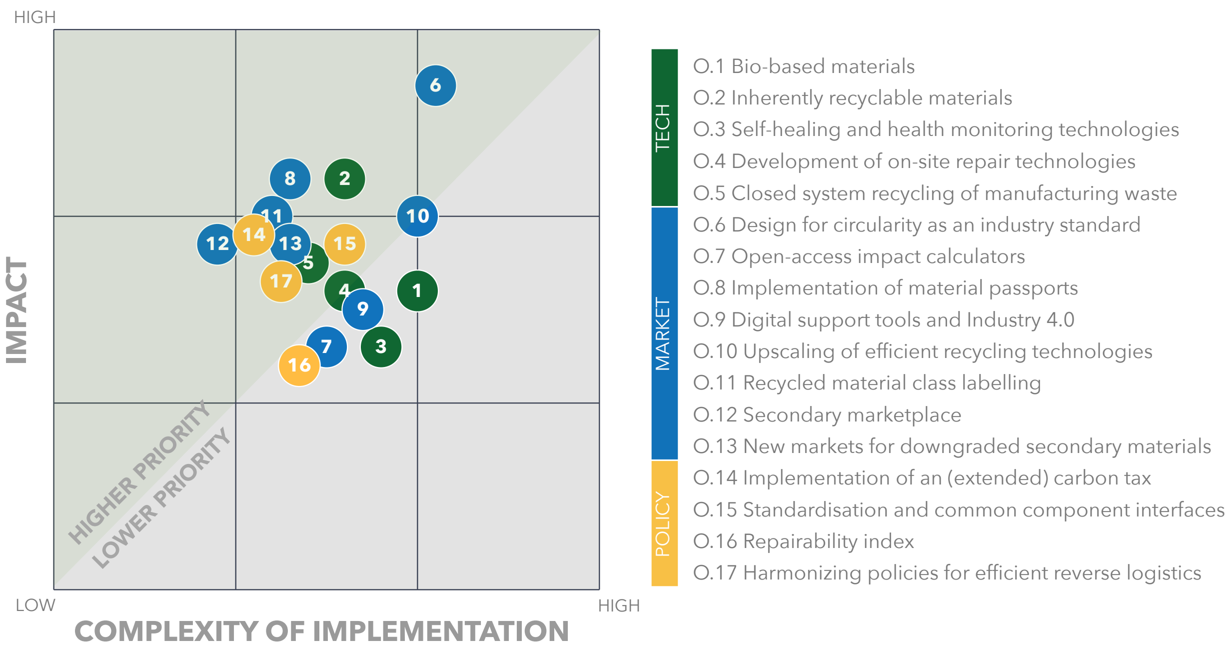
While the opportunities in sum paint an ideal picture for a new state of the composite industry, in reality, their implementation will neither happen at once nor at the same speed nor generate the same impact. Therefore, **opportunities have been evaluated by multiple stakeholders according to the impact and complexity of their implementation presented in Figure 13**:

- **Impact** refers to how strongly the opportunity contributes to increasing the circularity of composites considering: the desirability of the outcome according to Circular Economy priorities; and the potential scale (e.g. volume of composites affected) of the respective opportunity.
- **The complexity of implementation** refers to the resources (e.g. time, investment) and the number of stakeholders needed to realise the opportunity.

All in all, the opportunities suggested in this blueprint can help concretise the next steps in the transition of the composites value chain to a Circular Economy. **European stakeholders are in a favourable position to seize the opportunity** if they manage to build on the significant know-how and expertise developed at the local level, which is the result of Europe's pioneering role in the Circular Economy and the innovation capacity of the European composite landscape. Realisation of these opportunities can present additional challenges which require the involvement of several stakeholders to be addressed. Technical advances, stakeholder collaboration, knowledge transfer, access to data and favourable legislation must be implemented in all parts of the value chain to **empower stakeholders** but also to **enforce new strategies** that go beyond the current practices with the overall target to **reach maximum circularity in the composite industry**.

Figure 13:

Prioritisation of opportunities according to impact and complexity.



The Way Forward: A European Alliance for the Circularity of Composite Materials

Based on the example of the European Battery Alliance by the European Commission and in order to speed-up and enlarge the implementation of the countermeasures identified in the matrix above, the New Materials and Circular Economy Accelerator believes that the current transformative efforts in the composites landscape present an opportunity to explore the set-up of a *European Alliance for the Circularity of Composite Materials*. By involving stakeholders from relevant sectors such as chemical, wind, aerospace, defence and maritime, an innovative, competitive, and sustainable composite value chain in Europe can be developed that is in line with the priorities of the European Commission. Such an Alliance could stimulate the implementation of several of the opportunities named in this blueprint. As an example, the Alliance could be the host for a digital open-access platform that includes knowledge on markets, risks, opportunities (success cases), R&D outputs, and impact-costs assessments, and that links the stakeholders through secondary marketplaces, and enables opportunities for joint-ventures e.g. in reverse logistics networks.

New Materials &
Circular Economy Accelerator

About the Think Tank

The "New Materials and Circular Economy Accelerator" Think Tank aims at developing sustainable circular approaches for composite materials remains.

The Think Tank is led by CSR Europe in collaboration with Leonardo, the global high-tech player in Aerospace, Defence, and Security.

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Facilitated by CSR Europe

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About CSR Europe

CSR Europe is the leading European business network for Corporate Sustainability and Responsibility.

With our corporate members, National Partner Organisations (NPOs), and Associated Partners, we unite, inspire & support over 10,000 enterprises at local, European, and global level.

We support businesses & industry sectors in their transformation and collaboration towards practical solutions and sustainable growth. We are for systemic change. Following the SDGs, we want to co-build with the European leaders and stakeholders an overarching strategy for a Sustainable Europe 2030.