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Polymer Composites Circularity

White paper

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SUSCHEM

European Technology Platform
for Sustainable Chemistry

Throughout this white paper, several images are shown of people using or enjoying polymer composite materials. These materials are used widely in cars, public transport vehicles, buildings, sports equipment, pleasure boats, wind turbine blades and many other products that make life pleasant all over Europe.

Contents

Introduction

Polymer composites (PC) are materials defined by the combination of a polymer matrix (resin, either thermoset, thermoplastic or bio-based) and a reinforcing agent, mainly fibres (usually carbon, glass or natural fibres) and are often referred to as fibre-reinforced polymer (FRP) composites. Due to **unique characteristics** such as their high strength-to-weight ratio (enabling light-weighting) and long durability, FRP provides significant advantages over conventional materials such as steel or aluminium. This makes them very attractive for a growing number of applications across sectors; ranging from aerospace and automotive to construction, energy, and sports. The increasing diversity of applications, added to the unique improved characteristics these materials bring, has contributed to increasing demand and production in Europe.

Growing demand for composites, together with the increase in number of applications raises the next big question: what will happen to all the composite waste that is generated either from production or end-of-life parts? Just in Europe, some 40 000 tonnes of composite waste are deposited in landfills annually[1] and, **by the end of 2015, 304 000 tonnes of composite waste were estimated to have accumulated worldwide**[2]. As much as a 40% of the total production of composites ends up being wasted, either as scrap or defective parts[3], representing a major loss of resources and energy.

The European Commission, in collaboration with the Ellen McArthur Foundation, has taken some bold steps towards addressing the waste issue by developing the **Circular Economy Package**; a plan launched in 2015 to promote Europe's transition to a more circular model. Such a system enables the retention of the maximum value of resources during their useful life, minimises waste production and resource use, and loops materials back into production after reaching their End-of-Life (EoL) either in the form of secondary raw material, energy, or even reused parts.

However, the complexity of PC seems to be at odds with these objectives, since **the same inherent properties that make composite materials so attractive make their disassembly challenging and costly**. Fibres are impregnated within the matrix, and then treated to provide rigidity, firmly bonding them together. They might also contain fillers and additives to modify some properties, making separating one material from the other arduous. Although significant efforts have been made in Europe, including the Circular Economy Package and, in particular, its Plastics Strategy, the FRP space is not really included in the focus. Circular practices, such as designing, repairing, reusing and repurposing, need to be reinforced and some high potential recycling technologies also need to be further developed. The ultimate goal will be to reach an absolute circularity of composite materials.

Supporting the circularity of these materials could simultaneously help alleviate **Europe's external dependency on virgin resources**, hence control their price volatility, and reduce natural resources exploitation.

1: Composites Waste LIFE Project.

2: National Composites Network (2006), *Best Practice Guide; End of Life Options for Composite Waste*

3: Case Study: *Bringing Circularity to the Composites Industry*, Land Rover Bar (2016).

Market overview

Global and European market

Both carbon fibre reinforced polymers (CFRP) and glass fibre reinforced polymers (GFRP) are experiencing a **steady market growth**; average annual growth is estimated to be 4.5% and 10% in the next few years for the global GFRP and CFRP markets respectively[4]. And just in Europe, production of polymer composites has been growing at an average rate of 2.5% over the last decade[5].

Despite the absolute growth observed in production in recent years, **Europe's share of the worldwide composites market is still in decline**. Whereas Europe and North-America remain the principal locations for research and innovation developments, as well as an important sales market, their share of production is decreasing, compared to growth in developing regions. Since the largest polymer composites consumers are the transportation; wind energy; and construction sectors, the evolution of production in the long-term understandably follows very closely that of the economy as a whole. Subsequently, and in accord with the different regional economic growth rates around the globe, and derived increases in purchasing capacities, urbanisation and construction rates, the regions experiencing the fastest growing demand and manufacturing rates for composites comprise fast growing emerging economies in Asia Pacific, Middle East, and Africa[6].

Despite representing 85% of the global composites market, the GFRP volume in Europe is growing slower than the global composite industry. **The European GFRP composite market is the third largest**, with approximately 15% of the market share, after Asia-Pacific and North America with 45% and 29% market share, respectively.

Currently, **thermoplastics and thermosets composites, account for one-third and two-thirds of the market, respectively**.

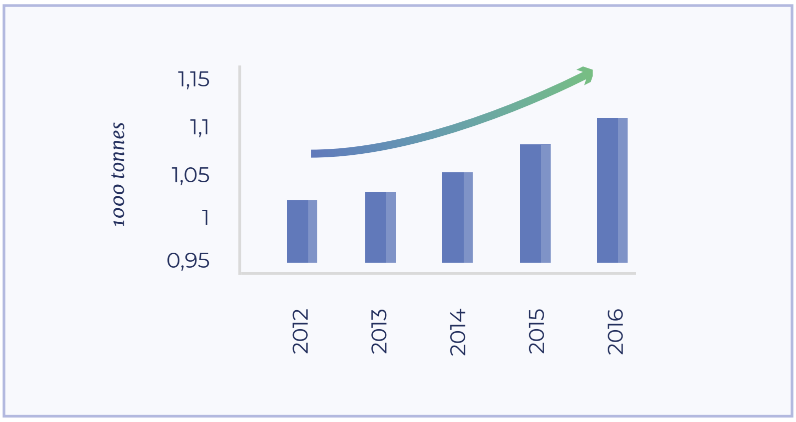


Figure 1. Polymer Composites production in Europe 2012-2016

4: AVK, CCeV (2016), *Composites Market Report 2016; Market developments, trends, outlook and challenges*
5: *Composites Market Report 2016*, Carbon Composites, (2016).
6: *State of the Composites Industry Report for 2017,* Composites Manufacturing, (2017).

While thermoplastics can be repeatedly melted, reshaped and hardened by cooling, thermosets contain polymers that crosslink forming an irreversible chemical bond that hardens permanently once heated. Even with prolonged heating they maintain their shape, structure and mechanical properties. This makes thermosets ideal for products that must endure high temperatures such as electronics, car, or insulation parts. Their low price, together with their heat and deformation resistance properties, helps explain the difference in demand between the two.

However, improvements in material performance of thermoplastics, lower overall manufacturing costs due to shorter cycle times, and considerable advantages in terms of cost and quality of recycling are expected to further increase their acceptance and demand in several markets including the automotive, industrial equipment and leisure segments.

Although the adoption of thermoplastics has been sluggish until recently, partly due to the industry's conservatism regarding certification and eligibility of new materials, **currently thermoplastics are the most rapidly growing market segment among composite materials**. On another note, natural fibre-based composites account for only about 1% of the total GFRP market, although these are forecast to grow at a compound annual growth rate (CAGR) of 8.2% from 2015 to 2020[7].

Due to changes in industry, regulation, and technology and material advances, the **coming years represent a great opportunity for new materials to be adopted in mass-production applications**. In the following section a brief description of the main areas of application of composites, comprising material types, trends and growth, will be presented.

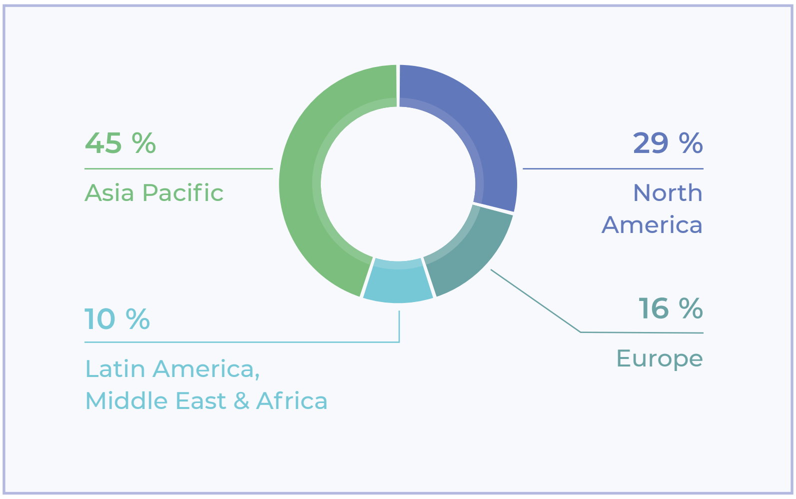


Figure 2. Glass Fibre Composites market share by region

7: Global Natural Fibre Composite Market 2015-2020: *Trends, Forecast, and Opportunity Analysis*, (2015).

Areas of application

The automotive, aerospace, defence, construction and infrastructure sectors have been the main drivers of composites demand in Europe. However, the wind energy, marine, electronics, and sports and leisure sectors are also large and growing consumer segments for composite materials.

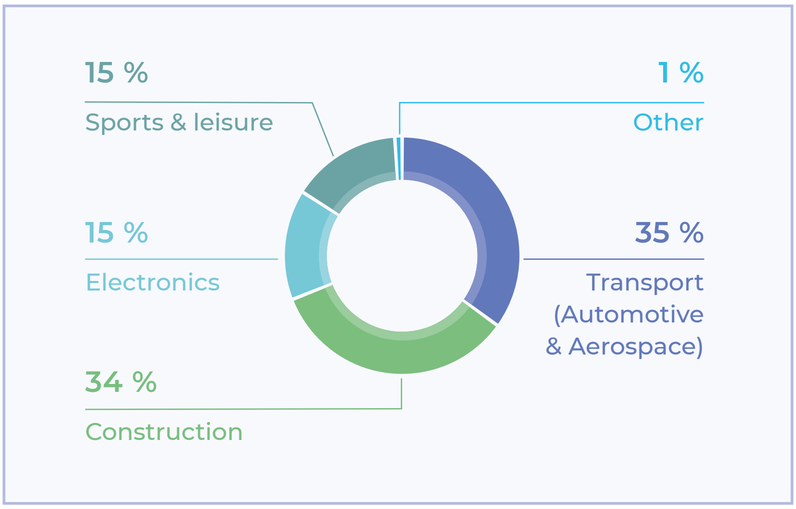


Figure 3. Composites production in Europe by type of application

The **automotive** sector is the largest consumer of FRP in Europe. Most applications are currently thermoset based, although the use of thermoplastics is increasing. This is due to key advantages for the industry, such as zero hazardous emissions, reduced material scrap, improved work safety conditions, shorter cycle times and improved recyclability.

European regulations targeting reduction of CO_2 emissions have urged original equipment manufacturers (OEMs) to implement lighter materials in their car fleet, triggering an increasing demand for composite materials. A 7.5% annual growth rate is forecast for automotive composites over the next few years as the automotive market itself is expected to account for 21.3% of the global market volume by 2024. The use of composites in automotive body structures has not yet reached widespread adoption in high-volume, lower end vehicles mainly due to cost, cycle time and end-of-life concerns compared to traditional materials. Nevertheless, as these issues are increasingly being tackled, adoption is growing.

Aerospace is the second largest market for the composites industry. The use of these materials is increasing, partly due to the industry's move to light weighting in response to rising fuel costs and stricter environmental regulations, as well as to the continuous increase in airline traffic, design flexibility and high corrosion resistance these materials offer. Commercial and military aircraft, as well as spacecraft, all incorporate composites in their structure.

Notwithstanding, the incorporation of these materials is slower compared to other industries due to the lengthy certification and approval times related to safety considerations.

Carbon fibre composites are the dominant material in the aerospace industry. However, despite having multiple potential applications that are yet to be exploited, their high cost and limited supply prevents a wider adoption.

Renewable energy is the fastest growing sector demanding composite materials. Lighter materials enable a more efficient production of wind and solar power and in many cases allow a more flexible design of large components such as wind turbine blades, solar panel frames and other structural parts. With the projected uptake of clean energy, this sector is forecast to consume more composites than any other. Wind turbine blades are the main end-use of GFRP, and CFRP to a lesser extent, and are expected to grow in size (and hence material usage) as the next turbine developments continue to evolve. The wind energy sector is projected to have a steady growth with a CAGR of 7% over the next five years.

The **construction** sector is adopting composites in multiple applications, particularly as reinforcement in industrial, commercial, housing and public buildings and infrastructure applications due to their performance, resilience and flexibility in design. The manufacturing of glass fibre composites for construction has a lower cost and complexity than traditional materials for similar safety and durability standards.

Adoption of composites in the **sports and leisure goods** sectors, both carbon and glass, is expected to experience significant growth mainly due to the growing demand for lighter, more durable and rigid sporting goods. Properties such as high tensile strength, impact absorption, long durability and extreme weather condition resistance are driving a rapid replacement of wood and metal in a wide range of sport's applications and equipment, such as fishing rods, tennis racquets, bicycle handlebars or boards. The less stringent regulations, together with the type of demand for this consumer group and the shorter lifetime of these products, makes it the best segment to test and introduce new materials and manufacturing methods.

The **electronics** sector is one of the longest running consumers of composites, since GFRP laminates have been the structural foundation of circuit boards for decades. The growing digitalisation and proliferation of new mobile devices amongst industry is increasing the demand for these materials. Furthermore, the demands that consumers are placing on electronic devices with respect to thickness, weight, strength and design are growing higher, increasing the applications for composites in such devices.

Circularity of composites – Technologies and practices

For the reasons mentioned above, the **global demand** for composites is growing in both well-established sectors and new sectors. By 2020 their use is projected to have experienced an increase of 40% from 2014[8].

Given the current scenario, this unavoidably results in **large amounts of waste** being produced and accumulated. It intensifies the need to develop more economically feasible circular routes, comprising repair, reuse, repurpose and recycling, and, in particular, looking at the cost efficiency of current recycling technologies and systemic practices to increase both product and raw material's lifetime.

The main highlights of the analysis point out the **limited availability and adoption of technologies enabling a higher value extraction** from composite materials, both in terms of resin and fibre (e.g. chemical and thermal recycling), as opposed to the growing adoption of more degrading processes (e.g. mechanical grinding or energy recovery) or still too high landfill rates.

Below, the **state of the art of composites circularity** is presented, followed by a brief description of each of the steps that build the strategy towards the circularity of these novel materials.

It is worth mentioning here that the **end of life of a material** needs to be distinguished from the end of life of a part, application, or product (e.g. fibres that have gone through several recycling/downcycling). EoL of a material is reached when no more value can be extracted from it. Likewise, EoL of a part, application or product is attained when it can no longer serve its original purpose (e.g. a car that has reached its maximum mileage).

However, both material and applications can have multiple lifetimes. For example, an application can reach its EoL and the materials contained in it still possess potential for several more lifecycles.

Process hierarchy for circularity

The **visual on the right illustrates the waste management categories hierarchy**. Desirability is highest at the top of the diagram and decreases going down (e.g. preventing a composite part from reaching its EoL is more desirable than recycling it, which is more desirable than disposing of it). For each step, the processes identified as being most promising and desirable are given.

8: Composites Recycling: *Where are we now?*, Composites UK, (2016).

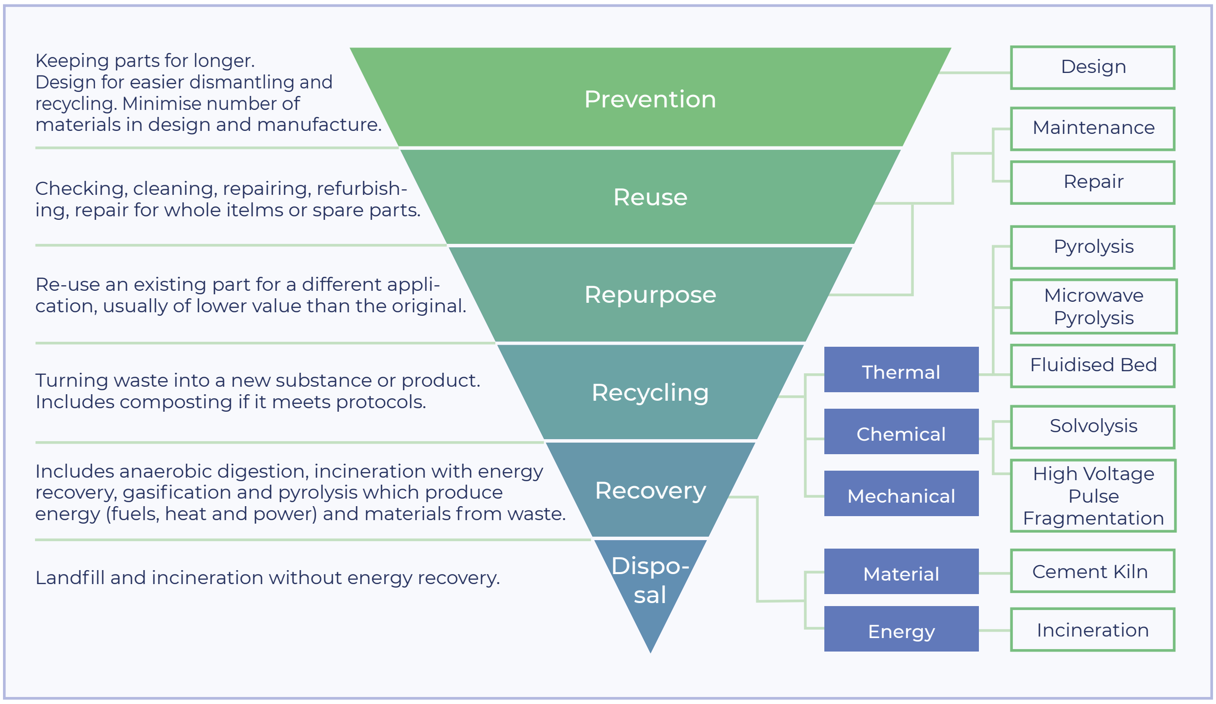


Figure 4. Waste management categories hierarchy

Process and technology overview

The **best strategy** is the one that, combining design, maintenance, repairing and the appropriate technology, ensures that the useful life is extended to its maximum capacity, while the maximal value of the material is retrieved during its different applications, by reusing, repurposing, recycling and finally through recovery, and systemically allows the re-use of materials for the same or similar purposes (e.g. allows polymer matrices to revert to monomers and avoids fibre damage during the process). **In the text box**, a brief description of each step of such a strategy, including the circularity potential and current state of each technology, is provided.

Prevention

Design is a critical step in determining the degree of circularity of any product. In the first place, it should serve the purpose of extending the life of the product, either by matching it with the application requirements or pre-defining possible second life applications (i.e. defining future reuse or repurpose applications). In the second place, it should consider the EoL phase of the product, i.e. ensure recycling, which is closely dependent on the material selection and combination, design for dismantling considerations, and material separation properties. Finally, it should incorporate the use of recycled materials in new products.

Maintenance, treatment and repair are key to postponing EoL as much as possible and ensuring maximum value for both resins and fibres is retained along the useful life. Recent developments in this field include health monitoring of applications, health forecasting, products for online repair (while the part is operational), and self-healing materials.

Reuse and repurpose

Design should consider incorporating spare composite parts or second life products in new products.

Treatment and repair of EoL and damaged parts, to be reused or repurposed for other applications.

Recycling

Solvolysis is a chemical treatment which offers many possibilities due to a wide range of solvent, temperature and pressure options. Compared to thermal technologies, solvolysis requires lower temperatures to degrade the resins, resulting in a lower degradation of fibres. Solvolysis with super-critical water seems to be the most promising technology since both fibres and resins can be retrieved without major impacts on their mechanical properties. However, common solvolysis incorporates salts or other modifying components that damage fibres and can be highly polluting. Solvolysis is easily scalable but investment and running costs are high and it is still at a low Technology Readiness Level (TRL).

Pyrolysis is a thermal recycling process which allows the recovery of fibre, and matrix in the form of ash. Although it allows for the lowest value loss from industrial-scale technologies, it still is more of a down-cycling method than recycling and still requires high investment and running costs. Matrices are turned into powder or oil, potentially useable as additives and fillers, and the fibre surface is often damaged due to the high temperatures resulting in a decrease in mechanical properties. Some improvements, such as combining the process with robotic precision cutting, could increase the quality of the recycled material.

Microwave pyrolysis is a thermo-chemical process in which the material is heated with microwaves, allowing better and easier control of the heating process and therefore reducing the induced damage and resulting in gas, oil and fibres recovery[9].

9: LIFE project, (2012).

High voltage pulse fragmentation is an electromechanical process that effectively separates matrices from fibres with the use of electricity. However, only short fibres can be recovered from the process and obtaining quality fibres requires high levels of energy, an issue that could be overcome by operating at higher rates[10]. Compared to mechanical fragmentation, the quality of the fibres obtained is higher; fibres are longer and cleaner, and therefore less down-cycled.

Mechanical grinding is the most commonly used technology due to its effectiveness, low cost and low energy requirement. It is, however, the least desirable recycling technology since it drastically decreases the value of the recycled materials. The recycled products, short fibres and ground matrix, can be used as fillers or reinforcement. Because of the deterioration of the mechanical properties, the incorporation level of filler material is extremely limited (less than 10%). Therefore, they are often used as fillers for cement or for energy recovery in cement kilns, which translates to a dramatic losses of value. This could be minimised if separating and dismantling processes were upgraded and could be suitable in cases where no more value retention was possible.

Fluidised bed is a thermal method which only allows the fibre to be recovered and, compared to pyrolysis, with lower quality since the fibre surface seems to be more damaged[11]. The unique characteristic of this process is that it can treat mixed and contaminated material (e.g. painted surfaces or foam cores), and therefore could be particularly suitable for EoL waste.

Hybrid technology most commonly consists of a combination of thermochemical recycling technology (solvolysis or pyrolysis) and mechanical grinding. This process allows improved quality for the recycled material by retrieving the matrix in the first place.

Recovery

Cement kiln allows recovery of material and energy. Although it is very promising in terms of cost effectiveness and efficacy, this process is the most downgrading route of all these the technologies described here and, therefore, should be used only when the value of the composite materials no longer suits any other application.

Incineration is mainly used to recover energy. It is the least desirable technology since it results in major loss of material. The same process as the for the cement kiln route applies here.

Disposal

Landfilling translates into an absolute loss of resources and is, therefore, preferably to be avoided.

10: *High voltage fragmentation and mechanical recycling of glass fibre thermoset composite*, CIRP Annals, (2016).
11: *Composite Recycling Summary of recent research and development*, Materials KTN report, (2010).

In short, **pyrolysis and solvolysis seem to be the most promising technologies** since they allow recover of both matrix and fibre and involve the lowest value loss. Especially in the case of CFRP, both technologies have demonstrated the recovery of fibres without major loss of their reinforcement capacity. Fibres recovered by solvolysis are cleaner and less damaged than those recovered by pyrolysis. The quality of the recovered material ultimately relies on the temperature of the process, acidity of the solvents, and the disposition of the fibres (e.g. it is harder to remove resins which are reinforced with woven fibres). **The attractiveness and maturity of these technologies are portrayed in the figure below**.

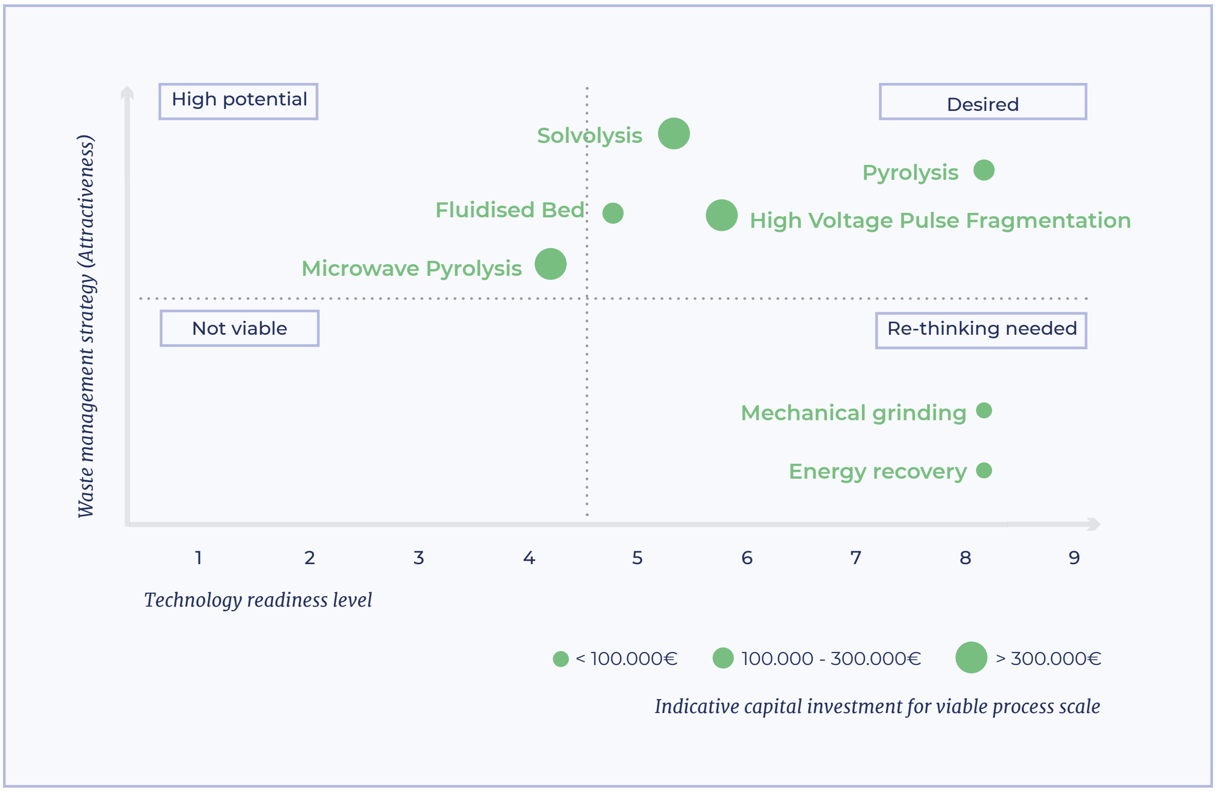
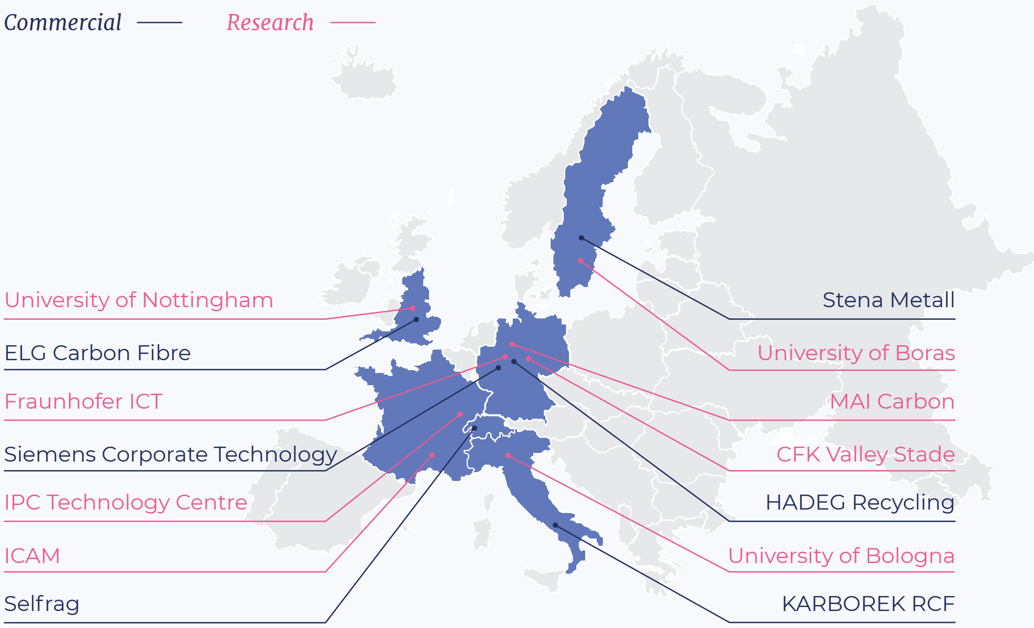


Figure 5. Attractiveness and maturity of each technology

European scenario

Key players

The map below illustrates the main industrial and academic players in Europe, selected based on their recycling capacity and their level of activity in the development of new technologies.



USA

- Materials Innovation Technologies
- Connora Technologies
- Firebird Advanced Technologies
- AdTech International
- Composite Recycling Technology Center
- Carbon Conversion Inc.
- Eco-Wolf

Japan

- Japan Carbon Fibre Manufacturers Association
- Hitachi Chemical

Figure 6. Main industrial and academic players

European projects

The most relevant projects addressing composites circularity in Europe in the last decade have been summarised and presented in the table below.

Project name	Objective	Funding	Partners
DACOMAT 2018-2020	Damage controlled composite materials.	Consor-tium	• Carbures Europe S.A (Spain) • Sintef (Norway)
RECO-TRANS 2017-2021	Integrated manufacturing of recyclable hybrid malthermo-plastic composites for the transport sector.	FP7 – H2020	• Arkema (France) • Mercedes-Benz turk (Turkey) • Inea informatizacija energetika avtomatizacija doo (Slovenia) • Synthesites innovative technologies (Greece) • Far-uk ltd (UK) • Polymec sl. (Spain)
ECOXY 2017-2020	Bio-based recyclable, reshapable and repairable (3R) fibre-reinforced epoxy composites for automotive and construction sectors.	H2020	• CIDETEC (Spain) • Centre National De la Recherche Scientifique (France) • Avantium Chemicals BV (Netherlands) • Centre Scientifique & Technique De L'industrie Textile Belge (Belgium) • Fraunhofer-Gesellschaft Zur Foerderung Der Angewandten Forschung E.V (Germany) • Centro Ricerche FIAT SCPA (Italy) • Asociación De Investigación De Materiales Plasticos Y Conexas – AIMPLAS (Spain) • Bergamo Tecnologie Spzoo (Poland) • European Composite Recycling Technology AS (Denmark)

Project name	Objective	Funding	Partners
FIBEREUSE 2017-2020	Large scale demonstration of new circular economy value-chains based on the reuse of end-of-life fibre reinforced composites.	H2020	• Aernnova Aerospace S.A.U (Spain), • Consiglio Nazionale Delle Ricerche (Italy) • Designaustria (Austria) • Edag Engineering Gmbh (Germany) • Fundación Tecnalia Research & Innovation (Spain) • Gamesa Innovation and Technology S.L (Spain) • Novellin
KARMA2020 2017-2019	Aims to the industrial manufacture and exploitation of sustainable raw materials from feather waste to develop innovative green products such as thermoset bio-based.	H2020	• CIDETEC (Spain) • Grupo Sada P A S (Spain) • Teknologian Tutkimuskeskus Vtt Oy (Finland) • Sp Sveriges Tekniska Forskningsinstitut Ab (Sweden) • Centre Scientifique & Technique De L'industrie Textile Belge (Belgium) • Asociacion De Investigacion De Materiales Plasticos Y Conexas – Aimplas (Spain) • Institute Of Biopolymers and Chemical Fibres Ibwch (Poland)Sioen Industries Nv (Belgium) • Centre National De La Recherche Scientifique (France) • Avantium Chemicals Bv (Netherlands) • Fkur Kunststoff Gmbh (Germany) • Fertiberia Sa (Spain) • Vertech Group (France) • Ciaotech Srl (Italy) • Daren Laboratories & Scientific Consultants Ltd (Israel) • Rise Processum Ab (Sweden)
RECYSITE 2016-2019	Production of fully recyclable and reusable green composites based on bio-resins and natural fibres.	LIFE Prog-ramme	• IK4-CIDETEC (Spain) • CENTEXBEL (Belgium) • LAZELOISE (Belgium) • AVANTIUM (The Netherlands) • CNRS (France) • AITIIP (Spain) • SISPRA (Spain

Project name	Objective	Funding	Partners
RECY-COMPOSITE 2016-2020	Composite materials recycling. Focus on mechanical and thermochemical recycling of composite materials (pyrolysis and solvolysis) and energy recovery if recycling is not possible.	Interreg	• CERTECH CTP (France) • VKC-CENTEXTBEL (Belgium) • Mines Douai (France) • ARMINES (France) • CREPIM (France)
MAI Recycling 2015-2015	Develop an integrated recycling process chain beginning with production waste or mixed materials and extending to treated carbon fiber.	National, Germany	• Audi AG (Germany) • BMW AG (Germany) • Fraunhofer-Institut für Bauphysik (Germany) • SGL Carbon GmbH (Germany) • Siemens AG (Germany
MAI Recytape 2015-2017	Development of an innovative recycling process line for carbon fibres.	National, Germany	• RWTH Aachen (Germany)
EURECOMP 2009-2012	Developing a novel recycling route for thermoset composites through solvolysis for reuse of organic components.	EU FP7	• Plastic Omnium Auto Exterieur (France) • Volvo Technology (Sweden) • ECRC (European Composites Recycling Services Company) • ICAM Nantes (France) • University of Exeter (UK) • COMPOSITEC (France)
GjenKOMP	Industrialisation of chemical recycling of Polyester and fibrebased composite waste.	National, Norway	• Sintef (Norway)

Project name	Objective	Funding	Partners
RECCO 2006-2007	Aeronautic CF composites recycling value chain implementation.	National, France	• IPC (France)
RECARB 2005-2006	Estimation of composite waste amounts in Europe coming from the aerospace sector.	National, France	• IPC (France)
RECOMP 2004-2005	First composite waste valorisation trial.	National, France	• IPC (France) • University of Leeds (UK) • Cray Valley (France) • Bristish Plastics Federation (UK)

Opportunities and challenges

Despite the efforts and resources invested in Europe in recent years in projects targeting re-using, repurposing and recycling of composite materials, circularity of composites is still far from becoming a reality. However, in view of the upcoming widespread adoption of composites across European industries, **developing and ensuring a systematic circular ecosystem for these materials needs to be a priority.**

To create a **roadmap for Europe** towards this objective, the main constraints, limitations and opportunities have been identified through interviews with relevant players along the whole composites value chain, including raw material suppliers, manufacturers, designers/end-users and recyclers, as well as representatives from the R&D field. The results, challenges and opportunities are presented below.

Main challenges

The **major barriers** that prevent the adoption and upscaling of composites circularity technologies and practices can be classified in three main categories: technical, financial/ market, and policy related. Technical challenges relate to the design of materials, applications and the maturity and capacity of the related technologies. Financial challenges refer to the constraints in the market or along the value chain both from supply and demand sides. Policy refers to existing, or non-existent, local, national or European regulations or guidelines that hinder the circularity of composite materials.

Technical and chemical

The inherent resilient nature of composites, together with the large variety of applications, and subsequent requirements in terms of chemical composition, manufacturing processes and recycling technologies **translate into a wide variety of materials, technologies and techniques** employed in the sector. This creates an extremely complex and fragmented environment for a smooth and effective circular system to take place in.

In the first place, the inherent nature of FRP makes it very challenging to separate fibres and matrix. Retrieving fibres in their full length is very difficult and usually recycling results in significant downgrading of the retrieved material, either due to damage to the fibres, reduction of size, or both. Regarding resins, thermoplastics, although inherently more recyclable, are relatively new engineering materials and their circular economy practices are in their infancy compared to thermosets.

Also, the often very large dimensions and increasing complexity of FRP parts, together with the lack of consideration for dismantling and separation issues during the design phase, increase the challenges of retrieving material without incurring major downgrading. The current trend is to make parts more complex and out of an increasing number of materials, which will only further compromise dismantling and therefore recycling quality. On another note, **the increasing diversity of material combinations also hinders the alignment of initiatives** in terms of up-scaling, recycling and reusing strategies and technologies (e.g. joining of FRP and metals that is often applied in the automotive sector).

Financial and market

Across the board in Europe, currently there is limited implementation of circular practices, technologies and private initiatives regarding composites in the market. While many recycling technologies and improved materials (easier to repair, recycle, reuse, etc.) are developed at a research level, few of them are reaching market maturity, and even less to full scale up. This represents an overwhelming loss of R&D results, capital and effort for Europe. This situation seems to arise due to a combination of reasons.

A lack of information dissemination across Europe, between sectors and between academia and industry; together with a lack of systematic business model analysis and lack of initiative and investments for upscaling capacity for mature material and process technologies. **An illustrative example** is the fragmentation of private initiatives towards circularity, mainly on developing recycling capacities, resulting in overlapping initiatives, loss of material value due to lack of capacity in areas where it is most necessary (e.g. next to manufacturing plants that could recycle scrap waste), and lack of exploitation of R&D results, etc.

The **lack of alignment** generated creates a persistent gap between new material's recycling properties and adequate and mature recycling technologies. Development of material properties happens at a greater speed than recycling technologies. By the time a recycling technology is mature and suitable for a specific material, the material is likely to be outdated. Current recycling processes are highly energy intensive (e.g. 23-30 MJ/kg on average for conventional pyrolysis or 63-91 MJ/kg for solvolysis[12]), require long cycle times (e.g. from 30 to 60 minutes for solvolysis) and are therefore very costly – ultimately generating a counterproductive environmental impact as well. Commercialising such recycling technologies or upscaling high-capacity recycling plants requires **high capital investment**, as well as the necessity of having a constant, homogeneous, and sufficient **supply of composite waste**. The absence of such a supply creates a highly unstable and unattractive market for private investors.

Moreover, treating higher volumes of composite waste can substantially reduce running costs. For instance, mechanical grinding energy requirement can be decreased up to 0.27 MJ/kg with a recycling rate of 150 kg/hr, from 2.03 MJ/kg at a rate of 10 kg/hr[13].

Furthermore, the **lack of both public and private financial support** or other incentives, together with the lack of dissemination of results in the academic sector, does not help to overcome these barriers.

High costs of recycling processes also translate into **high prices for secondary (recycled) material**, while at the same time, prices of imported virgin materials (for GF especially) are declining, further decreasing the demand for recycled materials and the financial appeal of the recycling market. Furthermore, the lack of understanding of the value and quality of recycled composite materials also prevents more widespread use. **The market still expects secondary raw materials to be significantly cheaper than virgin**, despite having similar or equal properties. Also, landfilling is still cheaper than dismantling and recycling large components such as wind turbine blades and boat parts.

12: Composites Recycling: *Where are we now?*, CompositesUK, (2016).

13: *Energy demand in mechanical recycling of glass fibre reinforced thermoset plastic composites*, Journal of Cleaner Production, (2016).

As previously stated, a large number of European programmes and initiatives seek to promote innovation and technological development. However, **systematic circular initiatives regarding composites do not seem to be visible yet.**

This could partly result from the fact that, since the main focus in Europe is in hi-tech development, more costly and difficult to implement, if simpler, effective and necessary, initiatives do not receive enough attention or are often discarded. Many of these initiatives include crucial reusing and repurposing strategies, but also development of practical initiatives, such as implementing **small recycling pilot plants** for industrial composite waste.

Furthermore, new materials require a process of certification before entering some sectors (e.g. fire-retardant specifications for rolling stock parts, failure specifications for aerospace parts)[14]. The **lengthy certification processes** delay the commercialisation of new, potentially more sustainable materials, such as bio-based thermoplastics that are easier to recycle[15].

Policy

Some of the **barriers** that hinder the increase of circular practices derive from the policy landscape in Europe. In particular, from the **unrealistic current regulations** that either don't match current technological developments, or are non-existent for some aspects (e.g. waste treatment), or a lack of legislative harmonisation across European countries, that in turn **demotivates investments** to increase recycling capacity.

In the first place, the lack of common (in fact often conflicting) **regulation** regarding waste management within Europe results in a fragmented regulatory environment that obstructs waste streams, making sourcing and transporting composite waste very challenging. In the second place, **the lack of harmonised standards** for design and material use in production further complicates sorting and recycling of composite waste as different materials require different recycling technologies.

Furthermore, the **complex regulatory environment** in Europe creates, in some cases, contradictory agendas and objectives (e.g. Circular economy actions vs. waste management) which can hinder the effective progression of initiatives. For instance, in general, European countries have **outdated waste management** legislation that does not regard or treat waste as a resource, thus hampering wider supply and commercialisation.

The **lack of understanding of the value** of composite waste and recycled material and technological advances translates into unrealistically strict regulations concerning the reuse and repurposing of these parts. The use of recycled materials in certain applications, such as boats or airplanes, is in some cases not allowed, although the current properties of many of the recycled materials meet the necessary safety requirements. This translates into a complete absence of specific regulations around composite waste, which is still regarded and treated as plastic waste, and a lack of enforcement of appropriate waste management, including reuse and recycling. In most European countries **landfilling of components containing large amounts of composite material is still allowed.**

14: *Recycled carbon fibre update: Closing the CFRP lifecycle loop*, CompositesWorld, (2014).

15: *Developing a circular economy for novel materials, green alliance*, (2017).

Opportunities

Despite the challenges previously stated, Europe can also enumerate multiple aspects that offer suitable opportunities to increase composites circularity and make Europe a global centre of excellence on this topic.

Europe possesses the **necessary know-how**, capital and human resources to develop and refine the required technology to achieve circularity in this field. This is evident from the fact that R&D initiatives and projects are fruitful, yielding positive results in terms of quality at low TRLs (projects such as EXHUME, MAI Recycling, KARMA2020, etc.). Industrial organisations, universities and RTOs are doing fundamental research in the recycling field, developing different niche technologies (e.g. ELG Carbon Fibre, UK; CFK Valley Recycling, Germany) and improved materials. **New recycling processes and materials can bring unique properties to composites**, allowing a total recovery of resins with minor loss of value (e.g. Arkema developed a resin that can be totally de-polymerised; Recyclamine by Connora Technologies, US/EU; ELG Carbon Fibre, UK).

On the other hand, the growing demand for fibres in Europe, across sectors, together with the increasing use of thermoplastics (especially bio-based) bring a **unique market opportunity** for the recycling industry to scale-up[16]. Carbon fibres are costly and energy intensive to produce – primary energy production of carbon fibres is about 183-704 MJ/kg[13]), and therefore enhancing their recyclability brings new opportunities for cost-effective production.

Also, the **growing interest in bio-based composites** brings a particularly interesting opportunity for enhancing circularity since this not only increases the recyclability of composites, but allows the channelling of other types of waste streams into fibres and resins. Several initiatives are ongoing in Europe focused on transforming organic waste, such as feather waste from the poultry industry, food waste or pulp wood, into polymer composites. Also, the **growing light-weighting priorities**, and the increasing demand for lighter materials and their potential applications, increase the opportunity for market adoption of recycled materials.

Furthermore, polymer composites themselves, due to their long-term durability, represent **a great opportunity to exploit** and establish reusing and repurposing strategies; parts containing composite materials offer a great potential to be refurbished in diverse applications due to their durability, corrosion resistance and light weight.

The EU actions and strict policies towards environmental protection, CO_2 emissions reduction, circular economy and recycling **create a favourable framework for a sustainable development of the composite industry**; and positioning the EU in a leading position in the field with respect to Asia and the USA.

16: *New materials and the circular economy*, Journal of the Institution of Environmental Sciences, (2015).

Strategy for moving forward

Life-cycle strategy

A strategy for moving forward towards composites circularity must take into account the **full life-cycle** of composite materials, identifying the challenges that hinder circularity in each part of the life-cycle, and determining cross-sectional (and across value chain actors) activities that can help to address them. Based on the challenges and opportunities identified and stated previously, and according to the input received from experts and literature research, a holistic strategy has been defined and is set out below.

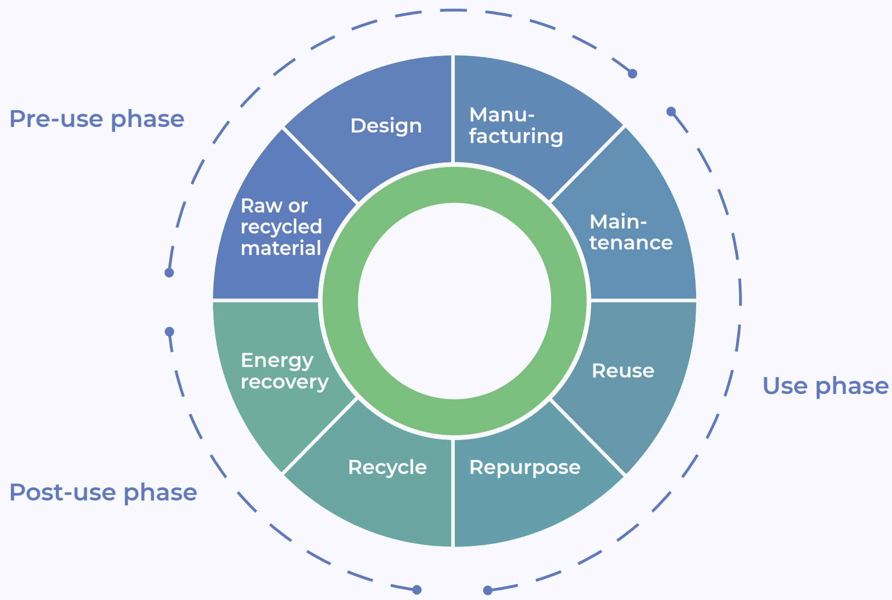


Figure 7. Life-cycle strategy

Raw materials

It is crucial to develop a certification and tracking system for materials in order to overcome the challenges arising from the lack of information symmetry, which results in materials not being optimally recycled or recycled at all, and recycling facilities not having sufficient supply of composite waste. A systematic and harmonised **certification** of each type of material (from raw to recycled), of the corresponding process (including repurpose, reuse, recycling, etc.), and the applicable technology, together with an appropriate tracking along the value chain, would support design and maximise the effectiveness of the processes involved, and therefore maximise material value retention and minimise loss of resources.

On the other side, the recycling capacity of materials can be further improved by focusing on **making resins recyclable** and reducing the loss of quality for recycled fibres. For instance, modifications in the synthesis of thermoset resins can be made to improve their recyclability through solvolysis or the use of additives can improve their recyclability (e.g. dispersion of nano-particles during the material production phase, that can later on help in the separation of the material layers).

Furthermore, minimising the number of material types used in applications can improve separation of materials and the effectiveness of recycling. As an example, chemical companies such as Arkema or BASF use the same type of matrices in their components to ensure **homogeneous waste streams** and therefore a higher quality of recyclate.

Design

The design phase is key when it comes to ensuring and optimising circularity. Design includes material selection and combination, structure design, surface finishing, product assembly and product design. It needs to take into consideration the full life-cycle of the product and its constituents, with special focus on dismantling and **second life of the component**. Ideally the design of material and applications should enable the definition of the reuse and/or recycling pathway(s) and second life of the product and all its components at the end of its first life-cycle.

On the other hand, the homogenisation of materials during production, simplification of products (when possible as in some cases the design complexity is crucial for the application) and prioritisation of mono-material applications as well as prioritisation of bio-based thermoplastics and recycled materials depend on the design phase and would largely contribute to make circularity more effective – in particular recycling. Also, the traceability and certification of materials together with a credible and **universal Life-Cycle Analysis** for both materials and applications can bring to the design phase the necessary tools to become circular, creating a more coherent and long-term vision for circular planning.

Moreover, enforcing and optimising design requires a solid and **systematic communication** between all players along the value chain (material suppliers, manufacturers, end-users, recyclers) in order to align design, not only with the end-use requirements, but with the reuse potential of the components and the recycling potential of the materials involved in a manner that does not alter the properties of composite materials in the application.

Manufacturing

Manufacturing processes and technologies should evolve in order to allow an easier incorporation of used or re-worked parts (coming from use as well as production).

Reusing

In order to enable reuse, it is key to create **common interface standards** for parts for which the expected lifetime is longer than the application lifetime, so they can be reused in similar applications (e.g. hydrogen tanks for automotive applications have a longer lifetime than the vehicles they are installed in). Reusing is the first step of circularity, its main goal is to capture the maximum value of materials by maximising their useful life, therefore avoiding an immediate down-cycling that inevitably occurs when the material is used for a different application.

Recycling

The efficiency of the recycling process, and subsequent quality of the outcome, depends, not only on the technology itself, but on the different steps of the process.

Pre-processing of waste

The quality of the recycled outcome is highly dependent on the quality of the initial waste management stages, i.e. collection, sorting, dismantling and separation. An **effective sorting and separation process** prevents material mixing and damaging each other and helps preserve the maximum purity of the waste resource and hence its related properties.

Recycling

After having analysed the different technology readiness levels and characteristics of the different available technologies, the next steps for the most promising technologies can be summarised below.

Even though solvolysis is considered by many experts to be the **most promising technology**, allowing the highest value retention of both fibres and matrix, some more development is needed to reduce the use of certain additives and components that damage the fibres and/ or can be highly polluting. Some progress can be made as well in pyrolysis regarding the recovery of both matrix and resin; mainly reducing the surface damage of fibres. Solvolysis would be a suitable process for recycling composites with second or later life resins, when no more value can be extracted with more efficient processes. For high voltage pulse fragmentation, some improvements have been made regarding the length and quality of the recovered fibres, which seems to indicate that more can be achieved. As far as fluidised bed is concerned, its biggest value arises from its ability to treat contaminated or non-separable material. This could be an interesting technology for specific waste streams if the fibres recovered were less damaged.

As far as all the reviewed technologies are concerned, the high costs of investment and energy requirements seem to be a common limitation to their greater implementation and scale-up. **Energy efficiency** can be further improved partly by reducing long cycle times and partly by increasing the efficiency of the processes. This would translate into lower and more affordable costs and allow a more acceptable energy use which would not offset the benefits of recycling materials. However, in order to make recycling technologies more efficient and sustainable, the evolution and development of technologies need to be coupled with material development.

Furthermore, **setting-up small recycling plants next to production plants** that would absorb all production waste in homogenous or separable waste streams, in collaboration with the manufacturer, and would recover the resources at a higher rate and better quality would help reduce the high upfront investments (due to the size), and also tackle the issue of collection of waste and materials that are not well characterised.

Post-processing of recycling output

The post-treatment of the recovered materials is also key in order to improve their mechanical properties and therefore maximise their quality and performance in future applications. Some of these include surface thermal or acid treatment of fibres.

Policy

In order to accelerate the implementation of a circular FRP economy, a suitable policy framework needs to be put in place.

In the first place, to achieve circularity at a European level the priority is to update and harmonise policies regarding composite waste management, usage and production between European countries. On the one hand, **updating policies and regulations** that limit the use of recycled materials requires revising and updating the properties, quality standards and applicability of recycled composites. On the other hand, aligning waste management policies and reducing related bureaucracy around Europe would eliminate a major barrier regarding their commercialisation and would help ensure constant and sufficient waste supplies.

Supporting the implementation of **interregional initiatives** would accelerate the alignment of regulations between countries and ultimately encourage an effective industrial scale-up of circular technologies beyond national borders. Updating waste management regulations should also seek to improve waste management quality across European countries. Better waste management, particularly better sorting, would translate in reduced recycling costs and higher resource value retained, therefore decelerating the material loss of value over their (multiple) lifecycles.

Secondly, **increasing the use of recycled material**, and therefore its demand, would in turn increase the attractiveness of the recycling industry, the amount of materials recovered and therefore reduce the amount of material sent to landfill. To support these objectives several incentive policies could be undertaken. These range from putting in place fiscal incentives or subsidies on recycled materials, to disincentives on virgin material, making the first more economically attractive than the second. Others include increasing the cost of landfill, turning reusing, repurposing and recycling into the most viable options.

Finally, more actions should target the **prioritisation of design**. Specific actions include promoting and incentivising R&D and commercial initiatives related to circular design (not only eco-design) especially the set-up of pilot plants or projects where designers and manufacturers work together. Furthermore, in the face of the current trend of increasing complexity of products and devices, circular design needs to be stimulated in order to ensure that circularity is maintained regardless of the complexity of the product. In addition, design standards should be defined at European level, ensuring alignment.

In parallel, it is crucial to raise awareness of the current and potential value of recycled composites across the value chain, primarily with designers, manufacturers and end-users. In addition, cross-value chain collaborations and communication between stakeholders to **align strategies** must be stimulated. It is important to support the implementation of interregional initiatives, in order to support alignment within countries and an effective industrial scale-up of technologies.

Impacts of composite circularity

Based on the opinion collected from experts and stakeholders along the entire composites value chain, the expected impact derived from putting in place a European strategy towards composites circularity has been evaluated.

The most substantial impacts foreseen are both environmental and economic and are often interlinked. In the first place, circularity, **by lowering the global cost of composites**, would enable their incorporation in many other fields and applications. Also, due to their long-lasting quality, this would substantially contribute to the reduction of raw material extraction worldwide.

Furthermore, the **increase in reusing and repurposing**, that translates into a reduction in the manufacturing rate of composites and other products, would have a direct positive impact on CO_2 emissions reduction. Mainstreaming composite recycling would further contribute, since energy demand for material processing is the main driver in terms of environmental impact; with electricity usage in manufacturing and recycling processes having the highest energy footprint in fibre production.

While the manufacturing stage accounts for as much as 183-286 MJ/kg for virgin carbon and 13-32 MJ/kg for virgin glass fibre, recycling requires 10 to 20 times less energy. In particular, mechanical recycling requires on average as little as 0.17-0.27 MJ/kg at maximum capacity, conventional pyrolysis 12-30 MJ/kg and microwave pyrolysis 5-10 MJ/kg. Therefore, extending the life of composite materials by at least one additional useful application would result in annual savings of at least 160 000 tonnes of CO_2 assuming 40 000 tonnes of composites waste production annually and an equivalence of 70 grams CO_{2eq} per MJ.

All in all, further reducing natural resource extraction and its associated environmental footprint, at the same time as decreasing Europe's external resource dependency, would ultimately translate into a reduced material price volatility and hence higher market stability.

On the other hand, the **circular economy has shown to boost local economy**, create employment and reinforce the links between different sectors and companies. This would be replicated in the composites sector with a 15% increase in employment foreseen in the recycling and waste management sector over the next 15 years. The need to strengthen the chemistry, design, and manufacturing phases, as well as further develop the recycling technologies, offer multiple opportunities for job creation.

Moreover, the **need to promote smaller and more localised initiatives**, such as setting up recycling plants next to production plants, will promote job creation, while it reduces the transportation share of CO_2 emissions and derived costs and impacts.

About SusChem

SusChem is the European Technology Platform for Sustainable Chemistry. It is a forum that brings together industry, academia, policy makers and the wider society.

SusChem's **vision** is for a competitive and innovative Europe where sustainable chemistry and biotechnology together provide solutions for future generations.

SusChem's **mission** is to initiate and inspire European chemical and biochemical innovation to respond effectively to societal's challenges by providing sustainable solutions.

SusChem was officially launched in 2004 as a European Commission supported initiative to revitalise and inspire European chemistry and industrial biotechnology research, development and innovation in a sustainable way.

At SusChem we believe that sustainable chemistry can inspire a change of pace and the new mind-set that society needs in order to become (more) sustainable, smart and inclusive.

In partnership with European and national public authorities, SusChem contributes to initiatives that aim to provide sustainable solutions to society's big challenges. Together we develop and lead large-scale, integrated research and innovation programmes with chemical sciences at their core. These public private initiatives link research and partners along the value chain to real world markets through accelerated innovations.

SusChem across Europe

SusChem has established a network of National Technology Platforms (NTPs) in 15 countries across Europe: Austria, Belgium, Bulgaria, Czech Republic, France, Germany, Greece, Italy, Netherlands, Poland, Romania, Slovenia, Spain, Switzerland and United Kingdom.

NTPs help to connect SusChem thinking with national and regional programmes. It also facilitates transnational collaboration and advice SusChem at the European level on collective national priorities that need to be considered in European initiatives.

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