Deliverable 1.1

Mapping and assessment of complex EoL composite waste stream

30th November 2022

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30/11/2022	6	Final version

RECREATE Project abstract

The main objective of the RECREATE project is to develop a set of innovative technologies aimed at exploiting the circularity potential of End-of-Life (EoL) complex composite waste (mainly carbon fiber reinforced composites CFRC, and glass fiber reinforced composites GFRC) as a feedstock for profitable reuse of parts and materials in the manufacturing industry.

The demand for both composites and high-performance fiber materials (especially carbon) at affordable costs is actually foreseen to grow steadily in the next few years. This trend is driven by progressive banning of landfilling of composite waste and growing needs in many sectors like automotive, transportation and in general for the lightweight design field. It is therefore crucial that **new technological alternatives to the more consolidated mechanical grinding and pyrolysis are identified**, so as to allow the recovery and reuse of materials and components in an environmental and economically convincing and sustainable way.

In the light of these considerations, **the ambition of RECREATE project is**:

- To develop and validate in relevant environment (TRL6) novel reuse strategies for current generation, large EoL composite parts (including complex multi-material composites) based on smart recognition and inspection for sorting (Laser Induced Breakdown Spectroscopy - LIBS), high precision dismantling (laser-shock) and repair, T-assisted reshaping, design for disassembly based on reversible joints, AI-assisted decision support systems.
- To develop and validate in relevant environment (TRL6) innovative physico-chemical upcycling technologies (catalyst-assisted green solvolysis, electro fragmentation) allowing simultaneous recovery of high quality, integer, clean fibers and of an organic resin fraction reusable as coating material, at the very end of the multiple reuse processes of parts.
- To demonstrate at TRL6 the use of smart and green reversible thermoset resins as enabling materials for the realization of the next generation of fiber-reinforced composites (FRCs) with easier repairability and enhanced reusability, facilitating the transition towards recyclable-by-design composite materials and structures.

Moreover, RECREATE addresses **another key objective** to develop a set of new digital tools for:

- Quantitative evaluation of the environmental and economic performance of the proposed technologies (LCA/LCC) as well as their circularity assessment;
- Co-design of innovative digital learning resources, including the realisation of MOOCs, serious games and digital twins of some specialty technologies developed in the project, with easy adoption and high replicability.

The objectives and the ambition of RECREATE are fully compliant with the general requirements of the Horizon Europe - Digital, Industry and Space 2021 Work Programme, and with the specific requirements of the call Horizon-CL4-2021-Resilience-01-01.

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List of abbreviations

CFRP	Carbon Fiber Reinforced Plastic
EoL	End of Life
FRC	Fiber Reinforced Composite
GFRP	Glass Fiber Reinforced Plastic
KPI	Key Performance Indicator
rCF	Recycled Carbon Fiber
rGF	Recycled Glass Fiber
TRL	Technology Readiness Level

Objectives of the task supporting the deliverable

Objectives

Task 1.1 opens the scouting and assessment activities of *WP1- Input EoL streams and output requirements*. It focuses on the existing main manufacturing markets which mostly exploit composites. It analyses the typology of composites available in the market, their end-of-life expectations, the current possibilities of end-of-life management. It puts the basis for a market adoption of the RECREATE technologies.

Task T1.1: Mapping of suitable EoL composite waste

A detailed assessment and mapping of the complex EoL composite waste stream sources in Europe in terms of composition, volumes, availability, and locations will be performed covering different sectors (wind, automotive, aviation, nautical, construction, etc.). The main objective is to map waste streams to be used as input materials for the validation of the proposed reuse and recycling solutions (WP2,3), for the definition of suitable design guidelines for next-gen FRC materials and parts (WP4), and in the development of demonstrators (WP5). The output of this task will put the basis for emerging digital business models (WP6).

Key activities undertaken

The task performed four combined studies, focusing on:

- The current recycling and recovery possibilities for composites in Europe.
- The current and future landfilling possibilities and economic viability for composites in Europe.
- An assessment of the overall composites European market.
- An assessment of six composites product categories, including technical characterization, European stock and end-of-life volumes forecast.

The merging of these analyses resulted in an assessment of the waste streams to be intercepted by the RECREATE innovative technologies portfolio.

Follow up

Being the first RECREATE *non-project-management* task, it somehow reflects its results on the entire rest of the project. More specifically:

- It characterizes the demo cases input products, better pictured in T1.3.
- It defines the reference products and market for the technologies, pilots and business models development in WP4 – WP6.
- The quantitative product characterizations and market volumes can be used to calculate the KPIs defined in T1.2.

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Executive Summary

This document presents the deliverable D1.1 “Mapping and assessment of complex EoL composite waste stream” of the RECREATE Project. The deliverable is the work performed under WP1 “Input EoL streams and output requirements”, and reports the main outcomes of Task 1.1 “Mapping of suitable EoL composite waste”.

Task T1.1 focuses on the assessment and mapping of complex EoL composite stream sources in Europe in terms of composition, volumes, availability, and locations. The analysis has been carried out considering different industrial sectors as potential providers of EoL composite and/or industrial by-products: aerospace, automotive, offshore and naval, wind energy, construction and sport equipment.

The main objective has been the mapping of waste streams to be used as input materials for the validation of the proposed reuse, remanufacturing and recycling solutions (WP2,3), for the definition of suitable design guidelines for next-generation of FRC materials and parts (WP4), and in the development of demonstrators (WP5). The output of this task will put the basis for emerging digital business models for reused and recycled composite parts and materials (WP6).

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Glossary

This document represents the first official result of the RECREATE project. It has been decided to include a glossary to define the main entities belonging to the Composites Circular Economy domain. It is not to be considered as an exhaustive list; it actually includes the most important definitions discussed in the preliminary phase of the project.

CARBON FIBERS - Reinforcing fiber produced by the pyrolysis of an organic precursor fiber, such as PAN (polyacrylonitrile), rayon or pitch, in an inert atmosphere at temperatures above 982°C/1800°F. The term carbon is often used interchangeably with the term graphite, but the fibers differ. Carbon fibers are typically carbonized at about 1315°C/2400°F and contain 93 percent to 95 percent carbon. Carbon fibers can be converted to graphite fibers by graphitization at 1900°C to 2480°C (3450°F to 4500°F), after which they contain more than 99 percent elemental carbon. Carbon fibers are known for their light weight, high strength and high stiffness.

CATALYST - Substance that promotes or controls curing of a compound without being consumed in the reaction.

COMPOSITE - A matrix material reinforced with continuous or discontinuous filaments. The constituents retain their identities in the composite; they do not dissolve or merge completely into each other although they act in concert.

COMPOUND - An intimate mixture of polymer or polymers with all the materials necessary for the finished product.

CURE - Irreversible alteration of the molecular structure and physical properties of a thermosetting resin induced by a chemical crosslinking reaction, typically stimulated by heat and/or the presence of catalysts, with or without applied pressure.

DEBOND - A deliberate separation of a bonded joint or interface, usually for repair or rework purposes.

DEFORMATION - The change in shape of a specimen caused by the application of a load or force.

DEGRADATION - A deleterious change in chemical structure, physical properties or appearance.

DELAMINATION - The separation of the layers of material in a laminate. This may be local or may cover a large area of the laminate. It may occur at any time in the cure or subsequent life of the laminate and may arise from a wide variety of causes.

EPOXY - A thermosetting polymer containing one or more epoxide or oxirane groups, curable by reaction with amines, carboxy acids or alcohols; used as a resin matrix in reinforced plastic products and as the primary component in certain structural adhesives. Cured epoxy resin is highly resistant to chemicals and water and its performance properties are relatively unaffected by extreme temperatures.

FABRIC - A material constructed of interlaced yarns, fibers or filaments. Also known as "cloth".

FIBER - A single homogeneous strand of material, essentially one-dimensional in the macro-behavioral sense, used as a principal constituent in composites because of its high axial strength and modulus.

FABRIC, NONWOVEN - Planar textile constructed by bonding or interlocking but not interlacing fibers or yarns by mechanical, chemical, thermal or solvent means.

FIBERGLASS - The generic name for glass fibers and for composites using glass fibers for reinforcement.

FIBER REINFORCED POLYMER - An engineered material consisting of reinforcement fibers, polymer resin, and additives to achieve targeted performance properties. This combination creates an extremely strong and durable material that can be used for applications ranging from equipment parts to large infrastructure components.

INTERFACE - The boundary between the individual, physically distinguishable constituents of a composite. In glass fibers, for instance, the area at which the glass and sizing meet; in a laminate, the area at which the reinforcement and laminating resin meet.

LAMINATE - A product made by bonding together two or more layers of laminate of material or materials.

MATRIX - The essentially homogeneous material in which the fiber system of a composite is embedded.

PREPREG - Fibrous reinforcement (sheet, tape, tow, fabric or mat) pre-impregnated with resin and capable of storage for later use. For thermosetting matrices, the resin is usually partially cured or otherwise brought to a controlled viscosity, called B-stage. Additives (e.g., catalysts, inhibitors and flame retardants) are used to obtain specific end-use properties and/or improve processing, storage and handling characteristics.

RECYCLING - In composite treatment, it is the process allowing the recovery of fibers (GFs/CFs) or resins from End-of-Life product or by-products.

REMANUFACTURING - In composite treatment, it is the process allowing the reuse of End-of-Life parts after reforming of reshaping procedures.

REUSE – Reuse can either refer to parts or materials. The first case refers to the reuse of End-of-Life parts in new assemblies. The second refers to the reuse of recycled materials into new composite products.

RESIN - A form of plastics/polymers commonly used in manufacturing. In FRP, resins provide the polymer component of Fiber Reinforced Polymer. The resin choice largely determines the properties of the FRP product. Most resins used in FRP are some types of thermosets.

THERMOPLASTIC - A plastic that repeatedly can be softened by heating and hardened by cooling through a temperature range characteristic of the plastic; in the softened stage, it can be shaped by flow into articles by molding or extrusion.

THERMOSET - A plastic that is substantially infusible and insoluble after having been cured by heat or other means.

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Introduction

Despite RECREATE is a scientific project, which aims to prove the scalability of a portfolio of circular economy technologies to intermediate TRLs (5-6), its strategical strength relies in the applicability of these technologies in already established commercial domains. Given this starting point, the scope of this document is to provide a comprehensive analysis of the current status of Circular Economy practices for composites in Europe.

Scope and objectives

The scope of this document is to assess the limitations and opportunities of the current European Circular Economy market for composites, with a particular focus on sectorial assessments, to highlight where the RECREATE technologies will gain more attraction in function of the specific composite products and volumes.

This goal is achieved by performing four combined studies, focusing on:

- The current recycling and recovery possibilities for composites in Europe.
- The current and future landfilling possibilities and economic viability for composites in Europe.
- An assessment of the overall composites European market.
- An assessment of six composites product categories, including technical characterization, European stock and end-of-life volumes forecast.

The merging of these analyses results in an assessment of the waste streams to be intercepted by the RECREATE innovative technologies portfolio.

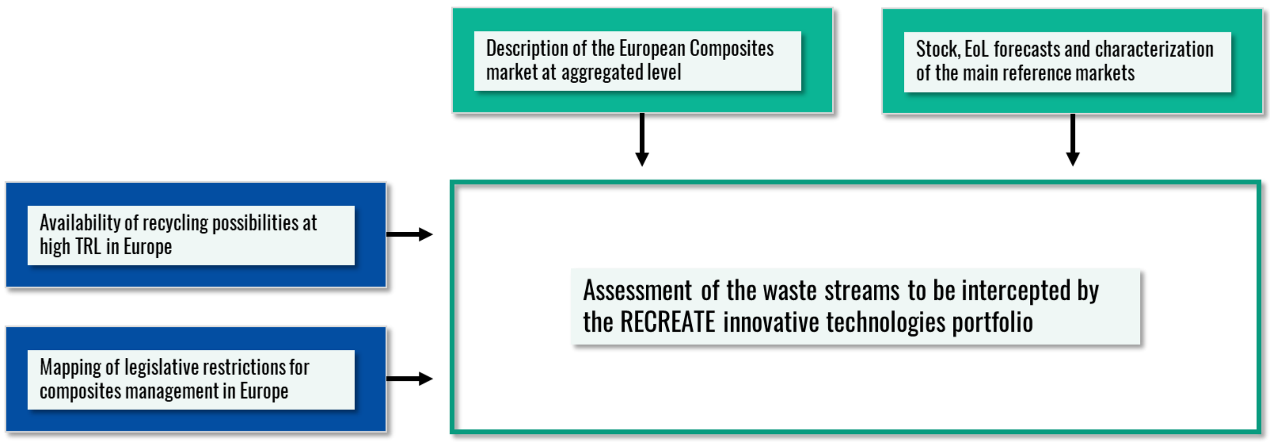

Figure 1: conceptual framework of the T1.1 analysis

Deliverable structure

The first core chapter introduces the composites European manufacturing market, specifying the reference segments, the typology of fibers and resins used as well as the manufacturing technologies.

Then, the European state-of-the-art Circular Economy options for composites are presented. Two analyses are combined: the first frames the legislative boundaries for composites landfilling; while the second maps the current technologies available for composites recycling or repurposing and their TRL.

The core quantitative part of the deliverable analyses six target sectors with important FRPs usage. For each segment, FRP components are qualitatively characterized, then, according to the availability of data source, an estimation of the market composites stock and forecast of returning volumes is performed.

Finally, the deliverable is concluded by presenting a matchmaking matrix which stresses the applicability of different RECREATE technologies to specific product families.

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The composites market

Composites have been in industrial use since the 1930s. Series production began as early as the 1940s. Since then, composites have been firmly established in numerous application segments. Both the composition of the materials and the range of applications are extremely heterogeneous. Since composites are a combination of materials, their properties and potential applications can vary greatly.

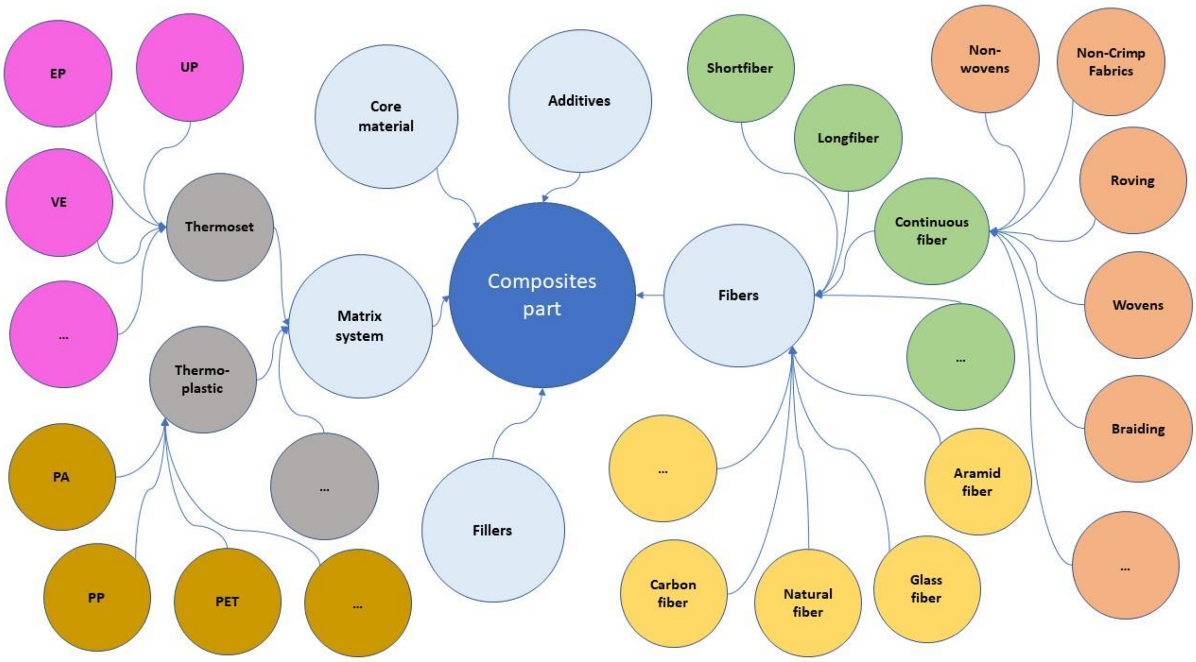

Figure 2: Exemplary input materials/combinations of composites

This does not make it easy to take a holistic view of the market and sometimes market assessments/distributions differ slightly from one another.

The worldwide composites market

Like other industrial sectors, the composites market has been heavily impacted by the corona pandemic and other negative factors in recent years. The JEC Group stated that the composites industry at global level is in a recovery in 2021 after a decline in 2020. Overall, the industry is back to a level comparable to 2019 (average growth of +2% p.a.). (See Figure 3).

In volume, the composite materials market is estimated at ~ 12.1 Mt in 2021. Asian is the first market in volume (~ 50%), followed by Americas (~ 25%) and EMEA (~ 25%). After 2021, the composites industry is expected to resume its long-term growth trend. The market growth is estimated at ~ 5% p.a. at global level for the 2021-2026 period (JEC Group, 2021).

The construction sector is the largest application area worldwide, followed by the transport sector. This is followed by the electrical/electronics sector and the energy sector (Figure 4).

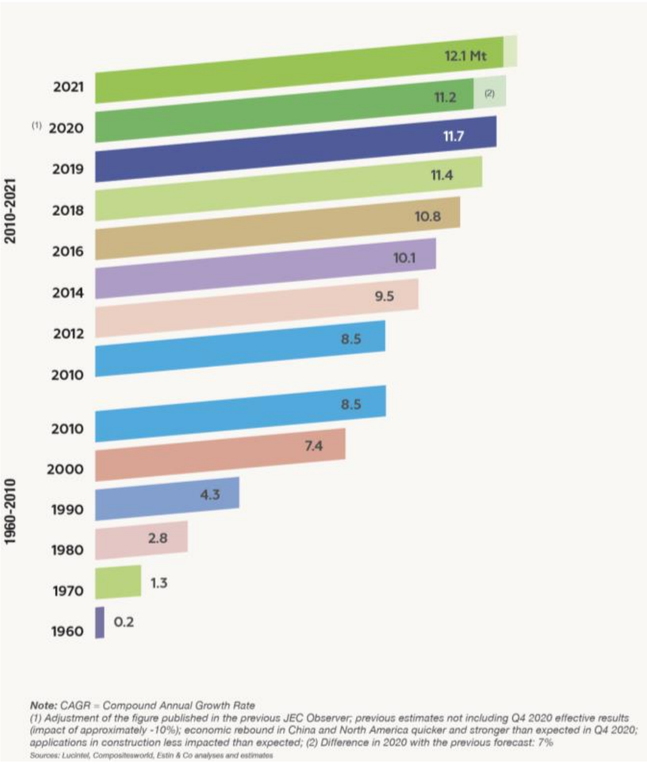

Figure 3: Evolution of the composite materials market – 1960-2021 – Global – In volume (Mt) (JEC Group, 2021)

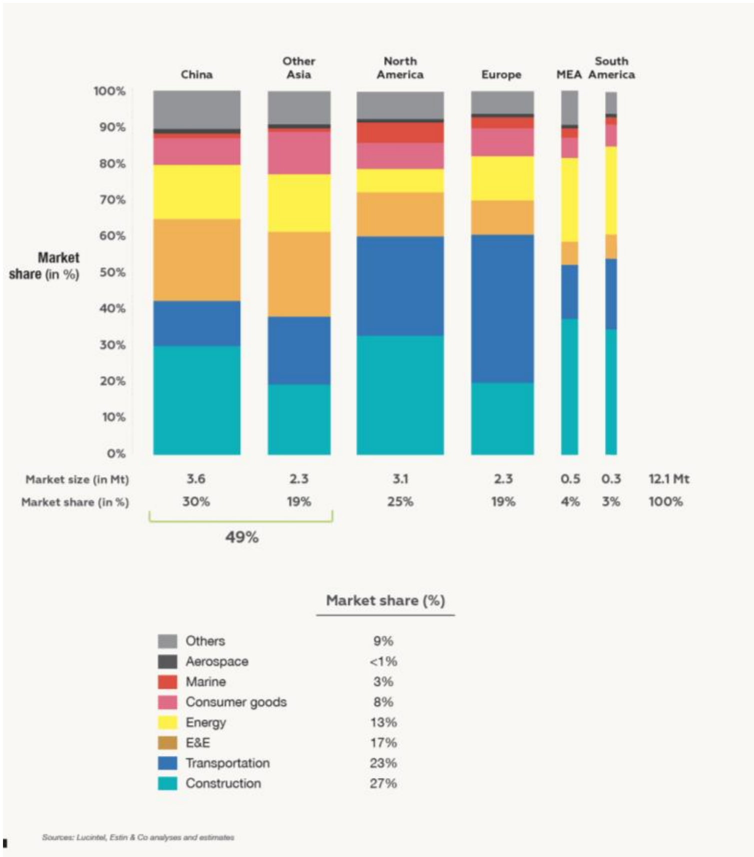

Figure 4: Perspective of applications markets – Global – 2021 – In volume (JEC Group, 2021)

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The European composites market

After a long period of growth from 2013 to 2018, the corona pandemic, which began in February 2020, as well as many other negative factors have severely impacted not only the economy as a whole, but the industrial sector and composites market in particular.

European composites production volumes declined by more than 15% in the period 2018-2020. In 2021, this trend was clearly reversed. With growth of 18.3%, the market almost returned to its pre-crisis level.

Glass fiber reinforced systems still account for over 95% of the overall market. By contrast, other material systems, such as CFRP (carbon fiber reinforced plastics) or NFRP (natural fiber reinforced plastics) remain specialties. However, they continue to develop positively in corresponding application segments.

Thermoplastic composites have been the prime beneficiaries of these developments, growing by more than 25% over the past year. Thermoset materials grew by just over 10%. Thermoplastics are highly dependent on the transport sector, which accounts for over 70% of their applications. The key area for thermosets is construction, which is several percentage points stronger than the transport sector (see Figure 5).

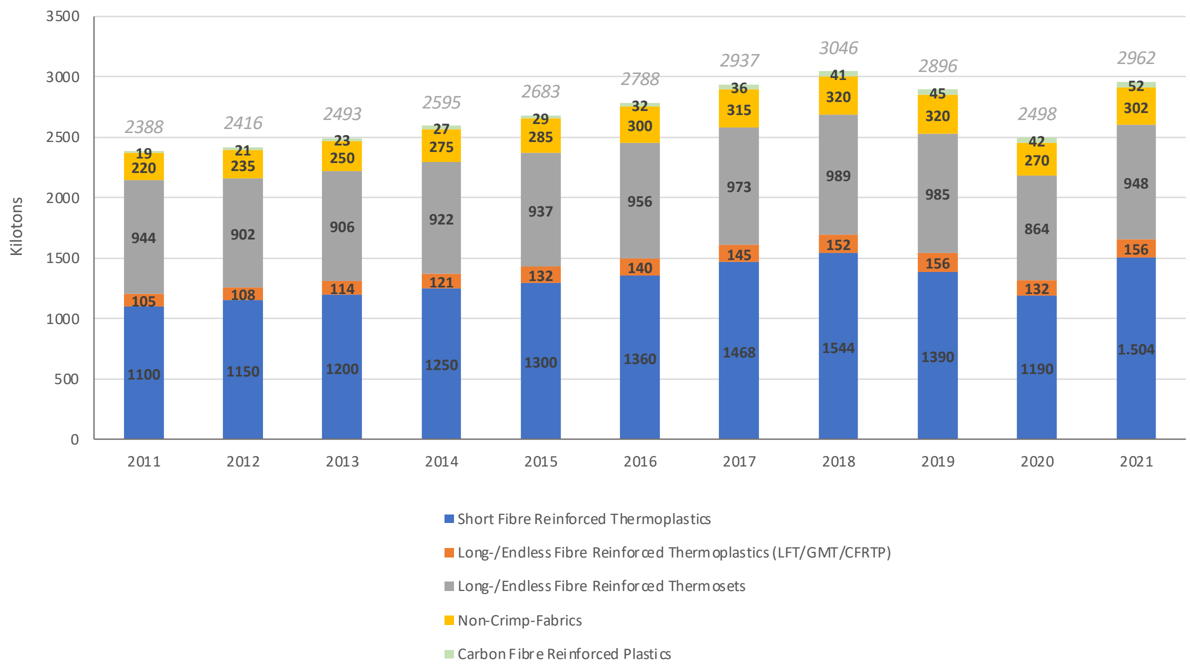

Figure 5: Composites production volume in Europe since 2011 (in 000 t) - Not included: Natural Fiber Reinforced Plastics (2012 = 90,000 tons) (AVK – Industrievereinigung Verstärkte Kunststoffe, 2021)

The increase was thus significantly higher than overall economic growth in the EU, which the European Commission reported as being 5.3 % in 2021. Growth in industrial production in the EU, which the Kiel Institute for the World Economy (IfW) estimates at 4 % for 2021, was also significantly slower than in the composites industry.

While the impact of the corona pandemic and its cuts and restrictions were the dominant factors in market activity worldwide for a long time, with no exception in Europe, its effects are now diminishing. The industrial sector faced many other challenges in 2021, but their impact on the composites industry varies widely. These include, e.g., the continuing weakness of automotive sales in Europe, the aviation industry, which has not yet regained its former strength, very high logistics costs and, most recent, energy costs, the lack of availability of raw materials and semi-finished products, and increasingly also political tensions, which are evident, for example, in the current war in Ukraine.

All these factors have led to a great deal of uncertainty in the markets and complicate the task of forecasting future developments. In addition, markets are becoming more dynamic. The close international links in the composites industry can also mean that events outside the core markets have a significant impact on market activity.

Despite numerous obstacles, key application segments performed very positively in 2021. These primarily included the transport sector, but also other application areas from the sports and leisure segment. In the transport sector, especially in passenger car production, an unusual phenomenon is currently emerging: OEMs' profit margins are rising significantly despite low sales figures. The impact of this phenomenon on the composites market is analysed in greater detail in the section on thermoplastics. The second major application area, construction and infrastructure, was significantly less affected by cuts as a whole. However, this is usually the case for the construction sector, which reacts much more slowly to macroeconomic changes – and with fewer swings – than the transport sector. Strong overall figures from the transport sector have led to a significant increase in production volumes. This applies, in particular, to the commercial vehicles sector, the consistently good trends in the construction and infrastructure sectors, and the positive developments in certain specific applications, e.g. in sports and leisure.

In regional terms, Germany, Spain/Portugal, Italy and Eastern European countries continued to maintain their strong positions in the European context. Germany remains the country with the highest market volume, with a share of almost 20% of the total market. These four regions together represent 2/3 of the European market volume.

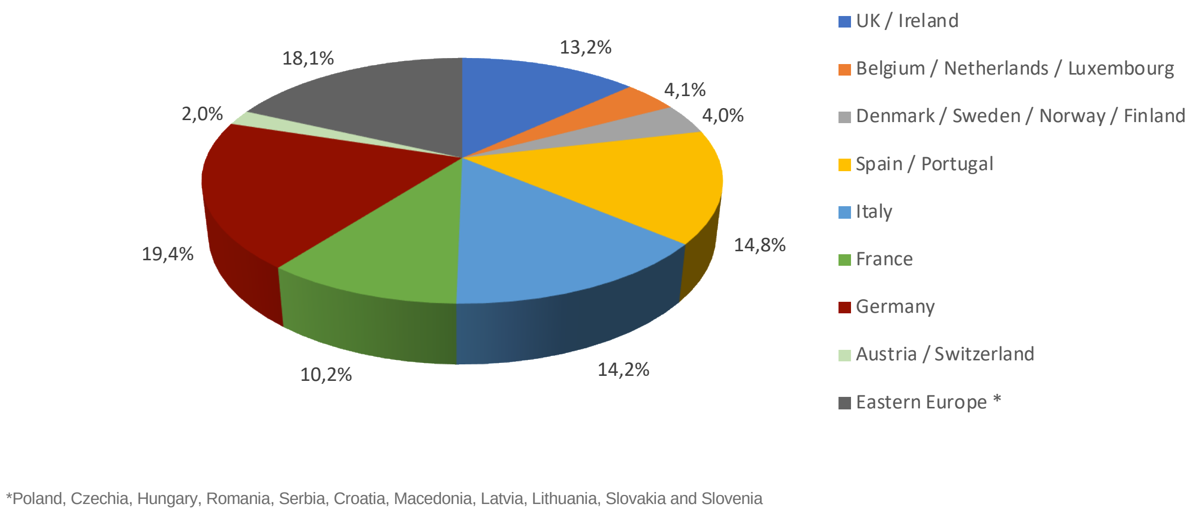

Figure 6: European Composites Market in % by region (AVK – Industrievereinigung Verstärkte Kunststoffe, 2021)

The market trend within Europe is not uniform. The differences can be attributed to wide variations between the regional core markets, the high variability of the materials processed, the broad spectrum of manufacturing processes and widely differing areas of application.

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The composites market by application

In terms of volume, the largest share of total composites production (50 %) is used in the transport sector (Figure 7). The next two largest sectors are construction and infrastructure and electro/electronics.

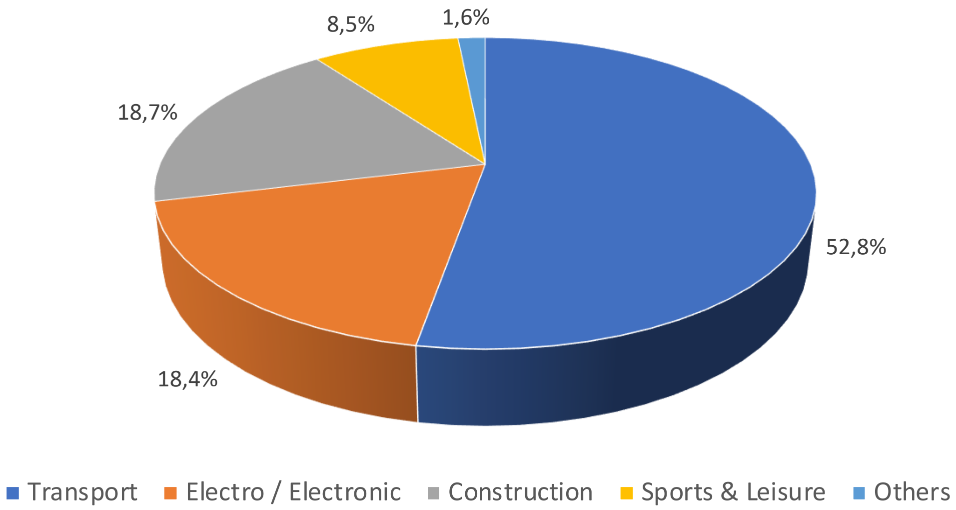

Figure 7: Total composites market by application in 2021 (in %; excluding CRP) (AVK – Industrievereinigung Verstärkte Kunststoffe, 2021)

The transport sector includes not only passenger car production, but also commercial vehicles, aviation, public transport, etc. The construction/infrastructure sector includes pipelines, containers, tanks, profiles, etc. The electro/electronics sector includes, e.g., switches, housings, telecommunications equipment or control cabinets.

The big group of non-crimp fabrics (NCF) is not included in the figure. Over the past ten years, this market segment has grown by almost 40 %. While the market level in 2011 was still 220,000 tons, it will reach 302,000 tons in 2021. This market segment has enjoyed above-average growth for the past ten years. Its two principal applications are in wind turbine blades and boat and ship building. Strong growth is forecast, especially for the wind energy sector, in the coming years. The wind energy industry, in particular, is likely to be the key driver in this segment over the next few years.

CRP market volume grew very dynamically in 2021, increasing by more than 23% compared to 2020 (Composites United e.V., 2022). The global market volume increased to 147,500 tons, of which Europe accounted for approx. 1/3. The total volume in Europe increased to 52,000 tons.

The largest areas of application for CFRP are aviation, other transport sectors and the wind industry. About 3/4 of the total amount of material flows into the three application segments mentioned. Aerospace is the largest single segment, followed by transportation and wind energy. Here, too, wind energy should develop very dynamically in the coming years (Composites United e.V., 2022).

Composite recycling in Europe

As any other source of waste, the waste hierarchy expressed in (*Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives (Text with EEA relevance)*, 2008) can be applied also to composite products.

Article 4

Waste hierarchy

1. The following waste hierarchy shall apply as a priority order in waste prevention and management legislation and policy:

(a) prevention;

(b) preparing for re-use;

(c) recycling;

(d) other recovery, e.g. energy recovery; and

(e) disposal.

Figure 8: waste hierarchy, (Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives (Text with EEA relevance), 2008)

Therefore, best-practices as material reuse or recycling are always preferred to incineration for energy recovery or landfilling. Nevertheless, such virtuous practices are not yet established in Europe (and worldwide) because of inadequate technological readiness of recycling and restoration technologies; low maturity of circular economy ecosystems and value chains; poor or null profitability.

This chapter is dedicated to present the state-of-the art recycling and repurposing technologies appliable to composites at different TRLs and to provide an overview of the most established industrial actors currently operating in Europe.

Circular economy options for composites

The first paragraph of this chapter is dedicated to briefly present the state-of-the-art technologies and processes for the circular economy management of composites. Examples are available in literature for both recycling and repurposing, and here proposed in the next two subparagraphs.

Recycling of composite materials

Recycling of composites is defined as a process or process chain capable to (partially) recover raw materials available inside the composite resin/fibers structure. Because of the chemically irreversible

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structure of thermoset matrixes, embedded in most of commercially available composite products, inhibits their recovery, recycling of composites is typically referred to the recovery of the fibers.

There is general agreement in the scientific and industrial communities in considering three main families of composites recycling technologies options, namely mechanical, thermal and chemical recycling (Figure 9) (Bledzki et al., 2021; Gonçalves et al., 2022; Karuppannan Gopalraj and Kärki, 2020; Krauklis et al., 2021; Xue et al., 2022; Zhang et al., 2020).

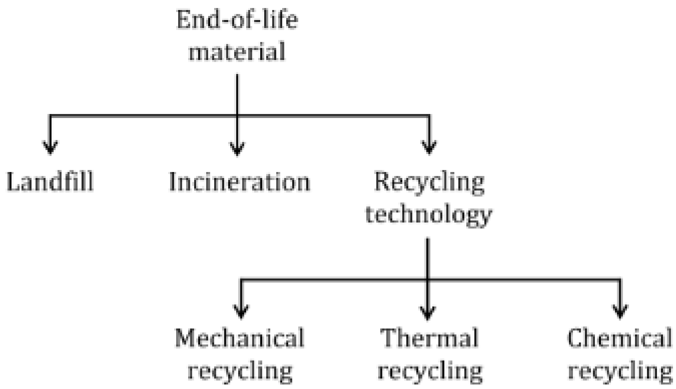

Figure 9: Representation of different recycling processes for thermoset composite materials. Simplified from (Gonçalves et al., 2022), [CC BY 4.0](#) license

A brief description of the operating principles and maturity level of technologies populating these macro categories is below provided. Finally, pros and cons of the three process families are highlighted in Table 2.

Mechanical recycling

Mechanical recycling is the most common and mature process to recycle thermoset composites. This process considers crushing of composites into smaller particles to achieve acceptable liberation of fibers from resin. Some more detailed technological considerations regarding mechanical recycling are here reported:

- Recycling pre-treatments, namely cutting or chopping of big composites infrastructures, must be applied to provide to the main crushing technology composite parts small enough to be fed into the machine hopper. Nevertheless, such treatments also have positive implications: as they can be decoupled from the main recycling stage, they can be performed on-site, reducing the volume of EoL products before transportation to the recycling facility. For examples, EoL wind blades are usually cut or chopped on-site, thus dramatically reducing their volume.
- Crushing equipment as hammer mills or cutting mills are most often used to perform composites shredding (*Figure* 10). Usually, classifier screens of different mesh size divide the shredding chamber and the collection bin, thus enabling selective collection of particles comminuted below a threshold size.
- Regardless the usage of screens under the shredding chamber, downstream classification steps are often used to sort and purify different material streams. Equipment like sieves or zig-zag classifiers enable the (partial) segregation of coarse fibers from resin rich fine powder. An example is visible in *Figure* 11.
- Output streams for mechanical recycled FRPs can be (roughly) identified in function of the size range, as summarized in *Table* 1.

Table 1: particle size and application range of mechanical recycling outputs. Taken from (Xue et al., 2022)

Particle size	Application range
> 25x25 mm	Building materials, such as cardboards made from waste paper, lightweight cement boards, floor covering materials and sound insulation materials.
3.2 ~ 9.5 mm	Reinforcers or fillers for bulk molding compounds, thermoplastics, concrete and asphalt.
< 60 µm	Fillers for sheet molding compounds, bulk molding compounds and thermoplastic.

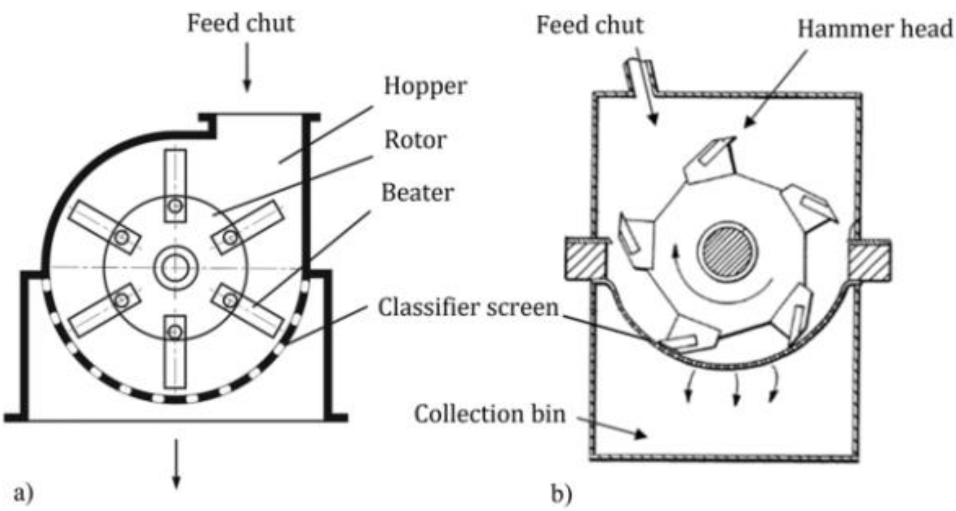

Figure 10: schematics of a rotating (a) hammer mill and (b) cutting mill, with changeable classifier screen. Taken from (Gonçalves et al., 2022), [CC BY 4.0](#) license

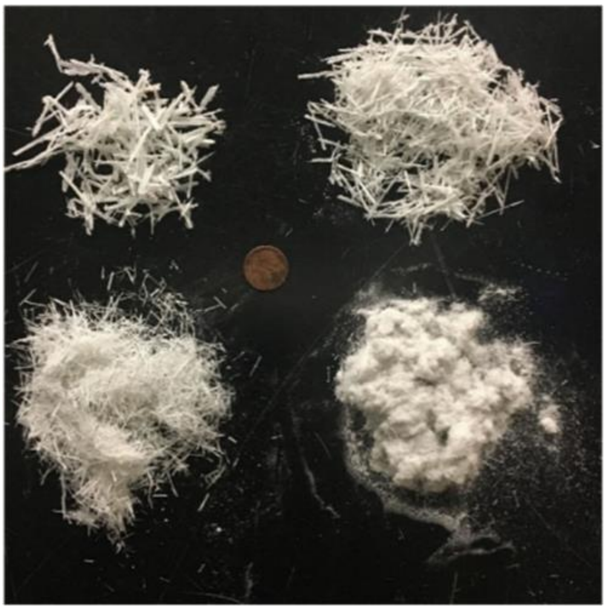

Figure 11: three stage classification of shredded GFRP. Taken from (Gonçalves et al., 2022), [CC BY 4.0](#) license

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Thermal recycling

Thermal recycling involves the treatment of composites materials using high-temperature stimulus. Sometimes, also incineration or combustion for energy recovery are included into the thermal recycling processes family. Nevertheless, as no material revalorization is considered in incineration and combustion, such practices are not included in this deliverable.

Some thermal treatment strategies are in between recycling and energy recovery. For example, burning waste composites in cement kilns converts in heat part of the GRFP waste, while the inert elements are embedded into cement.

Higher added value thermal recycling options are pyrolysis methods, including fluidized bed technology.

Pyrolysis exploits high temperature decomposition phenomena of plastic to decompose FRP waste in anaerobic or aerobic conditions. During pyrolysis, the organic part of the composite is decomposed into liquids or gasses, which after condensation can be used as fuel or chemical sources. The remaining inorganic part (glass and carbon fibers, other fillers) is recovered as a solid byproduct released from the resin.

Pyrolysis is particularly adequate for the recycling of carbon fibers, as carbon is capable of poor mechanical properties loss while undergoing this thermal cycle. Under specific operative conditions (temperature, oxidation level) recovered CFs can maintain > 90% of the initial mechanical properties and achieve > 120% of the interface mechanical strength (Jeong et al., 2019).

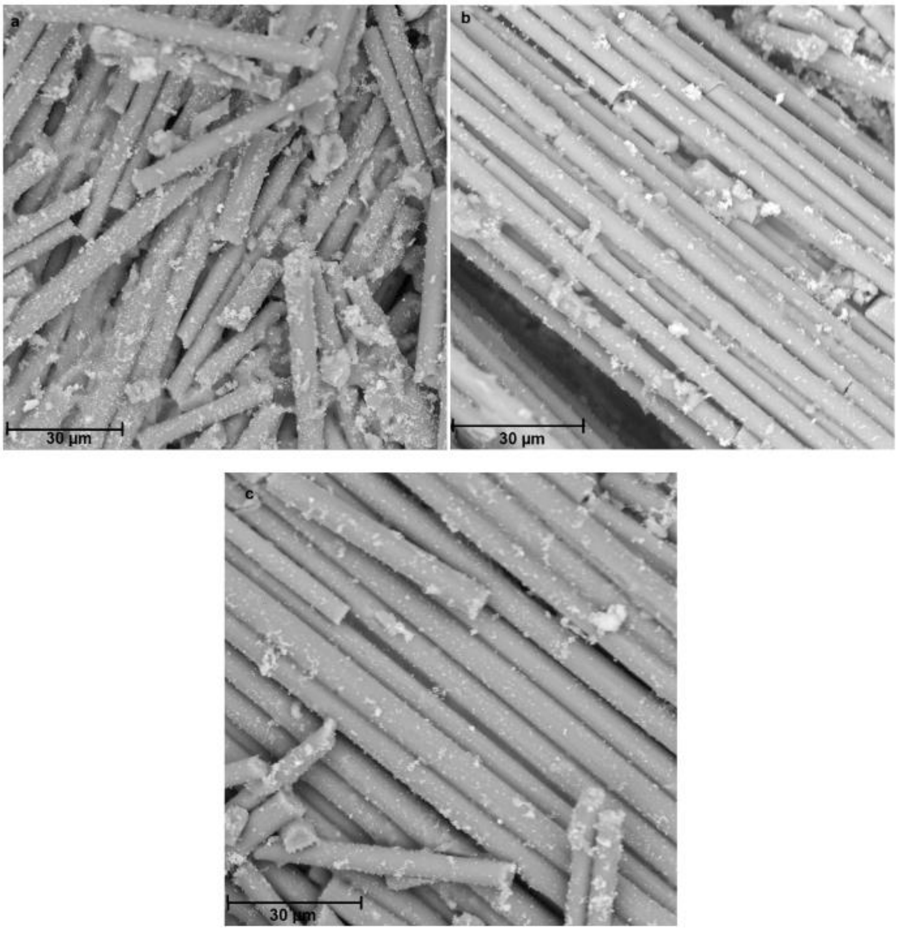

Figure 12: SEM images of carbon fibers after pyrolysis. (a) 480 °C, (b) 520 °C, (c) 560 °C. Taken from (Schwarz et al., 2020), CC BY 4.0 license

Fluidized bed recycling is a particular pyrolysis where FRPs are mechanically pre-treated and then guided on a distribution plate which enables the controlled flow of hot air (or other gasses) stream to create a fluidized bed of solid particles, as silica or sand. The hot stream volatilizes the polymer matrix and releases fibers and fillers. Then the different material families are classified by a rotary screen separator. Clean fibers are therefore collected with low resin and fillers contamination. Resin is then burnt in an afterburner.

Fluidized bed recycling provides both advantages and disadvantages with respect to traditional pyrolysis:

- Recycled fibers are mostly short fibers in fluffy form.
- Fluidized bed fibers recovery rates are high, above 90% wt.
- Fluidization makes the surface of recycled fibers clean without resin residue, but it also leads to fiber length and strength damage.
- The mechanical strength loss of fibers is higher in fluidized beds than in traditional pyrolysis.

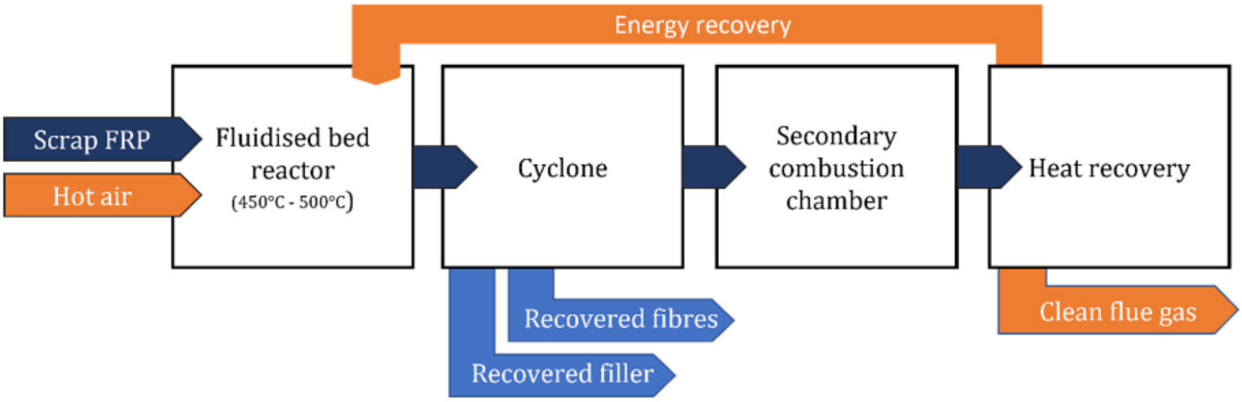

Figure 13: fluidized-bed recycling process. Taken from (Gonçalves et al., 2022), CC BY 4.0 license

Thermal recycling enables the recovery of longer and cleaner fibers which maintain better mechanical properties compared to mechanical recycling. Therefore, thermally recycled fibers are adequate for nobler applications, in structural components.

The non-negligible processing costs justify thermal recycling mainly for carbon fibers.

Chemical recycling

Chemical recycling involves the use of solvents to dissolve the polymeric matrix and release the fibers. This wide family of processes is typically divided in two macro sub-categories: low temperature solvolysis and supercritical fluids.

Solvolysis uses chemical agents as nitric acid at atmosphere pressure and controlled temperature to dissolve the resin (for example epoxy resin) from the fibers.

Supercritical fluids exploit water (hydrolysis) or glycols (glycolysis) in the supercritical region, namely with temperature and pressure both at their corresponding critical point. In this method, the resin polymer is decomposed through a chemical reaction to release fibers, and the final recycled products are fibers, fillers, and depolymerized resin monomers.

Chemical recycling enables the recovery of the organic part as well as high residual properties fibers. Nevertheless, the resources and energy consumption influence the profitability profile of these technologies, which appear to be suitable only for high end fibers and resins recovery.

This project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No. 101058756.

Remanufacturing of composite materials

Complementary to recycling, large composites infrastructures can be remanufactured. Products and installations can be made exploiting the disassembly, cutting, reworking of large composite bodies as wind blades. Despite fatigue cycles and corrosion force the decommissioning of composite structural parts from their main application, these components maintain sufficient mechanical properties to guarantee structural functions in less demanding applications.

In literature, it is possible to find many examples of reworked composite structures for architectural, decorative or furniture uses. See for example (Joustra et al., 2021), which presents the reuse of wind blades parts to build the structural chassis of a playground and the totality of a picnic table.

Figure 14: left, Wikado playground Rotterdam; right, Picnic table prototype, made from construction elements cut from a wind turbine blade. Taken from (Joustra et al., 2021), CC BY 4.0 license

The remanufacturing of large composite infrastructure in architectural or furniture domains dramatically optimize the added-value recovery and the environmental footprint related to the management of EoL composites. Nevertheless, large scale applicability of composites repurposing has limited potential.

Therefore, it is reasonable to expect in the near future composite infrastructures cross-sectorial remanufacturing only practiced at pilot and best practices level, especially for what concerns the recovery of composite products currently available in their use phase.

Comparison of circular economy solutions for composites

This paragraph is concluded with recapitulatory table which summarizes and compares the main recycling and repurposing options applicable to composites derived from previously cited bibliographies and (Ierides and Reiland, 2019).

Table 2: recapitulatory table of the main available technologies for composites recycling

Technology	Output materials	Pros and cons	TRL	Large adoption scalability
Remanufacturing	Composite sections embedded in smaller products	*P*: low environmental impact *P*: cost efficient *C*: poorly scalable	TRL 8	Pilot examples, poorly scalable
Mechanical recycling	Coarse mixtures: short fibers and fine powders.	*P*: high throughput *P*: cost efficient *C*: material downcycling and contamination	TRL 9	Large scale adoption
Co-Processing (Cement Kiln)	Energy recovery and cement filler	*P*: high throughput *P*: cost efficient *C*: material loss *C*: additional energy needed	TRL 9	Large scale adoption
Pyrolysis	Long fibers with high residual properties; gases and oils for energy recovery	*P*: high-added value recovery *C*: oxidation of recovered fibers *C*: high processing costs	TRL 8	Scalable to multi-tons capacity
Fluidized bed	Long clean fibers with high residual properties	*P*: high-added value recovery *P*: clean fibers *C*: challenging gas management	TRL 6	Profitability can be reached only with large scale-ups
Chemical recycling	Long fibers with high residual properties; reusable resins	*P*: recovery of fibers and resins *C*: high energy and solvents consumption *C*: gas emissions	TRL 5	Hardly scalable to large applications

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Analysis of Legislative Framework for waste composite management

This chapter intends to preliminarily analyze the regulatory framework for composite waste management to identify potential barriers affecting the implementation of future business based on the reuse of rGFs/rCFs. An in-depth investigation will be performed in the next months within T8.5. The analysis is performed at a first stage at European level to consequently deepen the norms at Member State level, aiming at preliminary recognize the current regulations and operative practices in waste management limiting the availability of EoL composites.

The European legislator, combining economy and environment, replaced the ***red economy***, based on the take, make, dispose model firstly with the ***green economy***, which requires companies to invest more and consumers to spend more to preserve the environment, and then with the model of the ***blue economy*** aimed at developing waste regeneration projects. In this particular framework, the European Commission presented the Circular Economy Package in July 2018 (European Parliament, n.d.), where, on landfill of waste, Directive (EU) 850/2018 - which amends Directive 1999/31/EC - stands out (European Parliament, 2018).

The European legislature aims to encourage an integrated policy that guarantees the correct application of the ***waste hierarchy*** and promote a transition to prevention, including reuse, preparation for reuse and recycling, and prevents a shift from landfilling to incineration (Art. 1 para. 1, no. 1 Directive 850/2018).

To support the implementation of circular economy solutions, the European Commission adopted the European Green Deal (European Commission, 2019) where the overarching aim is for the European Union to become the world's first “climate-neutral bloc” by 2050. Made this normative premise, it is clear that the concept of "circular economy" is in dialectical relationship with the waste hierarchy, aimed at environmental protection, where the legislator prefers prevention, preparation for reuse and, finally, recycling to landfilling.

It is of unquestionable inference how the decrease in disposal aims not only at eliminating waste but also at producing secondary raw materials, allowing the used product to become, at the end of its life, a reusable material again. In conclusion, the primary objective of the European legislator is not only to protect the environment but also to be able to equip itself with raw materials, resources being mostly concentrated outside the European Union.

Despite a renewed environmental awareness, the real criticality emerges from the analysis of supranational environmental law where the European legislature has not yet attended to the composite waste stream under the Extended Producer Responsibility (EPR) model. In order to analyze the specificity of the European MSs law, a survey has been sent to RECREATE’s partners. The core request was to describe the status of the composite waste management, answering to the following questions:

- What is the **current practice in your Member State** for the management of EoL composite? Is there any best practice?
- Is the **landfilling of EoL composites (GF/CF) permitted**? (If possible, please indicate the costs per ton)
- Is there any specific **norm, End of Waste criteria and/or Decrees** in your Member State that regulates the valorization, management and reuse of composites as secondary raw material? (If yes, please indicate if it's focused on a specific industrial sector)

- Which are in your opinion the **main barriers** posed by the legislation hindering the reuse of EoL composites?

Eight feedbacks have been received from six EU countries, namely France, Italy, Germany, Austria, Spain and Finland, from which emerged a very similar situation. The survey reveals a picture characterized by the total absence of specific legislation on the EoL of composite waste with the result that, currently, it is in most of the cases landfilled. The current practices include the following process, listed with a hierarchy approach:

- **landfilling;**
- **mechanical recycling;**
- **incineration/energy recovery;**
- **chemical recycling through pyrolysis or solvolysis.**

Due to the lack of norms, the so-called "best practices" have developed, which in Germany consist of incineration with energy recovery and use in the cement industry while in Spain there are some experiences related to recycling as mechanical recycling to recover GF for low-value uses, to use ground composite as filler material or to incinerate ground composite in clinker kilns, as well as chemical recycling through pyrolysis or solvolysis to recover fibers with better retention of physical properties and an organic fraction from which new chemicals can be produced.

Specifically, landfilling is the “preferred” practice for composite waste management and the related costs, which are borne by the waste producer, vary significantly among EU member states from 250 to 500 €/ton (where in Austria it is between 250 and 350 €/ton, while in Italy it is ranging from 250 and 500 €/ton). The fluctuation depends on many factors, among others the waste dimension (and so the volume shortage) and the landfill availability in the specific geographic area (e.g. the cost usually increase in islands).

According to extensive research, there are also some peculiar situations to be mentioned:

- in the Netherlands, landfilling of composite materials is prohibited in principle; however, wind farm operators benefit from an exemption if the cost of alternative treatment is more than €200/ton;
- in Austria the planned permission for landfilling will end in 2023;
- according to a survey conducted by Wind Europe (Wind Europe, 2020), the cost of wind turbine recycling is between 150€ and 300€ per ton therefore landfilling is still practiced;
- France, while lacking a general regulation on the EoL of composite materials, has adopted a specific regulation for wind turbine blades with the *Arrete du 22 juin 2020* (MINISTÈRE DE LA TRANSITION ÉCOLOGIQUE ET SOLIDAIRE, 2020) that set the following recycling targets for wind turbine blades:
    - From July 1, 2022, at least 35 percent of the blade must be reused or recycled.
    - From January 1, 2023, the recycling rate increases to 45%.
    - From January 1, 2025, at least 55% must be reused or recycled.

Concerning the main barriers for composite recycling/recovery, there is a common view identifying the following criticalities:

- landfilling and incineration are too cheap and do not reflect the real cost for society (land consumption, CO_2 footprint, mandatory redevelopment of landfills in the future will be very expensive);
- legal framework still geared towards linear economy; virgin materials prices do not reflect true cost (CO_2 tax). Recycling materials need clear credits e.g., subsidies, tax credits to overcome the initial higher costs for recycling materials in relation to virgin ones;

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- lack of norms (End of Waste Criteria) boosting and allowing the reuse of rCF/rGF;
- complexity of the material and the limitation of knowledge about the product composition;
- challenging requirements to achieve for secondary raw materials;
- low TRL for current recycling and recovery processes (except for mechanical approach allowing "low-value" applications).

Mapping of End-of-Life composite streams in Europe

This chapter represents the core quantitative part of the deliverable, as it collects six vertical analyses on the six sectors of interest foreseen by the grant agreement and agreed among the consortium.

The scope of these paragraphs is to provide, as far as possible, six parallel characterizations of the composites quote of the sectors maintaining a common analysis structure divided in:

- Composite materials stock and expected trends in the sector.
- Characterization of composite materials components in the sector.
- Forecast of sectorial composite waste volumes in Europe.

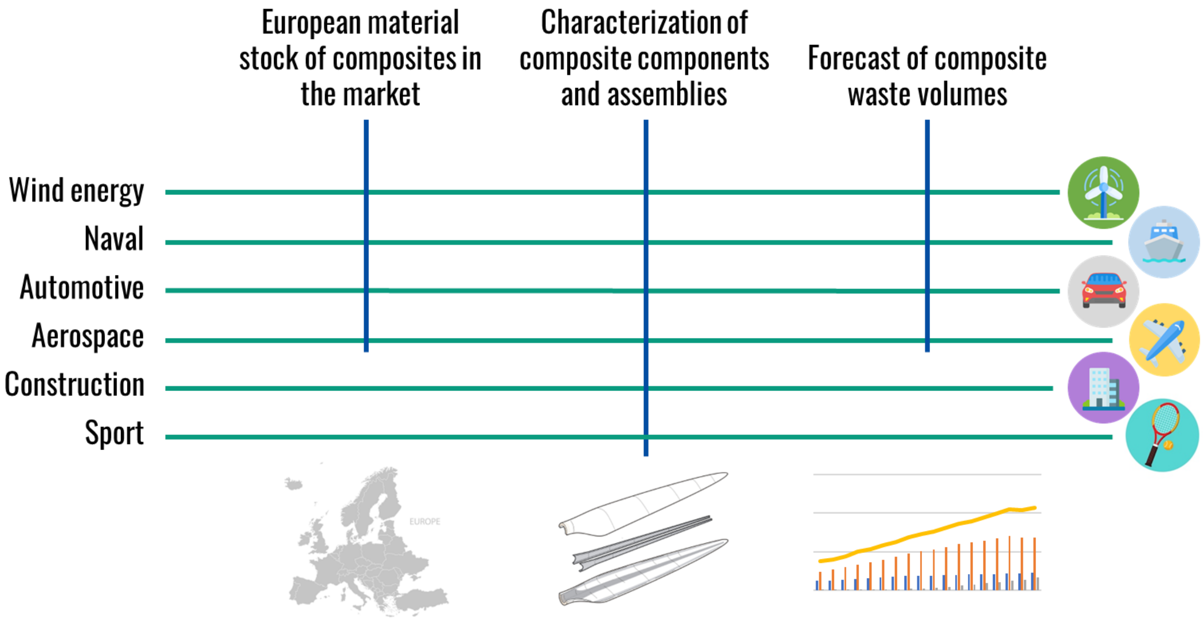

Figure 15: common methodology for the analysis of the six target sectors

Maintaining the common goal, quantitative vertical analyses are then diversified in function of the type and quality data availability.

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Wind Energy

GFRP and CFRP guarantee a unique combination of mechanical properties, lightness, reliability, and corrosion resistance, and are therefore used to manufacture the totality of commercial wind blades for both inshore and offshore applications. Moreover, modern wind turbines load composite materials parts of non-negligible size and weight also in the nacelle and in the tower.

Figure 16: wind turbines farm. Taken from Wikimedia Commons, CC BY 2.5 license

According to (Ierides and Reiland, 2019), it is possible to roughly estimate the quantity of composite materials installed in a wind farm in function of its capacity, with an approximate conversion factor of *1 MW = 12 to 15 tons of composites*.

The European wind energy industry covered the 15% of the electricity demand in the EU-27+UK in 2021. (Wind Europe, 2022), and its importance is expected to growth, as one of European Commission's target is to achieve greater percentages of renewables in the next years. Currently, the Renewable Energy Directive sets rules for the EU to achieve its 32% renewables target by 2030.

Given the size, number, and capillarity of wind energy installations all across Europe, and the related important availability of composite materials, the wind energy segment constitutes an important stream and stock of GFRP and CFRP large infrastructures.

Composite materials stock and expected trends in the wind energy sector

The first scope of this paragraph is to estimate and characterize with a sufficient level of detail the installed stock and expected trends of wind farms and wind blades, in order to enable an estimation of the upcoming streams of dismantled composites in the next years.

According to (Wind Europe, 2022), the cumulative capacity of wind energy plants in Europe reached 235 GW in 2021, 207 GW onshore and 28 GW offshore.

Aggregated data about the availability and expected growth of composite materials stock in the wind energy installations in Europe are not available in literature, therefore, some estimation must be done to derive data of other nature. In this deliverable, two parallel calculations are made and then compared.

Capacity-to–weight single conversion factor

As previously introduced, (Ierides and Reiland, 2019) propose a capacity-to–weight conversion factor to match the power of a wind energy installation with the availability of composites inside it. Moreover, market studies as (Wind Europe, 2022, 2021a, 2021b) report the cumulated installed European capacity of inshore and offshore windfarms, as well as its expected growth for at least the next five years.

It is therefore possible to simply derive the current and future composites stock in the wind energy plants in Europe exploiting the *1 MW = 12 to 15 tons of composites* factor the following equations.

Given the assumptions of:

- New installations forecasts as reported in the conservative scenario of (Wind Europe, 2022).
- Yearly decommissioning rate of 0.2% of overall capacity (it was 0.17% in 2021).

The cumulated wind energy capacity installed in Europe in 2021-2026 is reported in *Table* 3.

Table 3: European wind energy capacity, 2021-2026

Year	Installed capacity [GW]	
2021	235	(Wind Europe, 2022)
2022	252	Estimated
2023	265	Estimated
2024	279	Estimated
2025	292	Estimated
2026	308	Estimated

Finally, it is possible to derive the availability of composites populating these wind farms as reported in Table 4.

Table 4: stock of composite materials in the European wind energy systems, capacity-to – weight single conversion factor

Year	Composite materials European stock [kton] *1 MW = 12 tons of composites*	Composite materials European stock [kton] *1 MW = 15 tons of composites*
2021	2’820	3’525
2022	3’042	3’803
2023	3’228	4’035
2024	3’426	4’282
2025	3’605	4’506
2026	3’826	4’782

The simplicity of this method implies that its robustness is dramatically dependent on the quality and reliability of the conversion factor exploited in the capacity-weight conversion. Since available literature lacks of sources to confirm and better contextualize this data, in this deliverable, an alternative calculation method is proposed to confirm and balance the obtained data.

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Turbines population composites weight estimation

To propose an alternative to the single conversion factor method, in this section, another calculation method is proposed: a cascade calculation to estimate the number of turbines available in Europe, their weighted average dimensions and finally the quantity of composites available.

The calculation of the number and dimension of turbines installed in Europe is based on the following data:

- The total number of European offshore wind turbines is known and available in (Wind Europe, 2021a) for 2020.
- The number of new turbines installed in Europe is known for the years 2020 and 2021 (Wind Europe, 2022, 2021b).
- The numbers of turbines installed in the last decades can be estimated by comparing the installed capacity within the years and the average capacity of turbines of different periods (Ierides and Reiland, 2019).
- The dimension, and weight of wind blades loaded in turbines of different generations and capacity is estimated according to (Liu and Barlow, 2016).
- Composite materials (fiber and resin) account for 92% of the overall blade weight. This percentage remains valid for turbines of different generations and dimensions (Liu and Barlow, 2016).
- Three blades per turbine are considered for all turbines.

Conservative data are always preferred in case of conflict.

Data are summarized in Table 5 and Table 6.

Table 5: European offshore turbines stock and average blade weight, updated 2020

Offshore turbines		
Number of turbines	Average blade weight [ton]	Sources
5'402	25	(Liu and Barlow, 2016; Wind Europe, 2021a)

Table 6: European inshore turbines stock and average blade weight, updated 2021

Inshore turbines					
Installation period	Installed capacity [GW]	Average turbine capacity [MW]	Number of turbines installed	Average blade weight [ton]	Sources
2020, 2021			25'863	14	(Ierides and Reiland, 2019; Liu and Barlow, 2016; Wind Europe, 2022, 2021b)
2010 - 2019	99	2,75	Estimated: 36'000	10	
Before 2010	84	2	Estimated: 42'000	6,5	

Finally, it is possible to estimate the weight of composite available in the European wind turbines stock by populating the following equation.

$$Composites_{\ stock}[kton] == N.of\ turbines_{stock} \cdot 3\,\frac{blades}{turbine} \cdot Avg.weight \cdot 0.92\,\frac{\%\ composites}{Tot.\ weight} \cdot 10^{-3}\,\frac{[kton]}{[ton]}$$

Results of this calculation are reported in Table 7.

Table 7: stock of composite materials in the European wind energy systems, 2021, turbines population composites weight estimation

Category	Tot. Blades weight [kton]	Tot. Composites weight [kton]
Offshore	405	373
Inshore 2020, 2021	1’086	999
Inshore 2010 - 2019	1’080	994
Inshore before 2010	819	753
Tot	3’390	3’119

Results comparison

It is possible to appreciate how the estimations of the stock of composite materials in the European wind energy market made with the two approaches doesn’t create conflict, as the “turbines population” estimation remains between the low and high “single conversion factor” ones.

Characterization of composite materials components in the wind energy sector

To fully comprehend the circular economy opportunities related to composites in the wind energy sector, it is fundamental to clearly characterize such products, in terms of fiber and resin composition, geometry, and assembly characteristics.

Wind blades are the most important composite based part of the wind turbine, as well as the most cost impacting one. Wind blades consists of two faces (on the suction and pressure sides) adhesively joined together. One or several integral (shear) webs link the upper and lower parts of the blade shell (Mishnaevsky et al., 2017).

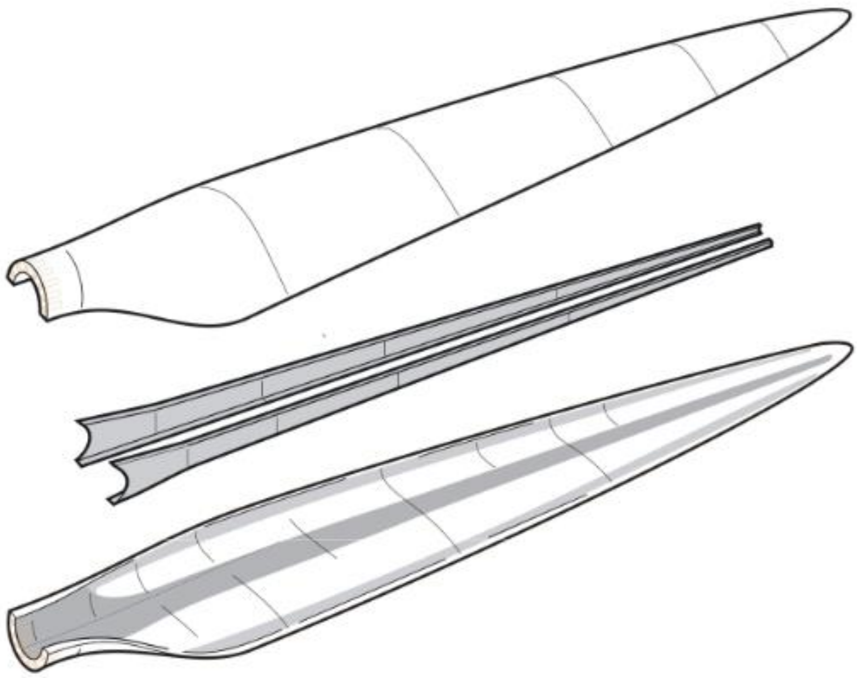

Figure 17: schematic longitudinal exploded view of a wind blade. Taken from (Mishnaevsky et al., 2017), CC BY 4.0 license

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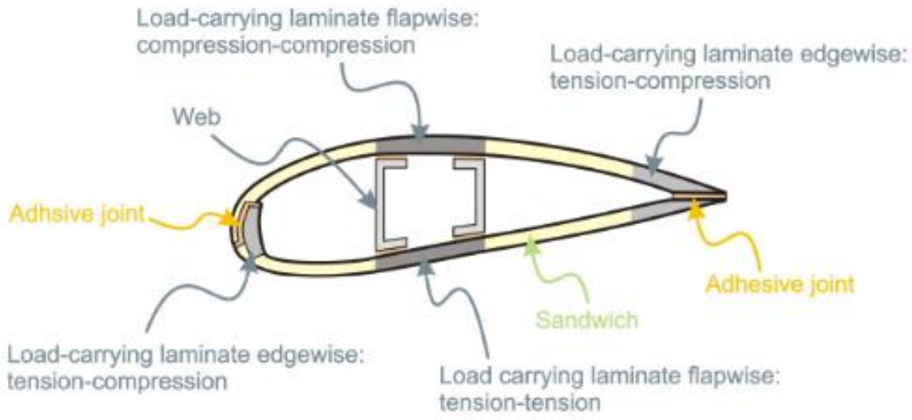

Figure 18: schema of the section of the blade. Taken from (Mishnaevsky et al., 2017), CC BY 4.0 license

Fibers and resins in wind blades

The first important focus needed to adequately describe wind blades is related to the materials populating them. Wind blades are complex products, whose fiber content, typology and concentration can vary in different longitudinal and transversal zones.

Typically, long/endless E-glass **fibers** are used as main reinforcement in the wind blades. Composites in wind blades have high glass-to-resin ration, as they contain up to 75% in weight of glass.

As manufacturing trends impose the increase of winds dimension in new generations of blades, much effort has been done to produce lighter and high-performance blades. As the overall blades mechanical properties mostly depend on the properties of the fibers, efforts have been made to find stronger alternatives to E-glass, including glass fibers with modified compositions (S-glass, R-glass, etc.), carbon fibers, basalt and aramid fibers:

- **High-performance glass fibers** (i.e., S-glass, S2 glass, R-Glass, WindStrandTM glass fibers) modify the E-glass chemical composition and manufacturing process to increase mechanical properties, mainly tensile and flexural strengths, compressive strength, stiffness. Nevertheless, also costs raise dramatically, for example, the price of S2-glass is around 10 times of that of E-glass.
- **Carbon fibers** are considered an effective alternative to glass fibers. They guarantee higher stiffness and lower density than the glass fibers, thus enabling the manufacturing of stiffer and lighter blades. Carbon fibers are used in the manufacturing of high-end commercial wind blades (examples: Vestas, Siemens Gamesa), often in structural spar caps of large blades.
- **Aramid and basalt fibers** are considered an interesting alternative to glass and carbon, nevertheless, their application is yet to be demonstrated at TRL 9.
- **Hybrid composites**, namely populated by two or more types of fibers, represent an interesting option for a cost-effective reinforcement of standard E-glass. It is demonstrated (Ong and Tsai, 2000) that a partial (30%) replacement of glass with carbon fibers would lead to 90% cost increase and 50% weight reduction for a medium-small size blade. Hybrid GF-CF blades are currently manufactured by important market players (i.e., LM Wind Power) for big and offshore turbines.

Regardless the type and concentration of fibers, thermosets (epoxies, unsaturated polyesters, vinylesters) are almost always used as **resins** in wind blade composites.

- **Thermoset resins** are preferred to thermoplastics because their low temperature cure and low viscosity ease high volumes production. speed). Initially, polyester resins were used for composite blades. Nowadays, epoxy resin is preferred to polyester.
- **Thermoplastic resins** are hindered by high processing temperature, high viscosity and low fatigue and creep resistance. Therefore, despite thermoplastics have better elongation and fracture toughness, thermoset matrixes are preferred for commercial wind blades.

Composites assembly in wind blades

Wind blades are complex assemblies, where the structural composites frames need to be joined together and integrated with complementary components to guarantee the complete set of functions which the turbine demands. Since the dedicated composites recycling is mandatorily enabled by a complete liberation of the composite parts, it is useful to describe how complementary materials are assembled together with others.

The (Bortolotti et al., 2019) report is here taken as an example, as it describe in detail the manufacturing steps of a commercial modern wind blade and the associated materials. The overall wind blade structure can be therefore populated by:

- **Multiple types of composites fabrics**: the same blade can house unidirectional, biaxial and triaxial fabrics matrixes layers, regardless the material (GF or CF).
- **Fillers as foam or balsa wood**: since composite layers sandwiches cannot be modeled perfectly tracing the final aerodynamic shape of the blade, fillers as foams (for example polyurethane foam) or balsa wood are included in the blade to shape its external surface.
- **Paint for external coating (and putty)**: commercial wind blades are coated with a protective painting layer of non-negligible thickness.
- **Bolts and barrel nuts:** available at the blade root ring for the blade-nacelle joining.
- **Lightning protection system**: a metallic receptor is available on the tip of each wind blade, as it represents a defined point of strike for flashes. An adequately dimensioned copper wire ensures blade grounding, and therefore crosses the whole blade.
- **Sensors and electronics**: most modern wind blades have electronic monitoring systems which then remain in the dismantled blade.

An average bill-of-material (in percentage) of commercial wind blades is proposed by (Liu and Barlow, 2016) and here reported.

Table 8: average material usage of a commercial wind blade

	Material by weight
CF/GF fabric	60.4%
Resin	32.3%
Steel	1.1%
Copper	0.6%
Balsa	2.3%
Foam	1.7%
Paint	0.9%
Putty	0.7%

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Manufacturing waste

To conclude this paragraph, it is important to include a brief focus about scraps generated during the manufacturing phase. Wind blades are large and complex products, whose commercialization is achieved after many subsequent production, assembly and testing steps.

Technical reports as (Liu and Barlow, 2017, 2015) quantify the wastes generated during the manufacturing phase of commercial wind blades manufacturing processes between 12% and 30% of the finished mass of the blade, with median value set at 17%.

These studies also focused on the testing phase of manufactured blades and on early recalls of defective blades. In fact, waste is generated in low volumes from these activities (usually <0.1%), and therefore not considered in this report.

Forecast of wind energy composite waste volumes in Europe

Data presented in the previous sections of this paragraph are here merged, integrated and used to generate a forecast of the expected wind energy composite waste volumes for the period 2023 – 2040.

Manufacturing waste

The first waste stream analyzed in this section is the manufacturing waste. To forecast the manufacturing waste volumes expected for 2023 – 2040, calculations are based on these assumptions:

- Since manufacturing waste is based on turbines production and not on turbines installation, this computation considers the yearly European wind turbines production, and not wind energy local installation.
- The yearly European wind turbines production is calculated by multiplying the yearly global wind energy systems demand with the European production market share percentage.
- The yearly global wind energy systems demand is taken from (GWEC, 2022), conservative scenario, for the 2023 – 2030 period, and then maintained at constant 2% growth for the 2030 – 2040 period.
- European production market share is set to 39% (en:former, 2019), maintained constant for the whole forecast. Major European wind turbines manufacturers: Vestas, Siemens Gamesa, Nordex Acciona.
- Wastes generated during the manufacturing phase of commercial wind blades manufacturing processes is estimated starting from (Liu and Barlow, 2017), with low value (12%). Neither in this or other publications available in literature, there is evidence about the nature of this waste stream (consumables, shrinkages, etc.). In this deliverable, a conservative approach sets the actual composites waste rate as 5% of the overall composites mass of the blade.

The firsts step to forecast the expected European manufacturing waste is therefore to estimate the European market size of new wind energy systems manufacturing. Results or this computation are represented in Figure 19.

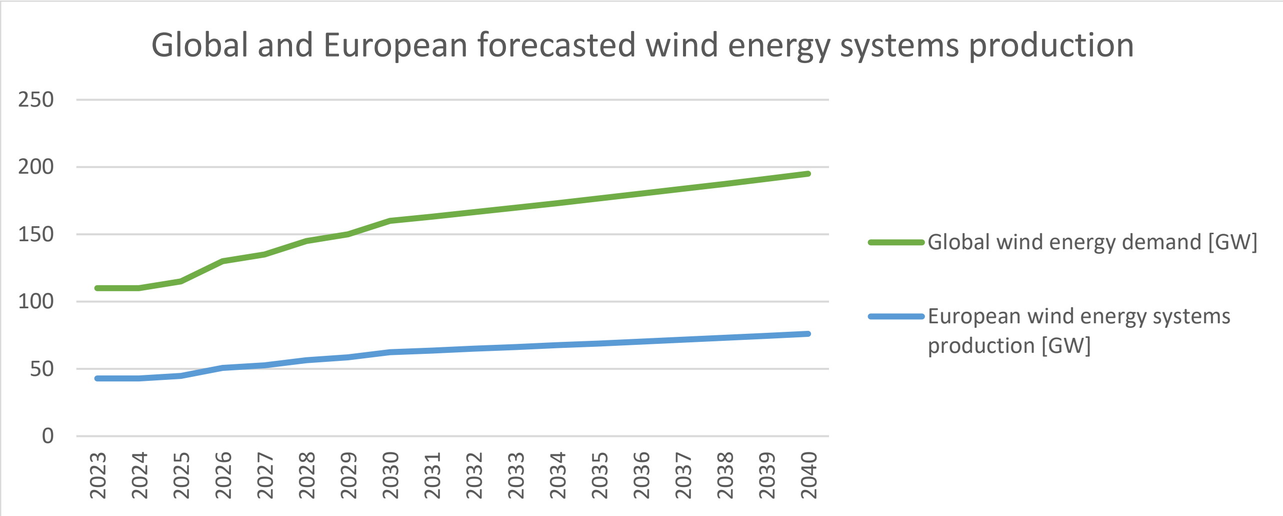

Figure 19: global and European forecasted wind energy systems production

Finally, it is possible to derive the estimated volumes of manufacturing wastes by:

- Converting the expected total capacity of wind energy systems manufactured in Europe in equivalent weight of composites embedded in wind turbines by using the capacity-to – weight single conversion factors proposed by (Ierides and Reiland, 2019).
- Deriving the quantity of associated production wastes.

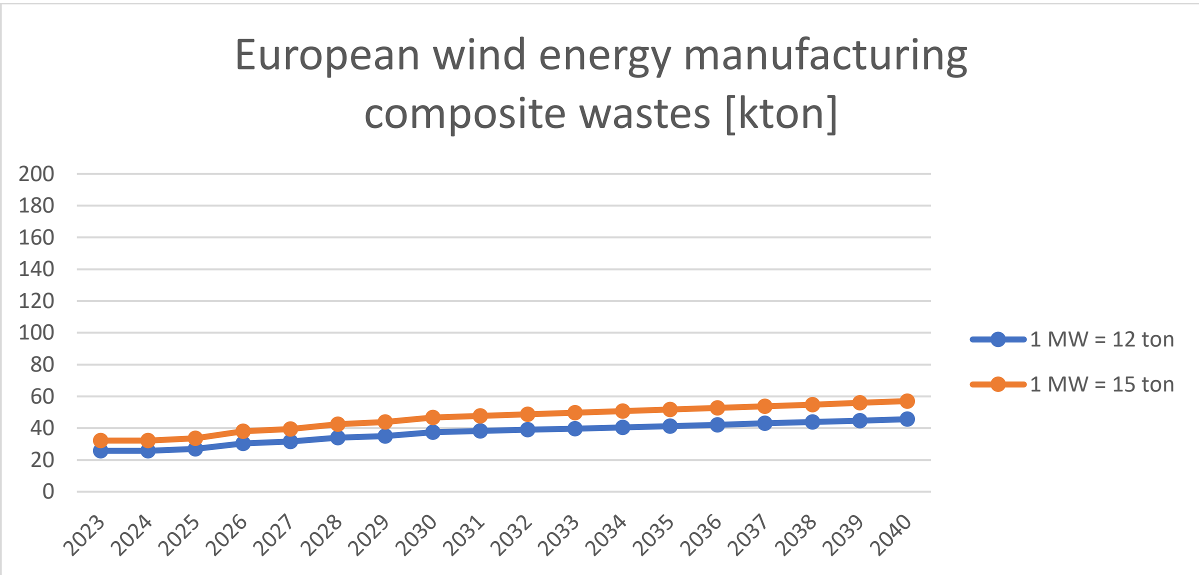

Figure 20: European wind energy manufacturing composite wastes

End-of-life wind energy systems

To estimate the European return volumes of end-of-life wind energy systems, data related to the current composites stock presented in the previous sections must be enriched with a more granular identification of yearly installed wind energy capacity through the years.

Since the end-of-life blades forecast starts from the tracking of yearly installed new systems in the last decades, the already cited sources are enforced by auxiliary ones (EWEA, 2016), to achieve a yearly based definition of the installed capacity in Europe for the 2000 – 2022 period.

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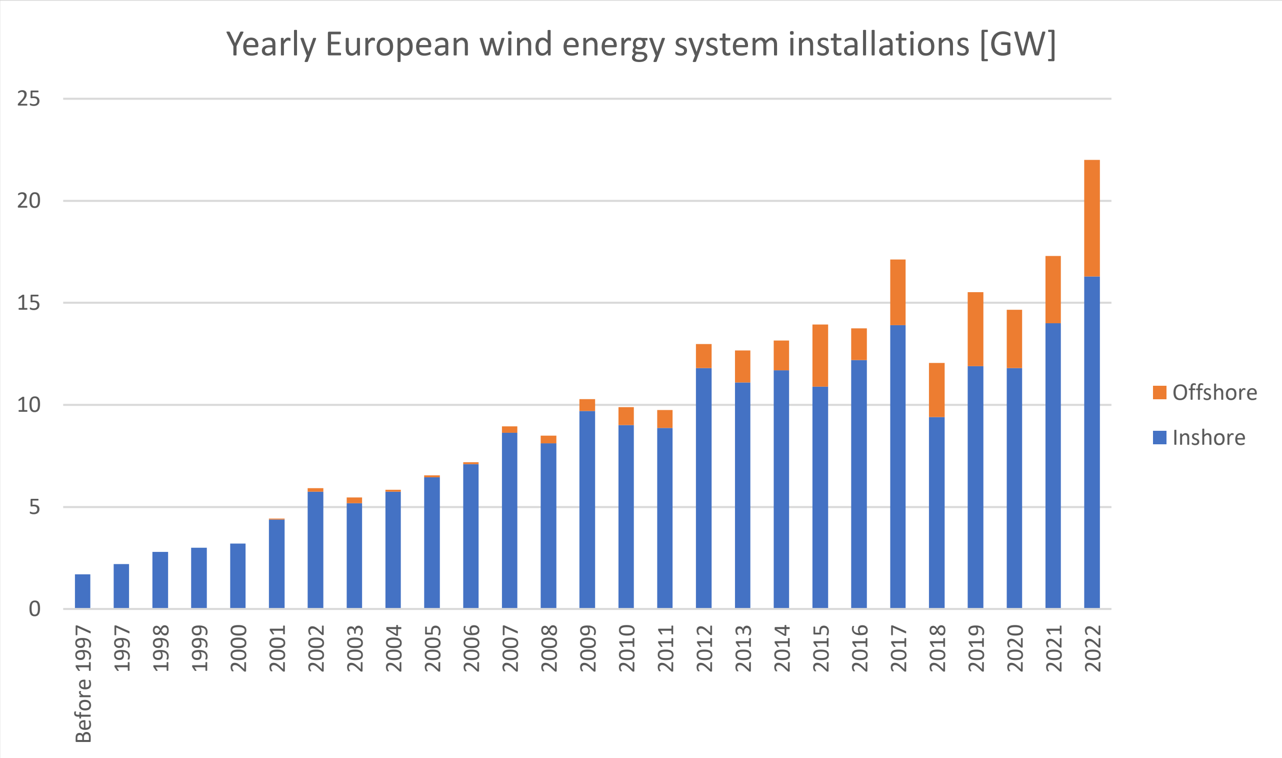

Figure 21: yearly European wind energy system installations

Finally, it is possible to forecast the expected return of decommissioned wind blades. Once again, equivalent weight of composites embedded in wind turbines is calculated by applying the capacity-to – weight single conversion factors proposed by (Ierides and Reiland, 2019).

To derive the volumes of decommissioned wind turbines, this deliverable considers two decommissioning possibilities for wind blades:

- Wind blades can be decommissioned before their natural end-of-life because of failure or turbine repowering. It is estimated that 3% of wind blades are decommissioned before their natural end-of-life.
- Wind blades can be decommissioned reaching their natural end-of-life. Typical wind blades lifecycle is 20-25 years (Liu and Barlow, 2017).

Considering this double possibility, the wind blades yearly decommissioning profile is calculated as follows:

- Early decommissioning of blades is modelled with constant flat rate for the 20 years natural lifecycle. The 3% of wind blades marketized in year *y* are decommissioned within *y+1* and *y+20*, same quantity each year.
- Those blades which don't undergo early decommissioning are dismantled at their natural end-of-life with constant flat rate (same quantity each year) between 21st lifecycle year and 25th lifecycle year.

Forecasts about the volumes of composite waste coming from decommissioned inshore and offshore wind turbines are finally visible in Figure 22 and Figure 23.

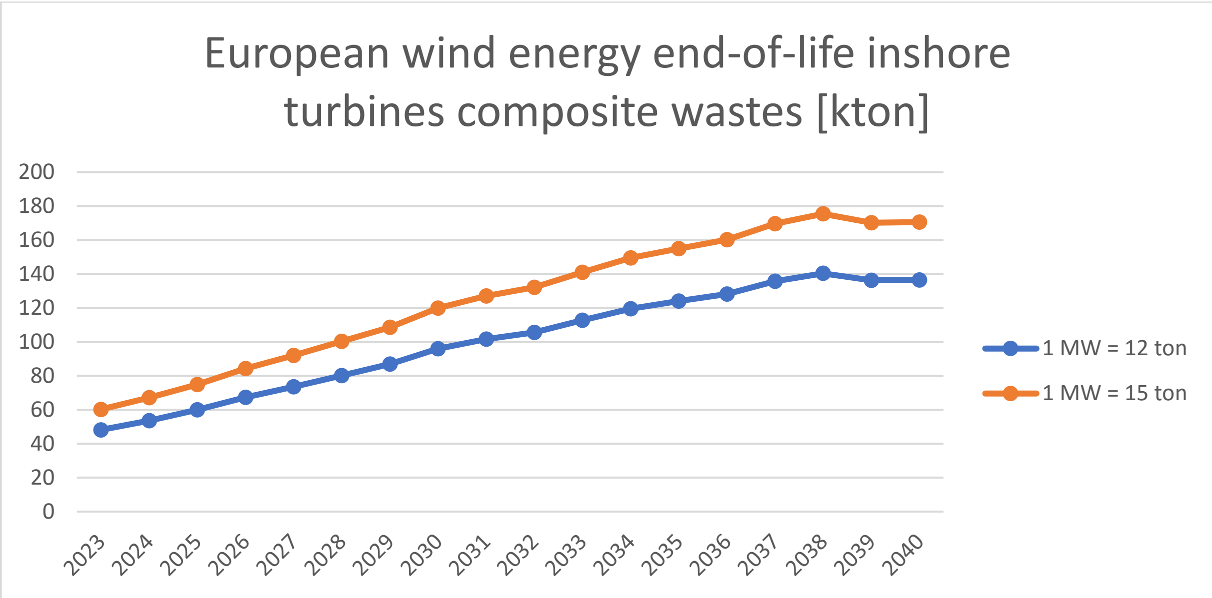

Figure 22: European wind energy end-of-life inshore turbines composite wastes

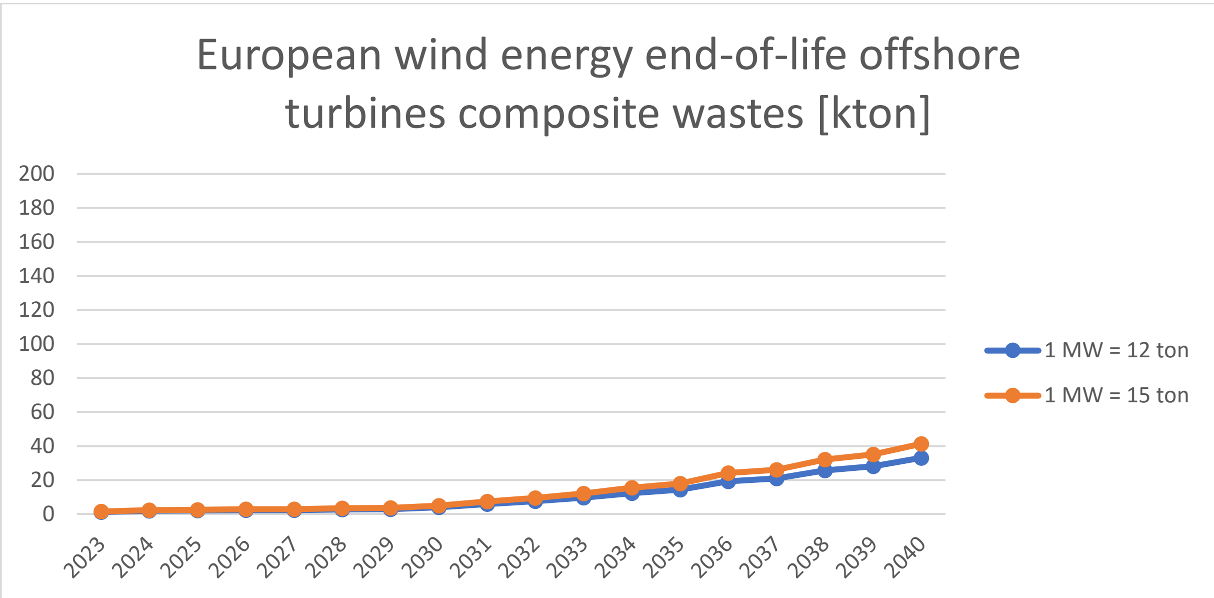

Figure 23: European wind energy end-of-life offshore turbines composite wastes

Waste streams comparison

To complete the forecasting analysis, Figure 24 compares and cumulates the three above presented waste streams, namely production waste, end-of-life inshore turbines and end-of-life offshore turbines (*1 MW = 12 ton* scenario). Considerations can be made on this recapitulatory graph:

- Composites wastes from the wind energy sector represent a concrete European circular economy challenge. Yearly return volumes in the next decades will reach more than 200 kton, summing up the manufacturing waste and dismantled turbines streams.
- Inshore end-of-life turbines represent the main composites waste channel, both present and in the future.

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- Offshore turbines installation volumes rose to GW magnitudes only in the last decade. Therefore, their related returning volumes are not expected to growth significantly before 2030. Nevertheless, difficulties in offshore wind farms decommissioning already represent a technical challenge for specialized dismantling companies.
- Manufacturing waste volumes are expected to remain rather constant through the years, following the gradual expected market growth. Nevertheless, their management is fundamental to guarantee a complete circular management of composites in the wind energy sector.

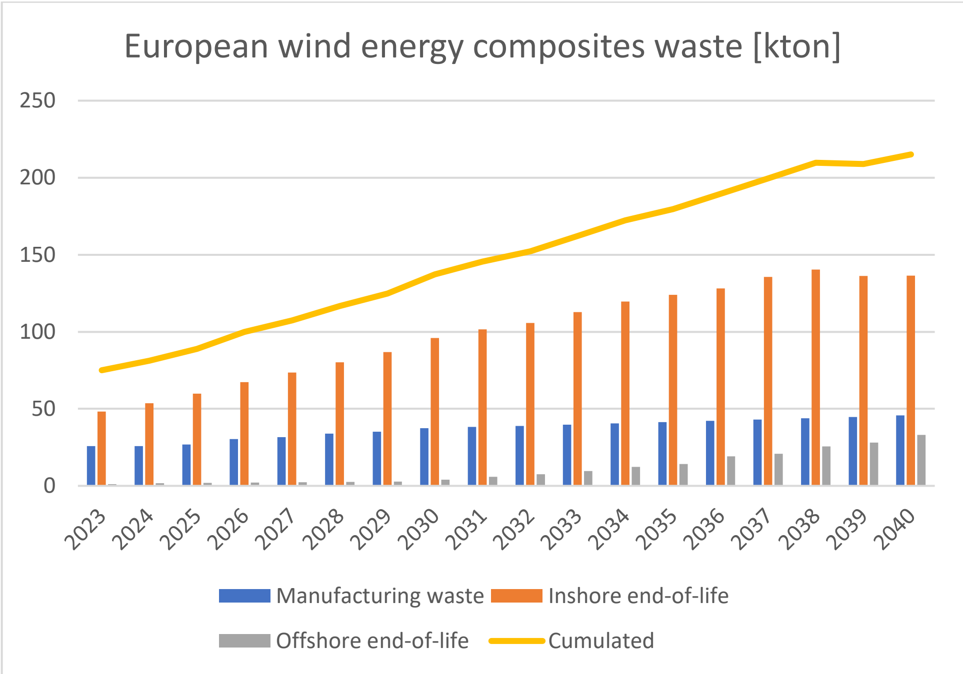

Figure 24: European wind energy composites waste

Offshore and Naval

FRPs are one of the material classes mainly exploited in the manufacturing of nautical vessels, especially of small and medium dimensions. They have been introduced in the naval sector during World War II, and their usage for boats production grew in the 1970s (International Maritime Organization and London Convention/Protocol and Ocean Affairs, 2019; Noury, 2020; Rubino et al., 2020).

Figure 25: a fleet of "Optimist" dinghy sailboats, typically manufactured in GFRP. Taken from Flickr, CC BY-NC-SA 2.0 license

European citizens have a deep boating and sailing culture, and millions of recreational boats populate European seas, lakes and rivers. The high resistance of composites vessels to fatigue cycles and corrosion guarantees very long-lasting boats. An average lifecycle of a FRP small craft is usually between 30-50 years, and it can last even longer in particularly compliant environments.

It is possible to estimate (Eklund et al., 2013) that boats with an FPR hulls represent the 40% of the overall fleet of European recreational boats.

Regardless their dimension, commercial boats are complex assemblies of different and complementary components as the hull, the sail, the motor, the onboard instruments, the design interiors, etc. Therefore, the percentage of composites in a commercial boat is mitigated by the availability of other materials. Nevertheless, it is estimated (Eklund et al., 2013) that FRPs typically account for the 25-50 wt% of an average size recreational boat.

Composite materials stock in the naval sector

The first scope of this paragraph is to estimate and characterize the stock of composite hulls and boats populating the European naval sector. There are no aggregated data about the availability of composites

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in European naval segment, therefore data must be derived from an analysis of the (few) available studies about the continental fleet of boats.

To approach this analysis, it is useful to define three main categories of boats:

- **Large commercial boats**, as cargo vessels, oil tankers, cruise ships.
- **Commercial** fishing boats and other commercial **vessels**.
- **Recreational boats**, which according to (European Boating Association, 2020) can be defined as *"boats that are designed or adapted for sport or leisure, whether propelled by sail and/or power, for the purposes for which they are designed or adapted"*.

This distinction is important for two main reasons:

- The hull of **large commercial boats** is typically manufactured using **metal** laminates. Therefore, such crafts marginally contribute to the sectorial composites stock. In fact, large commercial boats are not considered in this analysis.
- **Recreational boats** represent the large majority of the fleet of small and medium composite hulls sailing in Europe, and there is general consensus (Directorate-General for Maritime Affairs and Fisheries (European Commission) et al., 2016) in limiting the analysis of composites stock in the naval sector to this category alone.

Given these premises, it is possible to focus the analysis on recreational boats. The most complete study in terms of data collection and data availability on the population and characterization of European recreational boats fleet has been led by the European Commission and finalized in 2016: (Directorate-General for Maritime Affairs and Fisheries (European Commission) et al., 2016). More recent studies, for example (International Maritime Organization and London Convention/Protocol and Ocean Affairs, 2019), elaborate on the data originally organized in 2016.

According to (Directorate-General for Maritime Affairs and Fisheries (European Commission) et al., 2016), in 2014 the European recreational boats fleet was populated by 6 to 6.5 million crafts, as reported in Figure 26.

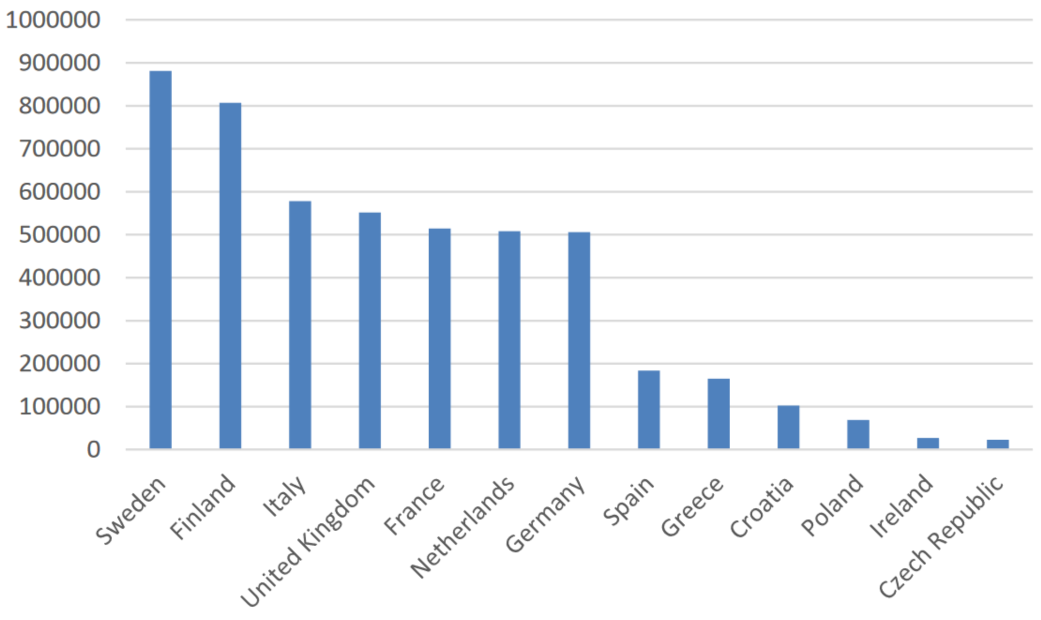

Figure 26: Number of recreational crafts in EU countries (2014). Source: (Directorate-General for Maritime Affairs and Fisheries (European Commission) et al., 2016)

It is then possible to furtherly characterize this vessels population by size and typology.

Table 9: differentiation of European recreational boats per size and typology

Size		Typology	
<7,5 m	74%	Motorboats	79%
7,5-12 m	21%	Sailboats	19%
12-24 m	5%	Personal watercrafts	2%

To derive the availability of composites in the recreational boats, data related to the fleet size distribution available in Table 9 can be combined with an estimation of the availability of composites per boat in function of the boat dimension.

First of all, it is possible to estimate that circa 40% of recreational boats have a composites made hull (Eklund et al., 2013). No data are available about the correlation between boat lengths and hull type.

Then, an estimation of the boat dimension / composites content relationship can be made exploiting data available in (Eklund et al., 2013). This study collects the bill of materials of nine types of composites commercial recreational boats, clarifying the composite content and the length of the boat. These data are summarized in Table 10.

Table 10: length and composites content of nine commercial recreative boats. Source: (Eklund et al., 2013)

	Length [feet]	Length [meter]	Composites content [kg]
Boat 1	10	3,0	200
Boat 2	15	4,6	250
Boat 3	20	6,1	360
Boat 4	16	4,9	260
Boat 5	21	6,4	430
Boat 6	24	7,3	550
Boat 7	21	6,4	530
Boat 8	22	6,7	370
Boat 9	18	5,5	420

Despite the limited availability of samples, it is possible to apply a linear regression to derive the composites quantity as function of the vessel length, as imposed in Figure 27.

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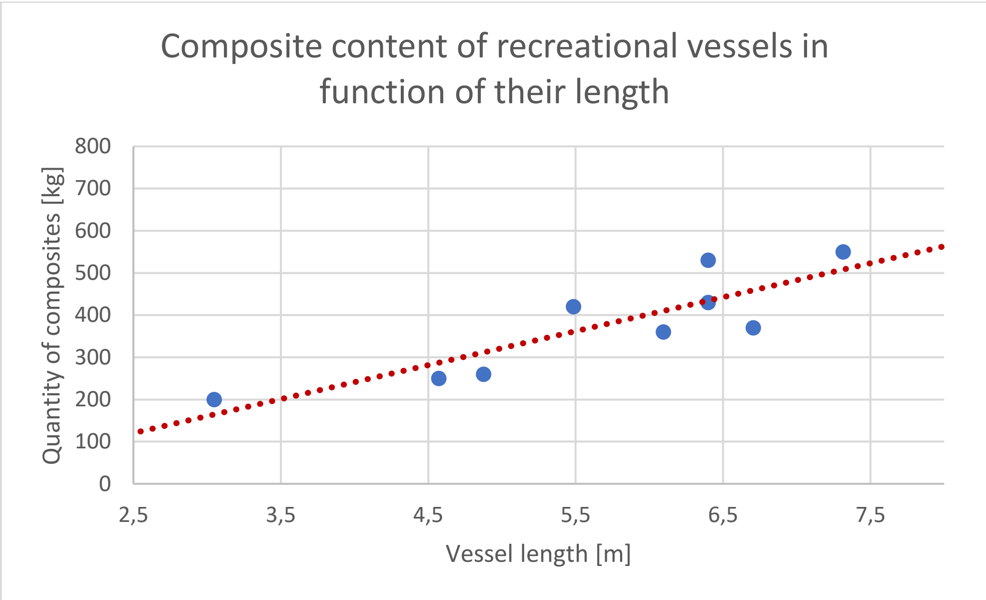

Figure 27: composite content of recreational vessels in function of their length

This best fit regression analysis generates the following equation.

$$Vessel\ composite\ content\ [kg] \cong 80 \cdot Vessel\ length\ [m] - 80$$

By combining the population of boats characterized by their length and the length / composites function it is possible to estimate the stock of composites embedded in the recreative vessels European fleet. This calculation is made under the following assumptions:

- The category of small boats, namely in the <7.5 m range, can't be simplified with an average length value, as commercial boats length can't be reduced below 2-3 meters. Therefore, the median value of boats length used in the calculation for the small boats category is set to 5 m.
- For the medium and long categories, median values of boats length used for the calculation correspond to the range average value.
- Composite hulls boats are estimated as 40% of the total fleet.

Results are reported in Table 11.

Table 11: stock of composites in the European recreational vessels fleet

Size class	Size median value [m]	Composites content per boat [kg]	Percentage of boats	Number of boats	Weight of composites [kton]
<7,5 m	5	320	74%	1'924'000	615,68
7,5-12 m	9,75	700	21%	546'000	382,2
12-24 m	18	1'360	5%	130'000	176,8
				Tot	**1'174**

Characterization of composite materials components in the naval sector

Composite materials are used in the naval sector, small and medium size boats manufacturing for three main functionalities (Rubino et al., 2020):

- The production of the boat hull, where composites are mainly exploited.
- The production of the sail masts, of course limited to sailboats.

- The production of propellers, even if more often propellers are manufactured using nickel-aluminum-bronze (NAB) alloy.

Due to the very peculiar availability of different types of components, it is almost useless to define a general bill of materials standard for recreational boats. In fact, (Eklund et al., 2013) proves that different boats of the same size can contain dramatically diverse percentages of composites. Nevertheless, as already explicated in By combining the population of boats characterized by their length and the length / composites function it is possible to estimate the stock of composites embedded in the recreative vessels European fleet. This calculation is made under the following assumptions:

- The category of small boats, namely in the <7.5 m range, can't be simplified with an average length value, as commercial boats length can't be reduced below 2-3 meters. Therefore, the median value of boats length used in the calculation for the small boats category is set to 5 m.
- For the medium and long categories, median values of boats length used for the calculation correspond to the range average value.
- Composite hulls boats are estimated as 40% of the total fleet.

Results are reported in Table 11.

Table 11, it is possible to link the size of a boat with its composites content. The percentage of composites in, in any case, generally between the 25% and 50% of the total weight of the boat (Eklund et al., 2013).

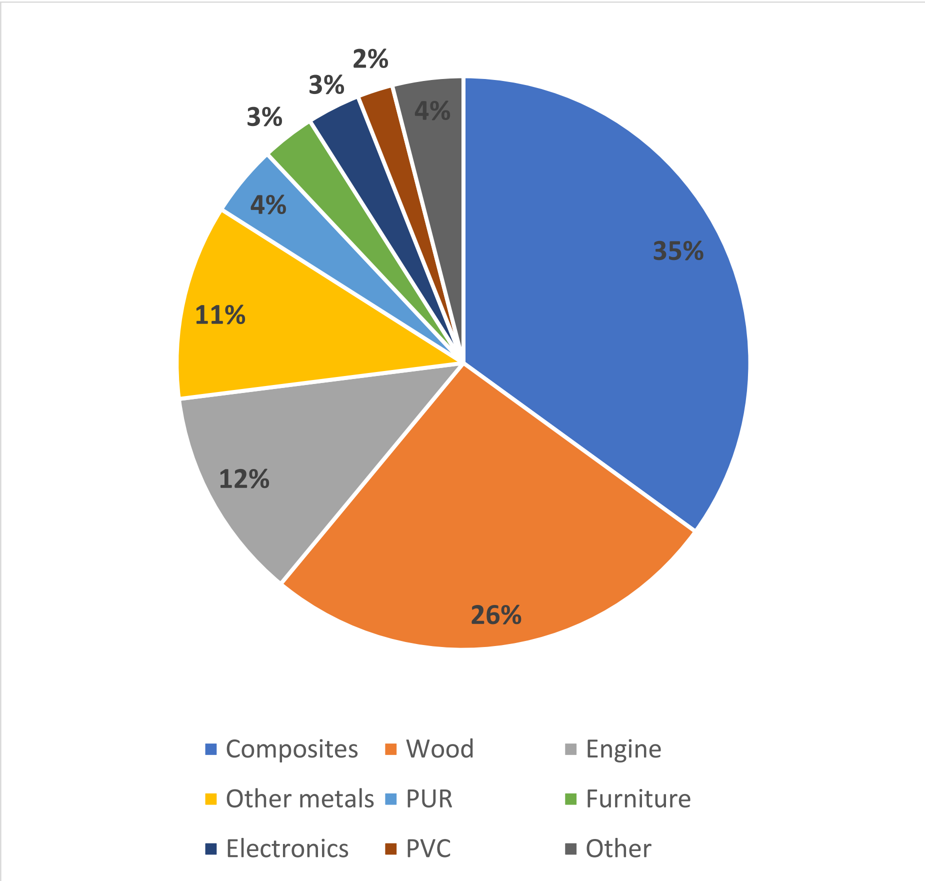

Figure 28: detailed material composition for a Selco queen 24 feet (Eklund et al., 2013)

Due to their economic viability, glass fibers based FRPs dominate the market of boat manufacturing, with the exception of sport and high performing vessels where carbon is also exploited. GFs are typically shaped to obtain the boat hull and other components by hand lay-up of laminates and spray-up

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techniques. Unsaturated polyester and vinyl esters are the most used resins. Resin concentration can vary in function of the mechanical properties imposed to the hull, but typically remains above 50% for non-high-performance vessels.

Regarding boats manufacturing, the most important market trend doesn't concern materials but manufacturing processes, as manual operations are gradually substituted by more automatized ones as closed molding techniques such as resin transfer molding (RTM), vacuum assisted RTM (VARTM), RTM Light, vacuum resin infusion molding (VRIM), vacuum infusion processing (VIP), closed cavity bag molding (CCBM) and the Seemann composites resin infusion molding process (SCRIMP) (Dokos, 2013).

Forecast of naval composite waste volumes in Europe

End-of-life management of small and medium private vessels (where most of the composites' stock is concentrated) differs from other composites waste management value chains.

Currently, there is no established dismantling procedure for EoL small boats, whose responsibility and effort are arbitrarily managed by the boat owner. (Directorate-General for Maritime Affairs and Fisheries (European Commission) et al., 2016) estimates an average disposal cost for a medium size boat of circa € 1'600.

For this main reason, the small and medium private vessels European situation is characterized by two main trends, described below.

Iterative restoration or set aside

In Europe, a non-negligible percentage of the overall fleet of recreational boats ((Eklund et al., 2013) estimates 6%) already reached the end of this natural lifecycle. Because of the inconvenience to dismantle these crafts, owners either decide to:

- Iteratively repair and restore such boats;
- Set aside their vessels without managing their disposal.

Figure 29: mid-size boat set aside. Taken from publicdomainpictures.net, CC0 1.0 license

Uncontrolled dismantling

According to (International Maritime Organization and London Convention/Protocol and Ocean Affairs, 2019, p.), 1.5% of the European recreational boats fleet is decommissioned every year. Nevertheless, the majority of EoL boats are "*currently abandoned, illegally landfilled [presumably in unlicensed sites] or sunk*" (Directorate-General for Maritime Affairs and Fisheries (European Commission) et al., 2016).

Cumulated forecast of EoL composites vessels

The two above-described trends influencing the management of EoL recreational boats demand for customized computational approach for the forecast of expected returning volumes.

For this specific market, a structured recycling supply chain would not substitute a less virtuous dismantling strategy, it would rather unlock the disposal of boats which are, nowadays, for the majority abandoned or set aside. Therefore, forecasts for this market are calculated cumulatively, and not with yearly expected volumes.

The assumptions are the following:

- The quote of vessels described above as "iteratively restored or set aside" are considered as ready for decommissioning.
- The quote of boats yearly dismantled increases the cumulated volumes.
- It is assumed that dismantled boats are replaced with new one with a flat rate, conservatively excluding market growths. Despite regarding the sailing fleet of boats, FRP hulls account only for the 4%, nowadays, the majority of boats are manufactured exploiting composites rather than wood or metal (Rubino et al., 2020).
  Composites manufacturing wastes are estimated as 5% (standard quote) of the totality of boat hulls entering the market.

This calculation leads to the cumulated waste availability profile visible in Figure 30.

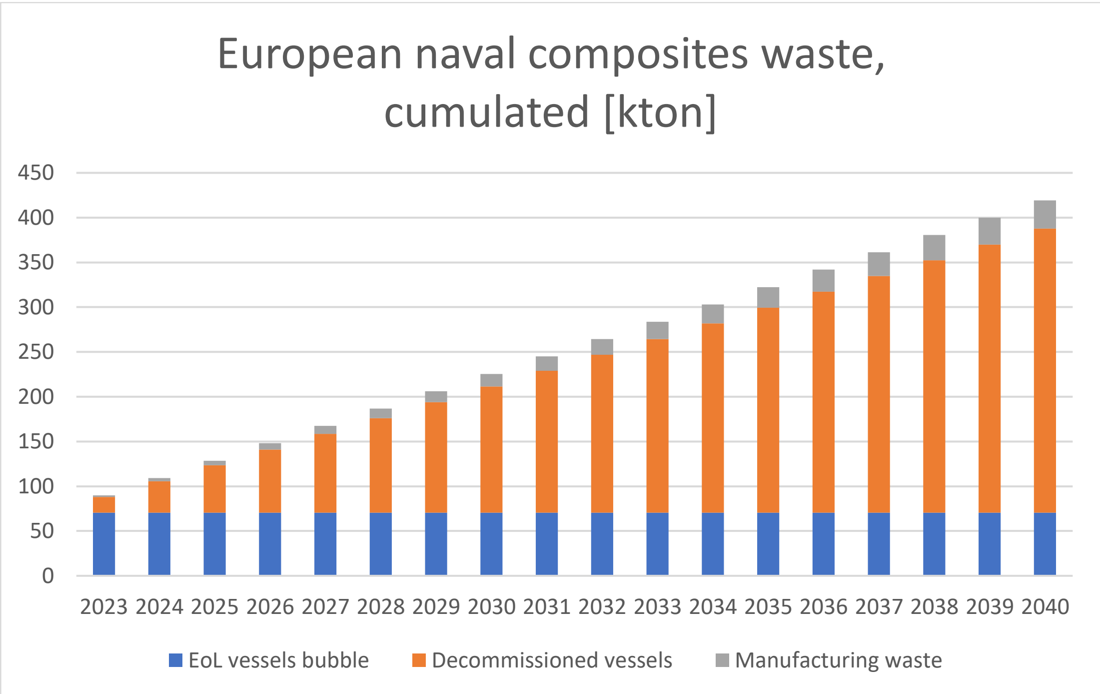

Figure 30: European naval composites waste, cumulated

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The main outcomes of this forecast are:

- The stock of EoL boats not dismantled by the owners for inconveniency represent a ~70 kton bubble of available composites, which might be theoretically unlocked by more advantageous conditions for the boats' disposal.
- Composites available in vessels to be dismantled are forecasted below 20 kton per year, nevertheless, since their virtuous disposal will not be implemented, their cumulation will lead to hundreds of ktons magnitude volumes of waste generated.
- Manufacturing waste is present in rather small quantities (around 2 ktons per year). Nevertheless, this material stream is particularly attractive for recycling, as manufacturing waste remains in good conditions and can be easily characterized via information sharing along the value chain.

Automotive

As in other commercial sectors, also automotive products define lightness and rigidity as key success factors to distinguish between high- and low-quality vehicles.

Figure 31: example of a Lexus LFA. Its entire body was made of CFRP; 65% of this material was used in its construction, which saved up to 220 lbs (100 kg) and increased the rigidity of the whole vehicle. Taken from Wikimedia Commons, CC BY-SA 3.0 license

The European automotive composites market has experienced a growth of 1,475.4 million $ in 2019. A further increase of 6.6% has been expected until 2026 (Graphical Research, 2020), resulting from a recovery after two years of restrictions due to the Covid-19 emergency. The analysis of market trends must consider the strong impact that Covid-19 had on manufacturing activities, with a dramatic impact on the automotive sector.

In the last decades, automotive has experienced an increasing use of composites in place of metallic materials. Composites are proving to be essential in giving cars the features necessary for the improvement of functionality such as good vibration resistance, high strength and light weight. Thanks to these innovative characteristics, carbon fiber seems to be the right material to produce more efficient and sustainable cars. A more lightweight car can lead to an overall fuel efficiency. This point aligned with the EU 2050 goal of CO_2 reduction. Over the long term, the increasing demand for lightweight materials and a growing interest in fuel economy are expected to play a primary role in the automotive market.

Characterization of composite materials components in the automotive sector

Composite material components are widely used in the automotive sector. This specific range of products can embed many parts made out of reinforced plastics. The composition, as well as the manufacturing process of these parts can dramatically vary.

For example, (Suschem et al., 2015) lists some components mounted on commercial cars made of different type of composites.

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Table 12: examples of composite components applied to automotive. Taken from (Suschem et al., 2015)

OEM-Model	Application	Material	Year
BMW i3	Passenger cell	CFRP	2013
BMW i8	Passenger cell	CFRP	2014
Alfa Romeo 4C	Chassis	Prepreg (CF, epoxy)	2013
Alfa Romeo 4C	Outer body	sMC	2013
Alfa Romeo 4C	Bumpers and mudguards	CF + PuR-RIM	2013
McLaren MP4-12C spider	Car roof, chassis, bodywork	CF monocell, lightweight CF body panels	2013
BMW M6 convertible	Roof compartment cover, trunk lid	GFRP	2013
BMW M6 Coupe	Car Roof	CFRP	2012
Daimler smart 3rd generation electric	Wheel rims	GFRP	2012
Callaway Corvette	Body aerodynamics Kit	CFRP	2012
Lexus LFA	Cabin, floor, roof, pillars, hood	CFRP	2012
Lamborghini Aventador LP700-4	Front and rear bumpers, body aerodynamics kit	CFRP	2012
Land Rover – Evoque	Instrument panel, inner door modules	GFRP	2011-12
Faurecia Jeep Liberty suV	Door module	GFRP	2010
Daimler AGt-Mercedes	Fluid filter module	GFRP	2009-10

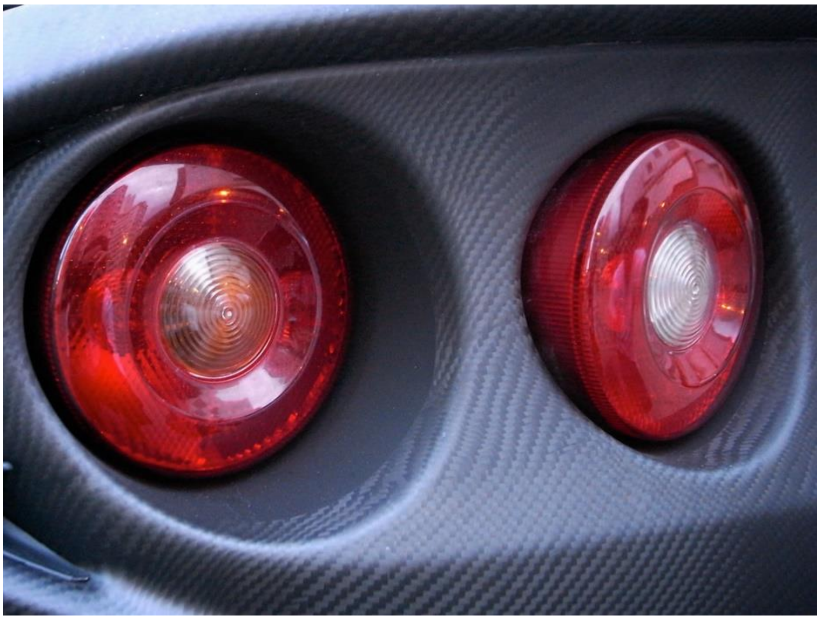

Figure 32: detail of a CFRP backlight frame. Taken from Flickr, CC BY-NC-ND 2.0 license

Composite components are used in the automotive sector in different quality ranges of cars. Small, short fiber, GFRP parts can be found in wider assemblies of several economy and mid-price cars. Long fibers loaded structural components guarantee the lightness and rigidity of luxury and sport vehicles.

The wide typology range of FRP components assembled into commercial cars intercepts the quasi-totality of fibers, resins, manufacturing processes available on the market (Patel et al., 2018; Suschem et al., 2015; Todor et al., 2017):

- Both glass fibers and carbon fibers are used in automotive components. E-Glass and PAN are the most exploited.
- Fiber length and orientation depends on the dimension and geometrical complexity of the product: structural frames can be made by long or endless oriented prepreg laminates while smaller components more often embed short fibers.
- Both thermoplastic and thermoset resins can be found in automotive applications; it is estimated that thermoplastics lead the market (70%). Examples of thermoplastic resins common in automotive composite applications are polypropylene (PP), thermoplastic polyurethane (tPu), polyethylene (PE), polyamide (PA) and polyvinyl chlorides (PVC).
- Both open moulding and closed moulding processes are used to manufacture composite components. High throughput and replicability demanded by large volumes production impose automated manufacturing processes for most of the composite parts assembled into commercial cars. Most of the exceptions belong to luxury and sport segments.

Composite materials stock and forecast of automotive composite waste volumes in Europe

The wide range of composite components types available in automotive products poses an issue in framing the quantitative analysis of the sector. A tentative holistic sectorial study would result in a merge of dramatically different components in term of composition, availability, and end-of-life state.

For this reason, this deliverable concentrates on a specific product type and associated composite components, namely CFRPs in sport luxury cars. This focus provides multiple benefits to the analysis:

- Despite focusing on a niche imposes a loss in market mass tracking, **luxury cars** represent the market segment which **embeds CFRP components with a greater wt%**. For this reason, it is reasonable to expect that circular economy actions applied to the automotive sector will start from the luxury segment, where composites are mostly available.
- Moreover, luxury cars are the vehicles typology where **CFRP frames made of long fibers prepreg laminates** are mostly available. The reduction of FPR components typologies results in a much more focused analysis, which can be more easily translated into a forecast functional to a specific recycling technology and related process chain.
- The numeric methodology here exploited for CFRPs into luxury vehicles can be eventually **extended to other automotive market categories** starting from the wider data provided in *"The composites market"* chapter of this document.

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Figure 33: CFRP based Lotus Elise. Taken from Flickr, CC BY-NC-ND 2.0 license

The quantitative analysis is based on the conceptual frame visible in Figure 34:

- The availability of CFRP composites in the luxury automotive segment is defined by combining three factors, namely: the average weight of a luxury car; the average wt% content of CFRPs inside a luxury car; the number of yearly put-on-market luxury cars in Europe.
- The waste returning volumes are estimated by applying a defined product lifespan delay between put-on-market and end-of-life.

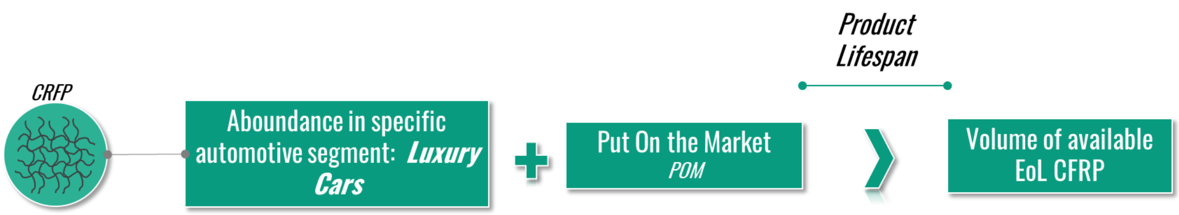

Figure 34: conceptual framework of the CFRP waste forecast for the luxury automotive sector

More details about the quantitative analysis below presented are here provided:

- 6% of luxury cars weights is made of composites (sensitivity 4-6-8%), (U.S. Commercial Service, 2020).
- The average weight of a luxury car is 2,5 tons (U.S. Commercial Service, 2020).
- 95% of the cars registered has an average life of 10 years (U.S. Commercial Service, 2020).
- Put-on-market 2010-2021: (ACEA - European Automobile Manufacturers' Association, 2022a).
- Put-on-market 2022-2027: it is expected a growth in the European market with a CAGR of more than 9%. For this reason, an increase of 1% in 2022, 2023 and 2024 and 2% in 2025, 2026 and 2027 has been calculated. The growth rates are maintained stable (2%) up to 2030 (ACEA - European Automobile Manufacturers' Association, 2022b).
- 5% of the cars registered could be dismissed early due to different reasons (e.g. accidents or general mechanical issues, etc.).

The above listed assumptions provide an EoL CFRPs availability from the luxury automotive segment in the next years.

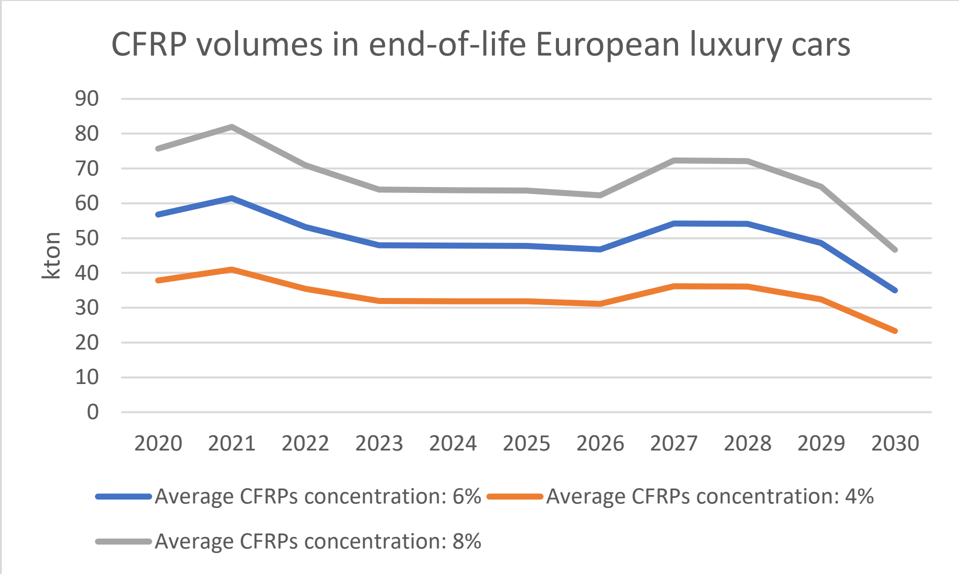

Figure 35: CFRP volumes in end-of-life European luxury cars

Despite this quantitative analysis is limited to a niche of products and related composites, its results are interesting and deserve to be commented. The automotive sector is a broad market. Inside it, specific product sub-categories produce volumes of composites components and waste with the same magnitudes of other complete sectors as the ones analysed in this chapter.

This picture translates into the possibility to frame stand-alone circular economy technologies and value chains on peculiar composite component types belonging to the automotive sector.

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Aerospace

Glass and fiber composites materials are largely applied in aerospace sector, both for passengers and cargo aircrafts and in luxury and military applications. Their usage in the sector began in the 1950s. Nowadays, composites can account for up to the 50% of the total weight of a commercial aircraft (e.g., Boeing 787 Dreamliner, Figure 36).

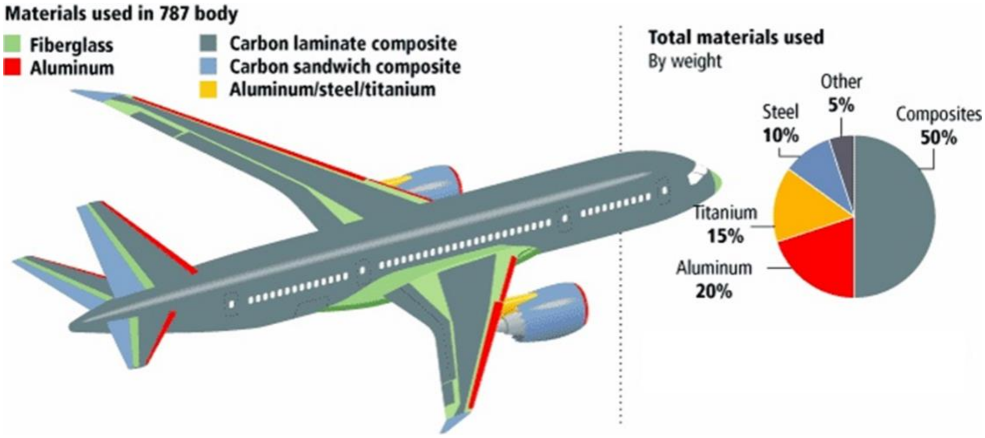

Figure 36: bill of materials of a Boeing 787 Dreamliner. Taken from (Shivi Kesarwani, 2017), [CC BY 4.0] license

The advantage of weight reduction with respect to metal components led to composites large adoption in the commercial aircrafts market, as GFRPs and CFRPs are currently widely exploited for the production of structural parts by the main airplanes manufacturers (namely Boeing and Airbus).

European commercial aircrafts population consists of more than 6'000 units. Considering that large planes can weight more than 200 tons and that the percentage of composites ranges between 10-50% in weight, these products represent an important stock of high quality FRPs which needs to be considered in future market returns scenario.

Composite materials stock and expected trends in the aerospace sector

To address the analysis related to the availability of composites in the aerospace sector, the first important step is to define the boundaries and targets of this study.

This document will specifically focus con commercial aircrafts, for both passengers and freight usage. Commercial aircrafts concentrate the majority of material volumes within the sector and are the most aggregated and homogenous family of products, while other niches as small jets, helicopters, military units and others demand for a more granular analysis whose material volumes are out-of-scope for this document.

Figure 37: commercial aircrafts parked in Frankfurt Airport. Taken from [Wikimedia Commons](), [CC0 1.0]() license

The strategy to assess the composites stock in the commercial aircrafts fleet is based on the combination of two main data categories:

- The population of European commercial aircrafts, characterized by the age of flying planes.
- The estimated average composites availability in planes of different generations.

The first set of data is available in the Eurostat datasets (Eurostat, 2022a). The population of European commercial aircrafts in 2021, including UK, was made of 6'807 units, distributed by age as visible in Figure 38.

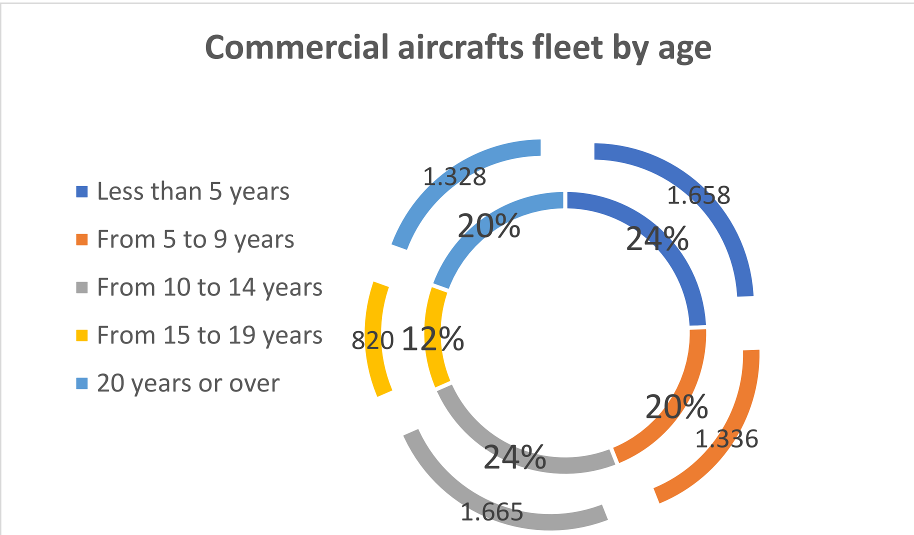

Figure 38: European commercial aircrafts fleet by age, updated 2021, including UK. Source: (Eurostat, 2022a)

To estimate the average composites availability in planes of different generations, it is necessary to frame a small benchmarking approaching the most relevant models of commercial aircrafts marketized in the last decades.

This analysis focuses on well-known and largely marketized models of medium size commercial aircrafts, (double engine, 300-500 seats). It is assumed that small short-range aircrafts and big quadruple engine aircrafts mutually compensate the average dispersion of medium data here considered (Eurostat, 2022b).

The market of commercial aircrafts can be basically simplified as a duopoly, as Airbus and Boeing cumulated market share always remained between 85-95% in the last decades (Statista, 2022). The two

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players similarly commercialized two generations of mid-size aircrafts in the last years. The benchmarking of these planes families is reported in Table 13.

Table 13: benchmarking of largely marketized commercial aircrafts of different generations

Model	Variants	Year	Average operative empty weight (OEW) [tons]	Composite content	Sources
Airbus A330	A330-200, A330-300, A330-200F	First flight: 1992	120	10%	(European Union Aviation Safety Agency, 2022a, 2022b, 2022c, 2022d; Wong et al., 2017)
Airbus A350	A350-900, A350-1000	First flight: 2013	150	53%	
Boeing 777	777-200, 777-300	First flight: 1994	145	11%	
Boeing 787 Dreamliner	787-8, 787-9, 787-10	First flight: 2009	128	50%	

Despite Table 13 provides a benchmarking limited to four airplanes, it is sufficient to derive some useful considerations:

- The average weight of a mid-side commercial airplane remains in the 120-150 tons range.
- New generations airplanes, commercialized since the 2010s, brought a composites revolution, strongly increasing their percentage.

To continue the evaluation of composites stock in the European aerospace sector, data provided in Table 13 must be adapted to the age ranges of (Eurostat, 2022a). This fitting results in Table 14, which summarized the assumptions behind the evaluation of composites stock in the European commercial planes fleet.

Table 14: assumptions for the estimation of composites content in the European aircrafts fleet

Generation	Average weight [ton]	Composite wt%	Notes
Less than 5 years	125	45%	*"A350, 787 Dreamliner"* generation
From 5 to 9 years		40%	*"A350, 787 Dreamliner"* generation
From 10 to 14 years		25%	In between generations
From 15 to 19 years		15%	*"A330, 777 Dreamliner"* generation
20 years or over		10%	Earlier generations

Finally, it is possible to calculate the generation dependent and overall stock of composites in the market, as reported in Table 15.

Table 15: composites content in the European commercial aircrafts fleet

Generation	Numbers of aircrafts	Composite wt%	Composites stock [kton]
Less than 5 years	1658	45%	93,3
From 5 to 9 years	1336	40%	66,8
From 10 to 14 years	1665	25%	52,0
From 15 to 19 years	820	10%	10,3
20 years or over	1328	5%	8,3
		Tot	**231**

Characterization of composite materials components in the aerospace sector

The characterization of composite usages in aerospace starts from the definition of their advantages in the sector. Composite components are adopted in aerospace usage for multiple reasons (Shivi Kesarwani, 2017):

- Weight reduction with respect to other materials.
- Mechanical properties can be tailored by 'lay-up' design, with tapering thicknesses of reinforcing cloth and cloth orientation.
- Technical fibers as Kevlar (aramid) ensure high impact resistance.
- High damage tolerance improves accident survivability.
- Avoidance of 'Galvanic' - electrical – corrosion problems which would using two dissimilar metals.

Composites assembly in aircrafts

The above-described advantages and the possibility to cover composites usage costs in this typology of products lead to a large adoption of FRPs for the production of different types of components within the same aircraft. A comprehensive example is the Airbus A350XWB, whose composite structures are represented in Figure 39 (Airbus S.A.S., 2014).

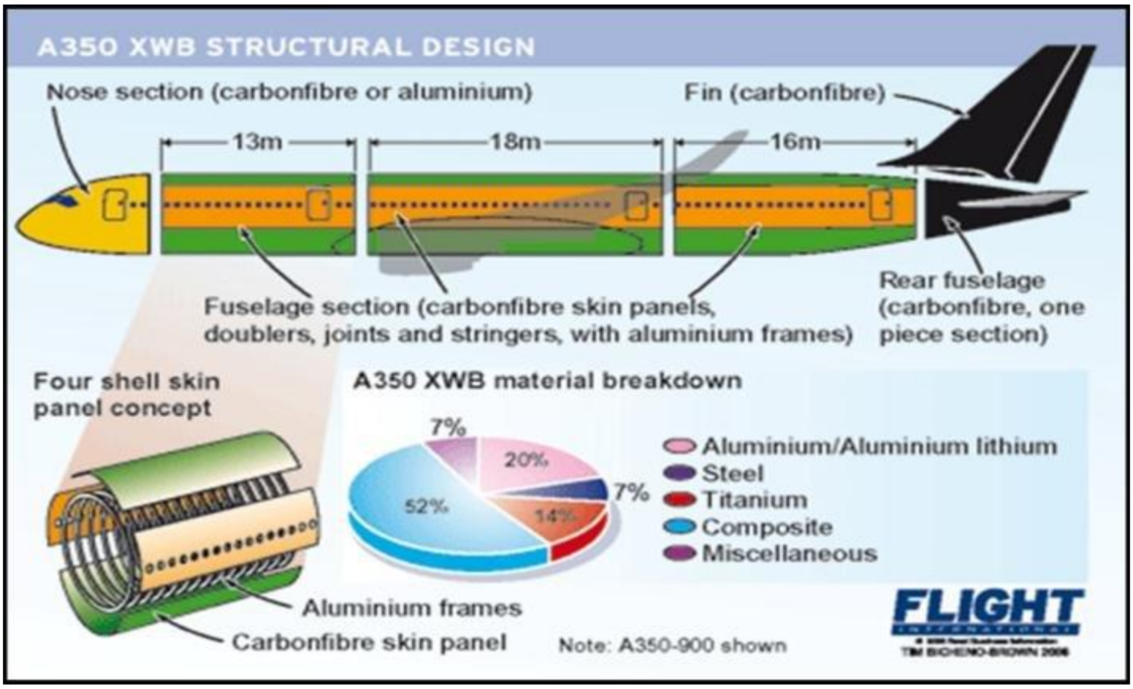

Figure 39: Composite structures of an Airbus A350XWB. Taken from (Shivi Kesarwani, 2017), CC BY 4.0 license

Composites can be used to manufacture wings, tail, doors, interiors, and most of the fuselage (panels, frames, window frames, clips).

Aircrafts are large-sized complex vehicles. In modern planes many different composite parts are separately manufactured and then assembled together.

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Figure 40: Airbus assembly hangar in Toulouse. Taken from [Wikimedia Commons](), [CC BY-SA 4.0]() license

Fibers and resins in aircrafts and manufacturing waste

FRPs are exploited by aircraft manufacturers in diverse and peculiar components and exploiting different design strategies. It is therefore difficult to report common practices in the usage of specific fiber types, orientation, length, resins.

More generally, carbon fibers in epoxy resin is the mostly exploited composition (Wong et al., 2017), typically using long fibers prepreg foils. Composites may be in monolithic or sandwich form. Monolithic if they are solid and sandwich if the laminate sheets are separated by a core of different material type, usually honeycomb or foam.

Manufacturing waste is particularly severe for aerospace composites: long squared prepreg foils are cut in mid-small size shapes to create many different components. Despite accurate and automated processes aided by nesting algorithms to reduce the quote of non-utilized foil, the buy-to-fly ratio for composite materials is estimated around 1.5 (Bihlman, 2015). This means that composites manufacturing scraps can be estimated as the 50% of the composite mass embedded in each new aircraft.

Forecast of aerospace composite waste volumes in Europe

Data presented in the previous sections of this paragraph are here merged, integrated and extended to generate a forecast of the expected wind energy composite waste volumes for the period 2023 – 2040.

Manufacturing waste

The first waste stream analyzed in this section is the manufacturing waste. The European analysis boundary imposes to estimate the manufacturing waste related to aircrafts produced within the continent.

This analysis can be easily framed with some assumptions:

- As before introduced, the commercial aircrafts market is almost completely saturated by two main players, namely Airbus and Boeing. The first is European and the second is American.

- The number of yearly commercialized aircrafts is available for each manufacturer: (Statista, 2022). In 2021, Airbus commercialized 611 aircrafts.
- Conservatively, stable flat market is assumed in the upcoming years, as recent worldwide experiences as COVID-19 pandemic and Ukrainian-Russian war put uncertainty on market outlooks.
- The quote of composites scraps can be reasonably estimated as 50% of the composites available in newly produced Airbus aircrafts, assuming an average plane weight and a composite content coherent with new generation aircrafts.

Table 16: European yearly manufacturing waste in the commercial aircrafts segment

Yearly commercialized aircrafts	611
Average weight [ton]	125
Composites wt%	50%
Buy-to-fly ratio	1,5
Yearly manufacturing waste [kton]	19

End of life aircrafts

To complete the forecast, the upcoming analysis derives the data related to the currently flying European commercial aircrafts fleet to estimate the associated EoL expectations and associated composites volumes.

The estimation of the expected lifecycle of commercial aircrafts is derived by data available in (Elsayed et al., 2018). This study collects historical data about the lifecycle duration of more than 14'000 planes, divided in passenger and freight categories. This dataset has been elaborated to produce the statistical distribution of airplanes lifecycle expectations visible in Figure 41.

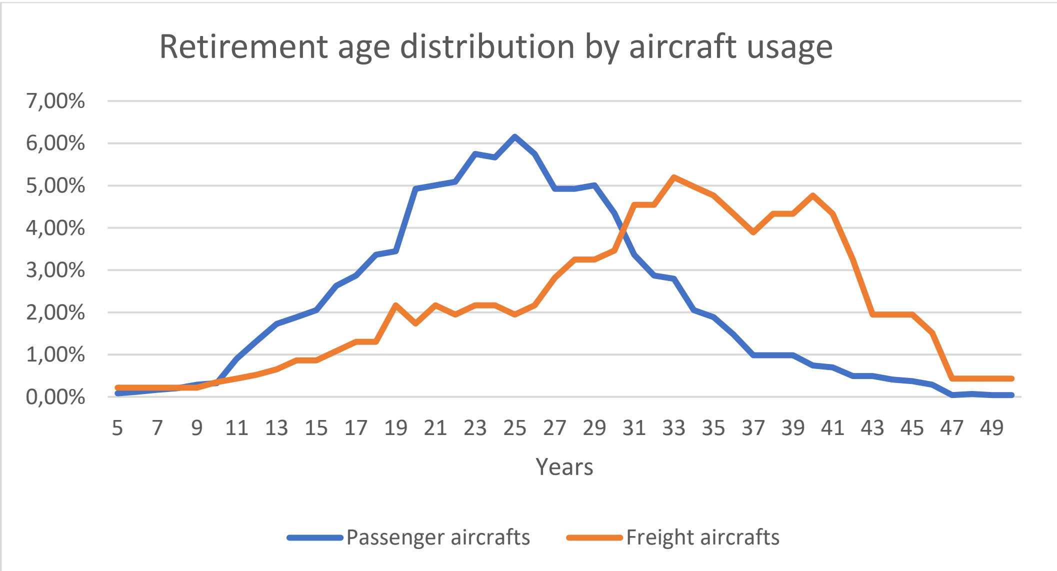

Figure 41: retirement age distribution by aircraft usage

These two trends are combined with data available in Table 15 under the following assumptions:

- Age of aircrafts belonging to the "older than 20 years" (Table 15) generation is estimated deriving the statistical distribution presented in Figure 41.

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- Aircrafts of different generations (Table 15) are distributed with flat rate within the generation range.
- Each retired plane is replaced by a new one, with modern composites content (Table 16). No market growth is modelled, respecting the conservative scenario presented in the previous paragraph.
- Also newly commercialized planes undergo the same retirement prospect modelled in Figure 41.
- Passenger aircrafts account for the 65% of the total fleet (Eurostat, 2022b).
- Composite content in each retired airplane is estimated according to (Table 15).

Following the above presented assumptions, Figure 42 presents the forecast of retired commercial passenger aircrafts up to 2014. Figure 43 does the same for freight crafts.

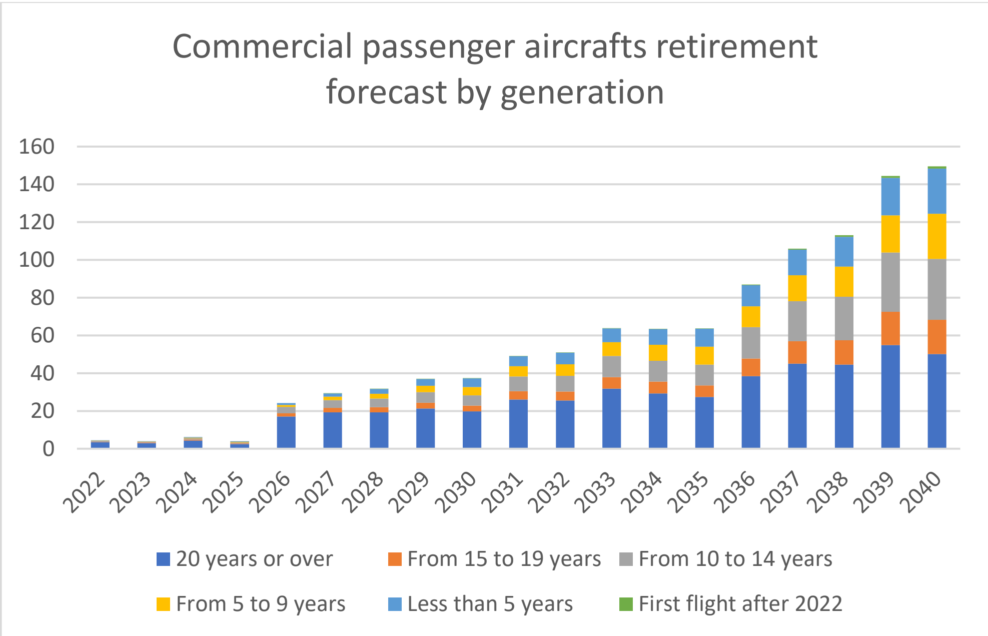

Figure 42: commercial passenger aircrafts retirement forecast by generation

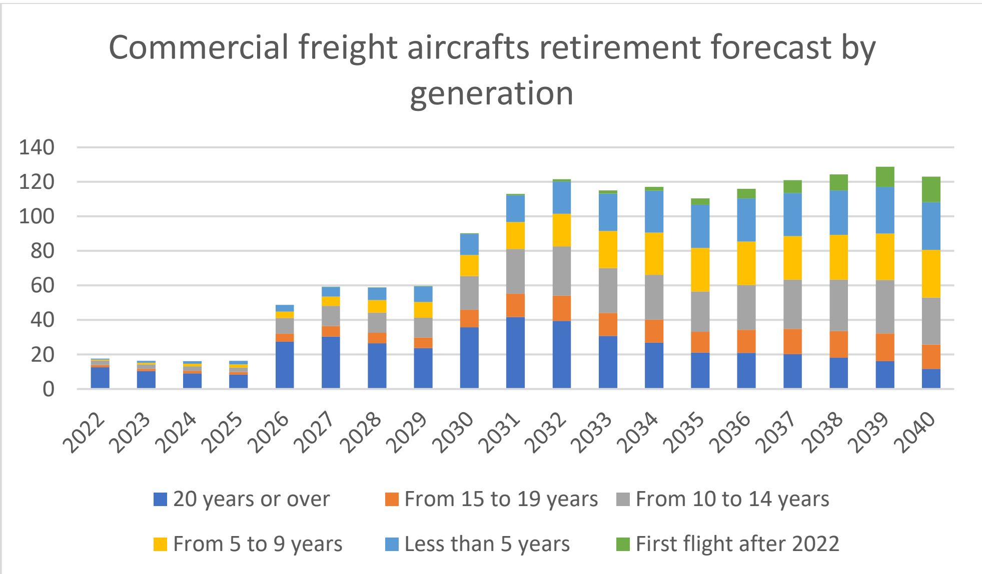

Figure 43: commercial freight aircrafts retirement forecast by generation

Finally, Figure 44 derives the availability of EoL composite wastes of passenger aircrafts, Figure 45 does it of freight crafts and Figure 46 merges the three waste streams analysed, namely manufacturing waste, EoL passenger aircrafts and EoL freight aircrafts.

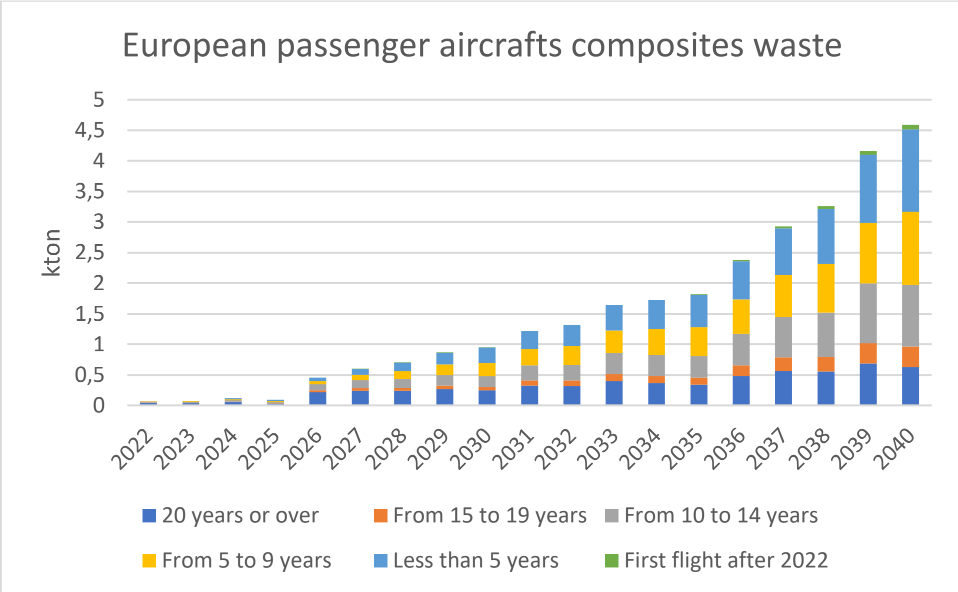

Figure 44: European passenger aircrafts composites waste

Figure 45: European freight aircrafts composites waste

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Figure 46: European composites waste forecast in aerospace sector

Figure 46 visualizes a clear situation: aircrafts which are expected to be retired in the next years mostly belong to old manufacturing generation, and therefore don't embed major percentages of composites. For this reason, the composite waste volumes will be mostly generated by manufacturing waste.

Nevertheless, the 2040 forecast is enough extended to picture the first retirements of composite based crafts, which will increase in the following decades, worsening the composite wastes duties in this value chain.

Construction

Multi-material structures are widely used in modern civil infrastructures and buildings, as different functionalities (structural, insulation, aesthetic, etc.) are managed by different components. In fact, technical literature of the construction sector usually refers to *composites* as multi-material, typically multi-layer, structures (Tangent, 2018). FRPs are one of the types of composite structures used in the sector.

Figure 47: Construction site of Henn's Cube will, the world's first building made of carbon fiber-reinforced concrete. Taken from [Wikimedia Common](), [CC BY-SA 4.0]() license

Of course, this deliverable focuses only on glass and carbon fibers reinforced polymers, according to the main reference framework of the RECREATE project. This distinction poses a limit to quantitatively analyse the sector, because available statistical literature includes proper GFRPs and CFRPs into the broader family of construction composite structures. Moreover, the in force European regulation on waste statistics (European Parliament, 2002) doesn't specify composites as a sub-category of demolition waste (code 06.1 – Metallic waste, ferrous; 06.2 – Metallic waste, non-ferrous; 06.3 – Metallic waste, mixed ferrous and non-ferrous; 07.1 – Glass waste; 07.4 – Plastic wastes; 07.5 – Wood wastes; 12.1 – Mineral waste from construction and demolition).

For these reasons this deliverable section only provides a characterization of the typologies of composite material components used in the construction sector, and doesn't include quantitative analyses. Nevertheless, as highlighted in *"The composites market"* chapter of this document, construction segment covers a non-negligible share of the European composites market, especially regarding glass fibers.

Characterization of composite materials components in the construction sector

Composites utilization in the construction sector is divided into two main categories: construction of new buildings and infrastructures; maintenance, repair, and reinforcement of existing infrastructures (Hamakareem, 2021; Mosallam, 2014; Pendhari et al., 2008).

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Construction of new infrastructures

According to (Hamakareem, 2021), main utilizations of FRP components for the construction of new civil infrastructures can include the following applications:

- High-performance hybrid structures are made combining reinforced concrete and FRP laminates. Sometimes, FRP bars are used as internal reinforcement for concrete structures.
- Structural frames of stairways and walkways can be made of FRPs.
- Glass fiber composites are used for the construction of electrically neutral structures.
- Polymer composites are used for the construction of marine infrastructures (for example, offshore platforms), as they guarantee high corrosion resistance.
- Specific components used in the construction sector (for example, piping, roofing plates) are usually made of GFRPs.

Figure 48: stock of fiberglass pipes. Taken from Wikimedia Common, CC BY-SA 3.0 license

Reinforcement and maintenance of existing infrastructures

According to (Mosallam, 2014; Pendhari et al., 2008), FRPs are used for the maintenance, repair, and reinforcement of existing infrastructures with these specific usages:

- Epoxy bonded FRP plates are used for the external strengthening of prestressed concrete and reinforced concrete beams and columns.
- Particularly, FRP structures are employed for seismic repair and retrofitting.
- FRP sandwich systems can reinforce concrete bridges creating a buffer to protect bridge girders and piers.

Sport

The previous paragraphs already introduced how FRPs combine lightness, rigidity, elasticity, resistance to corrosion and other qualities which defines these materials as the best technological alternative in many application sectors.

One of those segments is sport equipment: many disciplines foresee the usage of specific objects as vehicles, rackets, rods, etc. The final measured performance largely depends on the athlete ability and training, but of course, also the involved equipment plays a role in achievement of better results.

Improving the performance and enjoyability of sport activities brings many professional and amatorial athletes to pretend from the market high-end equipment, and as a result, despite the high cost of composites (mainly CFRPs), these materials are largely adopted in state-of-the-art equipment of many disciplines.

Figure 49: left, a CFRP frame of a bike. Taken from [Flickr](), [CC BY-NC-ND 2.0]() license. Right, skies embedding GFRP recycled material, outcome of the FiberEUse H2020 project

This paragraph will not analyze quantitively the stock and expected return forecasts of composites in the sport sector for the following reasons:

- Volumes involved are lower than in other sectors (AVK – Industrievereinigung Verstärkte Kunststoffe, 2021).
- There is poor availability of data specifically related to composites in sport, as market analyses typically don't define the sport sector, as it is divided into other frames as leisure, transportation, consumer goods (AVK – Industrievereinigung Verstärkte Kunststoffe, 2021).
- Composites products are considerably different in the sport sector, and so it's their usage and therefore lifecycle and end-of-life conditions. Therefore, there are no conditions to produce a holistic analysis of the sport sector.

Despite the execution of a quantitative analysis regarding composites in the sport sector is not the scope of this deliverable, their introduction as a key segment for the application of circular economy options is important for three main reasons:

- Sport equipment is a high-end sector where state-of-the-art technologies are used. This concepts fully applies to composites. High-quality fibers, resins, manufacturing processes are used to produce performing hardware. This sector is therefore interesting for circular economy technologies, to see how they can be applied to innovative FRPs.

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- Sport equipment is, among the six sectors of the deliverable, the one whose market dynamics depend more on the customer perception of the product and brand. In this context, giving a circularity message attached to the commercialized products might play a role in the product placement mechanisms.
- Sport equipment composite parts are the focus of some RECREATE use cases.

This section provides a brief description of the usage of composites in the sport sector, with two main focuses: the first regards the typology of composites in terms of constituent materials, typology of components and manufacturing technologies; the second provides examples of sport equipment which are partially or totally made from composites.

Characterization of composite materials components in the sport sector

As already underlined, the best sports equipment in the world is closely related to science and innovation. Within this framework, best quality materials are adopted also for the manufacturing of sport equipment for competitive but non-professional athletes.

In fact, sport sector has a large adoption of carbon fiber composites. Different manufacturing processes are used in function of the final shape of the composite component to be manufactured. (Zhang, 2015) defines four main shape classes of composite components used in sport equipment, here reported in Table 17.

Table 17: shape classes of FRP composite materials application in the sports equipment

Shape class	Application
Plate-like structure	Skis, surfboards, windsurfing, table tennis boards, slats and gliding wing spar etc.
Tubular structures	Tennis, badminton, fishing rods, golf clubs, baseball bats, hockey sticks, pole shaft, etc.
Sheet structure	All kinds of helmets, golf club heads.
Other structures, complex structures	Match with a variety of vehicles (bicycles), Sword, climbing ropes, various lines etc.

Figure 50: CFRP sport equipment. Left, fishing rod, tubular structure. Taken from [Rawpixel](), [CC0 1.0]() license. Right, carbon and wooden tennis rackets. Taken from [Flickr](), [CC BY 2.0]() license

Conclusions

This deliverable introduced the market framework, related to circular economy opportunities for composite products, where RECREATE technologies will be inserted when they will reach higher TRLs.

The first core chapter introduced the composites European manufacturing market, specifying the reference segments, the typology of fibers and resins used as well as the manufacturing technologies.

Then, the European state-of-the-art Circular Economy options for composites are presented. Two analyses are combined: the first frames the legislative boundaries for composites landfilling; while the second maps the current technologies available for composites recycling or repurposing and their TRL.

The core quantitative part of the deliverable analyses six target sectors with important FRPs usage. For each segment, FRP components are qualitatively characterized, then, according to the availability of data source, an estimation of the market composites stock and forecast of returning volumes is performed.

To adequately conclude this deliverable, this chapter introduces a matchmaking matrix (Table 18) which preliminarily identifies the applicability of the circular economy technologies whose development is foreseen in RECREATE to the different typologies of analyzed products.

The goal of this exercise is to give a first business assessment about the potential market placement of the RECREATE technological portfolio. By doing so, this deliverable is more strongly linked to the core scientific part of the project and can be taken as a reference by technology developers of RECREATE in order to customize and shape their processes into close-to-market use cases.

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Table 18: matchmaking between composite waste typologies and RECREATE circular economy technologies

	Market sector	Wind energy	Naval	Aerospace	Automotive	Construc tion	Sport
	Yearly EoL volume in 2030 [kton]	140 wind blades	50 recreational vessels	23 commercial airplanes	40 luxury CF	/	/
RECREATE Opportunity	Temperature assisted reshaping				Short lifecycle		Short lifecycle
	Reversible adhesives	Reusable layers		Reusable components	Reusable components		Reusable components
	Design for disassembly	Complex assemblies		Complex assemblies		Complex assemblies	
	Laser based dismantling, machining	Multi materials		Multi materials	Multi materials		
	LIBS	Remote testing	Non destructive	Non destructive	Non destructive		Non destructive
	Catalyst assisted green solvolysis			CFRPs	CFRPs		CFRPs
	Electro-fragmentation	GFRPs laminates	GFRPs laminates	FRPs laminates	FRPs laminates		FRPs laminates
	Vitrimers, reversible green resins	Potentially applicable to innovative products in non-high-temperatures environments					
	Smart recognition for sorting		Disassembly components	Disassembly components	Disassembly components	Disassembly components	
	Decision Support Systems	Large infrastructure	Complex assembly	Complex assembly			
Backup	Microwave pyrolysis (Backup technology)			CFRPs	CFRPs		CFRPs
	Mechanical treatment (Backup technology)	Potentially applicable to all type of products					

Some considerations are made elaborating the Table 18 matrix:

- **Remanufacturing** oriented technologies as *Temperature assisted reshaping*, *Reversible adhesives*, *Design for disassembly* and *Active (laser based) dismantling of complex and multilayer structures* might be applied to those products which embed composite components into bigger assemblies. Controlled value chain and reasonably short lifecycles are key enablers for these business models.
- The **recycling** technologies included in RECREATE (*Catalyst assisted green solvolysis, Electro-fragmentation*) have high-added-value potentials. They can be applied to carbon-based products and they are particularly adequate to recover valuable long fibers from composites laminates. Actually, many of the analyzed products (wind blades, aerospace structures, boat hulls, automotive parts, sport equipment) fit the required input quality for these recycling strategies.

- **Vitrimers and reversible green resins** can be potentially applied to redesign the structure of all the product components analyzed, with the main limitation of the maximum operative temperatures.
- **Auxiliary technologies** for inspection, sorting and decision support can potentially be applied to a large set of products, with an adequate customization path.
- More conservative recycling approaches (mechanical and thermal) are considered as **backup** solutions/mitigation strategies to avoid risks associated to limited performance of the core recycling technologies proposed in the project.

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