Socio-economic analysis of recycled carbon fiber use

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Overview

The transition towards a circular economy in advanced materials is no longer driven solely by environmental considerations, but increasingly by economic, social, and strategic imperatives. Carbon fibre composites are a key enabling material for sectors such as transport, energy, aerospace, and construction, yet their production is resource-intensive, energy-demanding, and strongly dependent on imported raw materials. At the same time, growing volumes of composite waste are emerging from end-of-life products and industrial scrap. In this context, the recovery and reuse of carbon fibres (rCF) offers a unique opportunity to combine decarbonisation, resource efficiency, and industrial competitiveness.

This report focuses on the socio-economic aspects of using waste carbon fibres, with particular attention to the technologies and value chains developed within the EuReComp framework. Its main objective is to move beyond a purely technical or environmental assessment and to demonstrate how circular solutions for composites can generate tangible economic value, create jobs, strengthen skills, reduce strategic dependencies, and gain social acceptance. By translating environmental gains into economic metrics, assessing labour market impacts, and analysing value chain effects, the analysis aims to support evidence-based decision-making for industry stakeholders, policymakers, and project partners.

The importance of this assessment lies in three interconnected challenges currently faced by the European Union: (i) the need to decarbonise industry while maintaining competitiveness, (ii) the growing pressure on critical raw material supply chains, including virgin carbon fibres, and (iii) the requirement to ensure that technological transitions are socially acceptable and deliver clear benefits for workers and communities. Demonstrating the socio-economic value of recycled carbon fibres is therefore essential to justify investments, de-risk deployment, and accelerate market uptake.

The report is structured into four complementary chapters, each addressing a key dimension of the socio-economic impact:

Labour Market and Skills Impact – This chapter identifies the occupations and skills required to implement EuReComp technologies and estimates the potential employment effects (in FTE). It maps technological activities such as pyrolysis, composite repair, and eco-design to relevant ESCO/ISCO occupations, analyses labour market data, and develops employment scenarios, resulting in a structured view of jobs and competencies needed for scaling up circular composite solutions

Monetised Environmental Benefits – This chapter translates environmental benefits—such as avoided CO_2 emissions and reduced demand for virgin carbon fibres—into economic values using shadow pricing. Based on data from technical and environmental assessments, it compares demonstration, national, and EU-level scenarios to illustrate the economic potential of green impacts and the added value of circular solutions

Material Substitution and Strategic Autonomy – This chapter assesses how recovered carbon fibres can reduce dependence on imported virgin materials and strengthen the resilience of the European value chain. It compares rCF outputs from demonstrators with import data, analyses substitution potential, and maps the segments of the value chain that benefit most, framing the results in the context of EU strategic autonomy and raw material security

Social Acceptance and Implementation Barriers – The final chapter examines how recycled carbon fibres and recovery installations are perceived by industry and society. Using survey-based evidence, it analyses acceptance of rCF quality, certification and safety, as well as potential NIMBY effects, and identifies key barriers to implementation together with possible recommendations for stakeholders

Taken together, these four chapters provide a coherent and comprehensive picture of the socio-economic relevance of waste carbon fibre recovery, supporting the case for scaling up circular composite technologies in Europe.

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1 Introduction

Socio-economic analysis (SEA) is a type of regulatory impact assessment applied in managing environmental and health risks. Public authorities use regulatory impact analysis to weigh the potential advantages and disadvantages of taking or not taking action, as stated in the EU treaty (Péry i in., 2013). The underlying approach to environmental policy assessment, as illustrated by this treaty reference, is based on welfare economics and cost–benefit analysis. Several EU directives and regulations, such as the Water Framework Directive, the Industrial Emissions Directive, and the REACH regulation, explicitly incorporate cost–benefit analysis or SEA (*Annual Full-Time Adjusted Salary in EU Grew in 2023*, 2024) (Dreyer i in., 2010).

In the field of chemicals management, SEA aims to provide a well-rounded, objective evaluation of the benefits and risks associated with either maintaining or phasing out a chemical from the market. Essentially, SEA involves identifying and assessing both the positive (benefits of the chemical's use) and negative (health and environmental risks) impacts of a substance and its potential alternatives. It then compares these options by calculating their overall social value, which is determined by subtracting costs from benefits. Additionally, SEA serves as a versatile tool for managing chemical risks within a broader framework that can also be applied to other types of risks, such as environmental, health, or technological risks. This enhances the coherence and effectiveness of policymaking (*Chemicals Strategy - European Commission*, b.d.).

1.1 Sustainable recycling chain

Sustainability aims to meet the world's current energy needs by considering environmental, economic, and quality-of-life factors. However, it does not always fully account for the ability of future generations to meet their own energy demands (Sabri & Beamon, 2000). Accurately assessing sustainability requires examining the processes of trading, production, and final conversion of biofuels. A precise evaluation of sustainability must take into account key environmental policies, socio-economic factors, and regulatory frameworks (Zahraee i in., 2020) (Amigun i in., 2011).

From an economic perspective, the concept of recycling involves several key issues (though it is not limited to them): (1) the cost of implementing and maintaining recycling systems, (2) the efficiency and profitability of the recycling process, and (3) the increasing financial investment in recycling programs. The first issue relates to the costs of collection, sorting, and processing waste, which may exceed the profits from recovered secondary raw materials. The efficiency of recycling depends on available technologies and the level of waste segregation, and a lack of proper infrastructure can lead to low-quality recycled materials and limited reuse potential.

The production of recyclable materials can also compete with other sectors of the economy. For example, an increased demand for secondary raw materials, such as recovered paper or recycled plastic, may affect the prices of primary raw materials. For this reason, growing attention is being paid to innovative waste processing methods, such as chemical recycling or biotechnological plastic degradation, which can improve material recovery efficiency and reduce production costs.

Recycling-related activities can also contribute to the economic growth of local communities. Financial support for recycling programs can lead to the creation of new jobs in waste collection, processing, and manufacturing from recycled materials. Additionally, investments in modern recycling technologies and infrastructure development can increase the revenues of businesses and households involved in the recycling process (Amigun i in., 2011).

In the context of social sustainability, key issues related to recycling include: (1) its impact on employment and income distribution, (2) its influence on land use and urban development, and (3) its effects on essential social resources such as water and air quality. Recycling initiatives can be particularly beneficial in urban and industrial areas where waste generation is high and there is significant potential for material recovery. These areas often include low-income communities that rely on waste collection and processing as a source of livelihood.

Recycling can contribute to poverty reduction by creating jobs, increasing household incomes, and improving economic conditions through the reuse of valuable materials. By fostering economic opportunities and reducing environmental hazards, recycling initiatives can enhance the overall quality of life for individuals in these communities while promoting a more equitable distribution of resources.

1.2 Strategic Decisions in Recycling

The strategic level of decision-making in recycling involves long-term planning and significant financial investments. Companies make such decisions for periods extending beyond a year, similar to building a new recycling facility or investing in innovative waste processing technologies. In the recycling industry, strategic decisions include selecting the types of materials to prioritize for recovery, determining the size and location of sorting and processing plants, investing in advanced recycling technologies, planning efficient transportation systems, and establishing long-term supply contracts for secondary raw materials.

Due to the evolving nature of waste generation patterns and recycling technologies, there is often limited historical data available. As a result, strategic decisions are typically made based on aggregated information and future projections. Most studies on recycling focus on a single time period (*(PDF) Analyzing Impact of Intermodal Facilities on Design and Management of Biofuel Supply Chain*, b.d.); however, incorporating multi-period analysis—such as planning over multiple years—can help account for fluctuations in material availability and market demand, ensuring a more sustainable and adaptive recycling system (Nguyen i in., 2019).

1.3 Tactical Decisions in Recycling

Tactical decisions in recycling focus on medium-term planning, typically spanning several months. These decisions involve optimizing operations within existing resource constraints to ensure efficiency and sustainability. In an industrial context, tactical planning includes determining the quantity of recyclable materials to be processed in each period, managing inventory levels, and coordinating logistics to maintain a steady flow of materials.

In recycling systems, tactical decisions may involve determining the number of collection vehicles required, scheduling waste collection and sorting processes, and setting appropriate buffer stocks of secondary raw materials to balance supply and demand fluctuations. The timeframe for such decisions can vary, ranging from daily operational adjustments to monthly planning cycles, depending on market conditions and facility capacities.

1.4 Operational Decisions in Recycling

Operational decisions in recycling focus on short-term planning and involve the detailed execution of previously made tactical decisions. These decisions ensure the smooth daily functioning of recycling operations by specifying the exact timing, sequencing, and execution of tasks. For example, in a recycling facility, operational planning includes scheduling the collection and sorting of waste, allocating workers to specific tasks, and optimizing machine usage to maximize efficiency.

Key aspects of operational decision-making in recycling include determining vehicle routes for waste collection, scheduling pickup times, and managing real-time adjustments in response to unforeseen circumstances such as equipment breakdowns or changes in waste volume. The distinction between tactical and operational decisions lies in the level of detail—if the exact timing and arrangement of activities are defined, the decision is considered operational. While most research in this field focuses on strategic and tactical decision-making, some studies have explored operational aspects, such as optimizing truck routes or developing precise sorting schedules. Ultimately, the goal is to provide decision-makers with effective tools to enhance the efficiency and performance of recycling systems. The decision-making levels in recycling systems shows in figure 1.4.1.

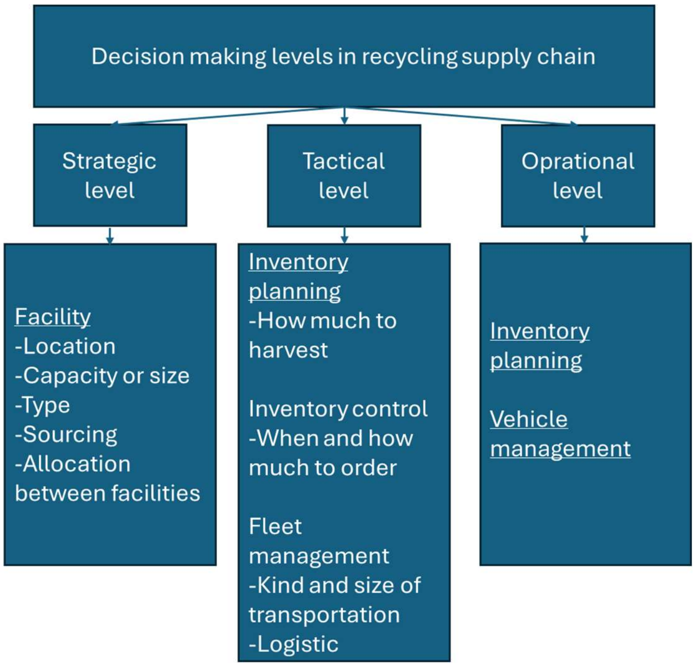

Figure 1.4.1. Decision-making levels in recycling systems

1.5 The impact of recycling on the economy and the community

According to the Ellen MacArthur Foundation report, the implementation of a circular economy (CE) could result in material savings of up to $630 billion annually by 2025. Transitioning to a CE could contribute to a reduction of global greenhouse gas emissions by 9.3 billion tons annually by 2050, which is equivalent to about a quarter of global annual emissions (*Towards the Circular Economy Vol. 1*, 2013).

Recycling significantly influences the economy through job creation, increased competitiveness, cost savings, and overall improvements in societal well-being. It generates employment across various sectors, including waste collection, material processing, and manufacturing of new products from recycled materials, with industries such as wind energy and automotive manufacturing directly benefiting from secondary raw materials. This process not only reduces dependence on imported resources but also lowers production costs, enhancing the economy's resilience. Furthermore, innovation in recycling technologies fosters the development of new industrial sectors, driving long-term growth and sustainability (Repp i in., 2021).

Despite the costs of establishing waste collection systems and processing facilities, recycling brings financial benefits by reducing landfill usage and lowering expenses tied to raw material extraction. Beyond economics, recycling boosts environmental awareness through education and public campaigns, encouraging more sustainable consumption habits. Health benefits also arise from decreased pollution, leading to better air, water, and soil quality, and lowering pollution-related disease rates. In terms of quality of life, recycling supports cleaner surroundings, reduces illegal dumping, and promotes the circular economy by increasing access to valuable secondary materials.

However, challenges persist, such as high infrastructure costs, uneven access to recycling facilities, and low public motivation due to insufficient information systems. Addressing these barriers is essential to maximizing the socio-economic potential of recycling and building a more sustainable, circular economy (*(PDF) The Economics of Recycling*, b.d.). Table 1.5.1 shows the possible impact of recycling on the economy and the community.

Table 1.5.1. Possible impact of recycling on the economy and the community

Category	**Impact/Description**
Job creation	Recycling generates employment in sectors such as collection, processing, and the production of new products from secondary raw materials.
Increase in economic competitiveness	The use of secondary raw materials reduces production costs and makes the economy less dependent on the import of primary raw materials.
	Innovations in recycling technology drive the development of new industrial sectors.
Costs and savings related to recycling	Costs of selective waste collection systems and processing technologies.
	Savings resulting from a reduced need for waste landfilling and lower costs of extracting natural resources.
Social environmental awareness	Environmental education and changing consumption habits.
	Social campaigns and local government initiatives promoting waste segregation.
Health benefits	Reduced environmental pollution improves air, water, and soil quality.
	Lower emissions of harmful substances decrease the incidence of pollution-related diseases.
Impact on quality of life	Recycling promotes a cleaner environment and reduces the number of illegal dumpsites.
	Increased availability of secondary raw materials supports the development of a circular economy.
Environmental awareness	Increasing environmental awareness influences the formation of more sustainable consumption habits, promotes waste segregation, and encourages responsible resource management. Environmental education and social campaigns inspire people to take everyday actions for environmental protection, such as reducing plastic use, reusing products, or choosing local and eco-friendly goods. Greater awareness makes society more likely to demand systemic change, support pro-environmental initiatives, and pressure companies and institutions to adopt more sustainable strategies. In the long run, this leads to improved quality of life, reduced pollution, and healthier ecosystems, benefiting both people and the planet.

2 Carbon fiber market

The carbon fiber market has been growing dynamically in recent years, driven mainly by demand in the aerospace, automotive, and wind energy sectors. In 2019, the market was valued at $4.7 billion, with forecasts suggesting it could grow to $13.3 billion by 2029, representing a compound annual growth rate (CAGR) of 11% (*Carbon Fiber Market Size, Share And Growth Report, 2030*, b.d.).

Figure 2.1 shows the size of the global carbon fiber market from 2020 to 2030, broken down by raw material: PAN (polyacrylonitrile) and pitch, with values in USD billion. The data indicates steady market growth, with the total size increasing from $3.7 billion in 2020 to $10.5 billion in 2030. PAN remains the dominant raw material, consistently accounting for the majority of the market share, while pitch contributes a smaller but gradually growing portion. The market experiences consistent year-over-year growth, with a notable compound annual growth rate (CAGR) of 10.9% from 2025 to 2030. This expansion reflects rising demand for carbon fiber across industries such as aerospace, automotive, wind energy, and sporting goods.

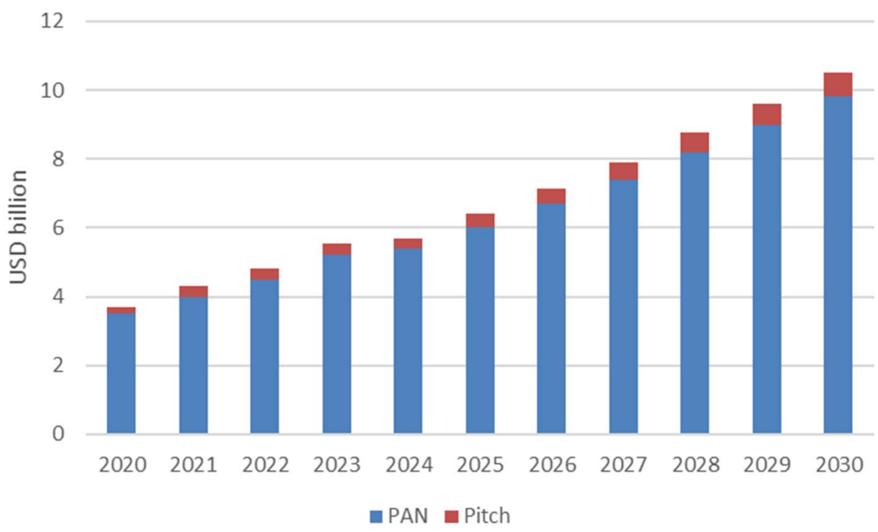

Figure 2.1 Carbon Fibre Market.

According to a 2023 MarketsandMarkets report, the global carbon fiber market is expected to reach approximately $8.5 billion by 2025. Earlier estimates from 2019 suggested the market could hit $8 billion by 2026, with a CAGR of 10.8%.

Geographically, the market spans key regions, including Europe, Asia-Pacific, North America, the Middle East and Africa, and Latin America. While the demand is rising, the market faces challenges, including the high cost of carbon fiber and the lack of standardized manufacturing technologies, which may slow down wider adoption.

The competitive landscape highlights Toray Industries Inc. as a leading player, with various other companies positioned across different levels of market share and product footprint. The ecosystem involves raw material providers like Minglang and Lanhai, carbon fiber manufacturers such as Toray and SGL Carbon, and end users including major global brands like Teijin, Mercedes, and Audi.

Overall, the data suggests that while the carbon fiber market holds immense growth potential, its expansion depends on addressing cost barriers and streamlining production processes to meet rising global demand (*Carbon Fiber Market Size & Forecast [Latest]*, b.d.).

The key drivers of this growth are the push to reduce vehicle and structure weight to improve energy efficiency and lower emissions. Carbon fibers, thanks to their lightweight and high-strength properties, are widely used in aerospace, automotive manufacturing, wind energy, and sports and recreational equipment production.

3 Carbon fibre production and recycling

The importance of carbon fiber recycling is also growing. By 2026, the global carbon fiber recycling market is expected to reach $203.8 million, with an annual growth rate of 11.3%. This reflects the increasing demand for sustainable and eco-friendly materials across various industries (Inc, b.d.).

The carbon fiber market is characterized by rapid growth, fueled by technological innovation and rising demand for lightweight, durable materials in key sectors of the economy. To estimate the global amount of carbon fiber-reinforced polymer (CFRP) waste since 2000, it can be considered that the growth of the CFRP market and the approximate percentage of waste generated. Table 3.1 shows estimated approach for CFRP Production Growth Rate, CFRP Waste as a Percentage of Production and Estimated Annual CFRP Waste.

Table 3.1. Estimated approach for CFRP Production Growth Rate, CFRP Waste as a Percentage of Production and Estimated Annual CFRP Waste.

<table>
<tr><th>CFRP Production Growth Rate</th><th>CFRP Waste as a Percentage of Production:</th><th>Estimated Annual CFRP Waste</th></tr>
<tr><td>In 2000, global CFRP production was approximately 10,000 tons per year.</td><td rowspan="4">Approximately 30% of CFRP production results in waste, including manufacturing scraps, post-production waste, and end-of-life components.</td><td>2000: ~3,000 Mg
2005: ~10,000 Mg
2010: ~12,000–15,000 Mg
2015: ~30,000–40,000 Mg
2020: ~42,000 Mg
2025 (forecast): 60,000+ Mg</td></tr>
<tr><td>By 2010, it had increased to around 40,000 tons per year.</td><td rowspan="3">Total Accumulated CFRP Waste (2000–2025):

Over 500,000 tons of CFRP waste may have accumulated globally between 2000 and 2025.</td></tr>
<tr><td>In 2020, production reached approximately 140,000 tons per year.</td></tr>
<tr><td>Forecasts suggest that by 2025, it will exceed 200,000 tons per year.</td></tr>
</table>

Carbon fiber waste from equipment, machinery, and post-use materials is more difficult to estimate than production waste because it depends on the lifespan of the products and their recycling. Table 3.2 shows estimated approach include CFRP product life, Growth in CFRP production and waste deposition and post-use waste (Aldosari i in., 2024; Ateeq, 2023; *Carbon Fiber Demand Worldwide by Market 2025*, b.d.; *Global Carbon Fiber Production Capacity by Country Distribution 2018*, b.d.; „Life Cycle Assessment of Carbon Fiber-Reinforced Polymer Composites | Request PDF", 2025; *Stratview Research Releases Carbon Fiber Recycling Outlook Report*, 2025; *Vartega Secures $10 Million to Promote Recycled Carbon Fiber*, 2025; Naqvi i in., 2018; Pakdel i in., 2021; Vogiantzi & Tserpes, 2025; Wang i in., 2023; Wu i in., 2023).

Table 3.2. Estimated approach include CFRP product life, Growth in CFRP production and waste deposition and post-use waste.

CFRP product life	Growth in CFRP production and waste deposition	Estimated post-use waste
Automotive: 10–20 years	CFRP production has been growing exponentially since the 2000s.	Assuming that 80–90% of materials produced 20 years ago are now landfilled, post-use waste can be estimated at 40–50% of total production 20 years ago.
Aviation: 20–30 years	Operational waste begins to accumulate after 10–30 years of use.	For the years 2000–2025, post-mining waste starts to increase from around 2015 and may now exceed 30,000 tonnes per year, with an upward trend.
Wind energy: 20–25 years		
Sports and recreation: 5–10 years		

Table 3.3 shows the estimated global amount of carbon fiber waste generated annually from 2010 to 2025. The data are approximate and based on production trends, production waste (20–40% of material), and increasing post-use waste resulting from product life cycles. Due to the lack of precise statistics, the values are interpolated based on available data and forecasts, which shows in figure 3.1.

Table 3.3. CFRP production, waste in CFRP production and CFRP post-consumer waste.

Year	CFRP production, Mg	Waste in production – CFRP, Mg	Post-consumer waste – CFRP, Mg	Waste CFRP, Mg
2010	40000	8000 – 16000	2000 – 5000	10000 – 21000
2011	45000	9000 – 18000	2500 – 6000	11500 – 24000
2012	50000	10000 – 20000	3000 – 7000	13000 – 27000
2013	55000	11000 – 22000	3500 – 8000	14500 – 30000
2014	60000	12000 – 24000	4000 – 9000	16000 – 33000
2015	70000	14000 – 28000	5000 – 10000	19000 – 38000
2016	80000	16000 – 32000	6000 – 12000	22000 – 44000
2017	90000	18000 – 36000	7000 – 14000	25000 – 50000
2018	100000	20000 – 40000	8000 – 16000	28000 – 56000
2019	110000	22000 – 44000	9000 – 18000	31000 – 62000
2020	120000	24000 – 48000	10000 – 20000	34000 – 68000
2021	125000	25000 – 50000	12000 – 22000	37000 – 72000
2022	130000	26000 – 52000	13000 – 24000	39000 – 76000
2023	140000	28000 – 56000	15000 – 25000	43000 – 81000
2024	145000	29000 – 58000	17000 – 27000	46000 – 85000
2025	150000	30000 – 60000	20000 – 30000	50000 – 90000

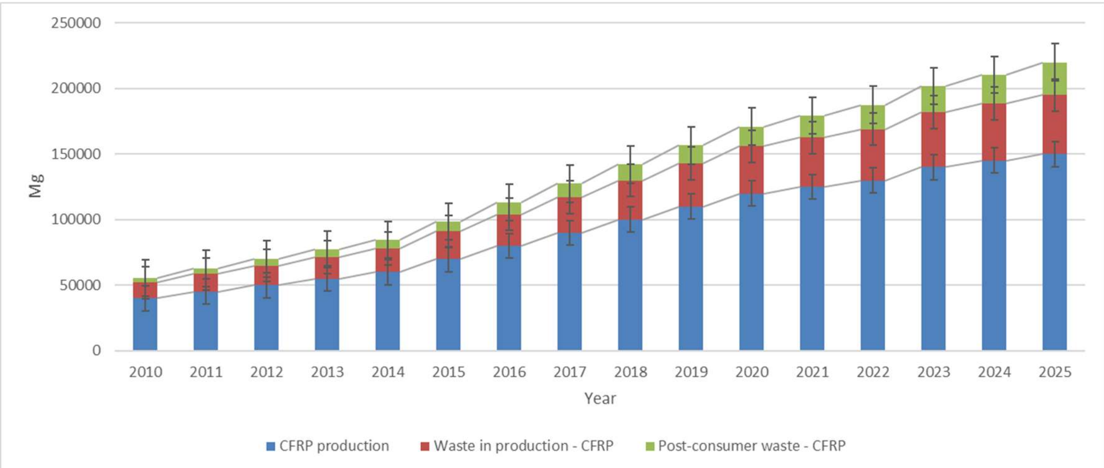

Figure 3.1. Estimated values of CFRP production and waste generated from manufacturing and post-consumer waste.

Total CFRP waste from 2000 to 2025: ~654,000 Mg, this means that since the early 2000s, the industry has generated over half a million tons of carbon fiber waste, most of which still ends up in landfills.

4 Employment in carbon fiber market

The number of people involved in producing 1 Mg of carbon fiber can vary depending on production technology, scale, and the degree of plant automation. However, in carbon fiber manufacturing facilities with a medium level of technological advancement, it is possible to provide general estimates based on industry data. Carbon fiber manufacturing is a multi-stage process that includes:

Precursor production: Typically, polyacrylonitrile (PAN) or pitch fibers serve as the primary raw material for carbon fiber production (Nguyen i in., 2024)

Carbonization: The precursor is subjected to high temperatures in an oxygen-free environment, converting it into carbon fiber („Preparation and Characterization of Carbon Fibers from Polyacrylonitrile Precursors | Request PDF", 2024)

Modification and stabilization: Further stages include stabilizing the carbon structure, modifying fibers (e.g., impregnating, cutting), and final packaging (*• Modification and stabilization: Further stages include stabilizing the carbon structure, modifying fibers (e.g., impregnating, cutting), and final packaging (Source: Journal of Materials Science, 2021). - Szukaj w Google*, b.d.)

Carbon fiber production is a highly technological and automated process, especially in modern plants, which reduces the number of workers needed per ton of production:

Small factory with low automation: Requires around 10–30 people per ton, depending on technology and process sophistication (*(PDF) Emerging Technologies in Digital Manufacturing and Smart Factories*, b.d.) (Gellrich i in., 2024)

Medium-sized factory with moderate automation: Typically needs 5–10 people per ton, as stages like carbonization and quality control are often partially automated (Gellrich i in., 2024; *Emerging Technologies in Digital Manufacturing and Smart Factories*, b.d.) (UNCTAD, 2023)

Large factory with high automation: In highly automated, state-of-the-art plants, the workforce needed per ton can drop to 2–5 people. In such facilities, many processes are monitored and controlled digitally, minimizing the need for human intervention(Gellrich i in., 2024; *Emerging Technologies in Digital Manufacturing and Smart Factories*, b.d.) (UNCTAD, 2023) (Production Plant and Warehouse Automation with IoT and Industry 5.0", 2025)

Depending on technology, plant size, and automation level, the number of workers per ton of carbon fiber production can range from 2 to 30 people. In modern, highly automated plants, this number is significantly lower, as advanced systems reduce the reliance on manual labor. These insights demonstrate how technology and process optimization drive efficiency in carbon fiber manufacturing, making it a scalable industry despite its complexity.

The interpolated data shows the projected growth of carbon fiber reinforced polymer (CFRP) production and associated waste from 2010 to 2040. According to the historical trend, CFRP production has been steadily increasing, starting at 40,000 tons in 2010 and reaching 150,000 tons in 2025. The corresponding waste also grows in parallel, starting at 15,500 tons in 2010 and reaching 70,000 tons by 2025.

If we assume a linear growth pattern based on the historical data, production is expected to rise to 225,000 tons by 2040, with CFRP waste reaching 137,500 tons. This trend reflects the increasing adoption of CFRP across industries like aerospace, automotive, and renewable energy, driven by the material's lightweight and high-strength properties. However, the significant rise in waste highlights the growing challenge of managing end-of-life CFRP materials, emphasizing the need for effective recycling and circular economy strategies.

Overall, while the production growth points to a booming market, waste management will become a critical issue in the coming decades, pushing industries toward more sustainable practices.

Figure 4.1 illustrates the actual and projected CFRP production and waste generation from 2010 to 2040. It is assumed that 5 employees are required for either the production or recycling of carbon fiber. With the implementation of recycling technologies and full utilization of production waste, new job opportunities will be created. By 2040, the number of employees in the sector could reach approximately 687.5 thousand, highlighting the significant socio-economic impact of transitioning to a circular economy model for carbon fiber production.

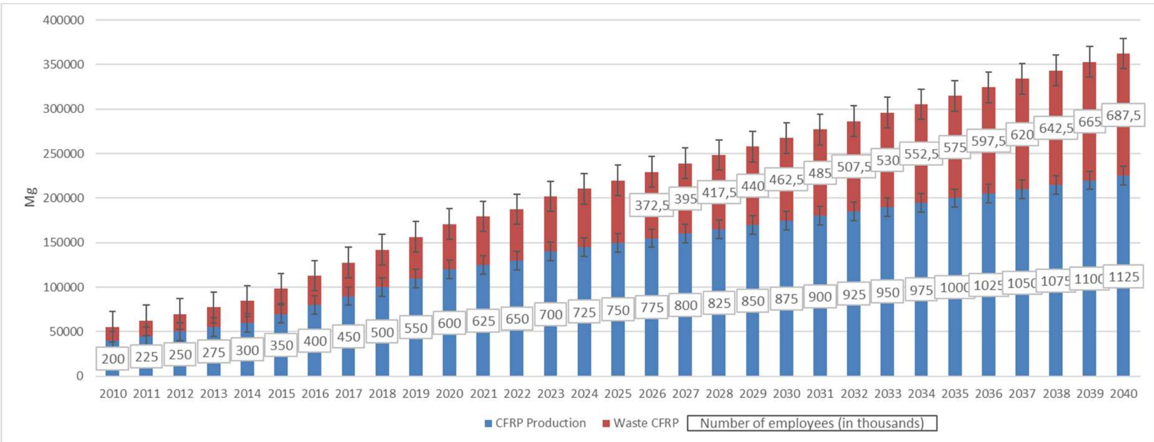

Figure 4.1. Actual and projected CFRP production, CFRP waste, and the number of employees needed in the years 2010–2040 globally.

4.1 Wind turbine as CF market: production, waste and recycling methods

Wind energy stands out as a mature and promising solution for electricity generation, offering cleanliness, safety, and renewability. According to the Global Wind Energy Council (GWEC) report, global wind power capacity reached 906 GW by the end of 2022 (Alex, 2023). However, wind turbines generally have a limited operational lifespan of 20 to 25 years („A Review on Recycling and Reuse Methods for Carbon Fiber/Glass Fiber Composites Waste from Wind Turbine Blades", 2021). The rapid growth of wind energy has led to a surge in end-of-life wind turbine blades, with the first wave of retirements becoming evident in recent years. Additionally, the replacement of advanced components and damage during operation further reduce the service life of wind turbine blades.

On average, a single decommissioned 1 MW wind turbine generates more than 10 tons of blade waste (Chen i in., 2019) (*Recycled wind turbine blades as a feedstock for second generation composites - ScienceDirect*, b.d.). It is estimated that by 2050, the global cumulative volume of waste blades will reach 43 million tons, (with 40% originating from China, 25% from Europe, 16% from USA and 19% from the rest of the world) as shown in Figure 4.1.1 (*Wind turbine blade waste in 2050 - ScienceDirect*, b.d.). Therefore, the proper disposal of end-of-life wind turbine blades has become a significant challenge for the sustainable development of wind power.

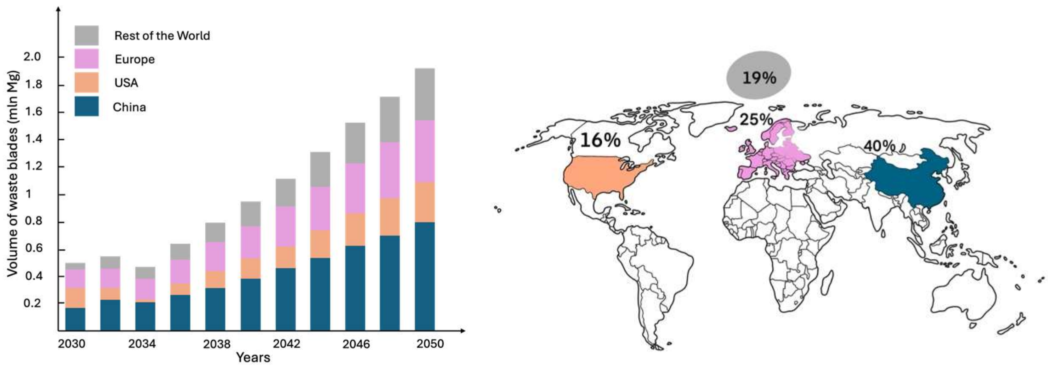

Figure 4.1.1. Prediction of waste wind turbine blades worldwide till 2050 („Recovering Glass Fibers from Waste Wind Turbine Blades", 2024; *Wind turbine blade waste in 2050 - ScienceDirect*, b.d.).

The waste management hierarchy includes options ranked from least to most preferred: disposal → energy recovery → recycling → repurposing for other uses, reuse → reducing waste generation and prevention (Karavida & Nõmmik, b.d.; *Sustainable End-of-Life Management of Wind Turbine Blades: Overview of Current and Coming Solutions*, b.d.; *Wind turbine blade waste in 2050 - ScienceDirect*, b.d.). Figure 7 presents a diagram of the available methods for recycling wind turbine blades („Recycling of Wind Turbine Blades", 2023; Wajda i in., 2022).

Most of a wind turbine is made from steel, copper, and concrete, which are not primary issues for recycling. A wind turbine consists of a foundation embedded in the ground, a tower or mast, a nacelle, and a hub containing mechanisms, including the generator, gearbox, and brake, as well as the most challenging part to recycle—the rotor blades.

Wind turbine blades are built from multi-layer laminates made of glass or carbon fibers and a thermosetting polymer matrix. Adhesives or foams, used to partially fill certain parts, may also be involved in their assembly.

Resin is a thermosetting material that undergoes a permanent chemical transformation, unlike thermoplastics, which presents a major challenge for recycling. Parts of boats, cars, and airplanes are made from these highly durable composite materials. Wind turbines account for only 5-10% of global composite material consumption. Therefore, research into the recycling of materials containing carbon fiber will also contribute to the development of recycling in other industries (Kozłowski i in., 2020). Figure 4.1.2. shows possibilities recycling methods: Reuse, repurpose, decomposition, energy recovery

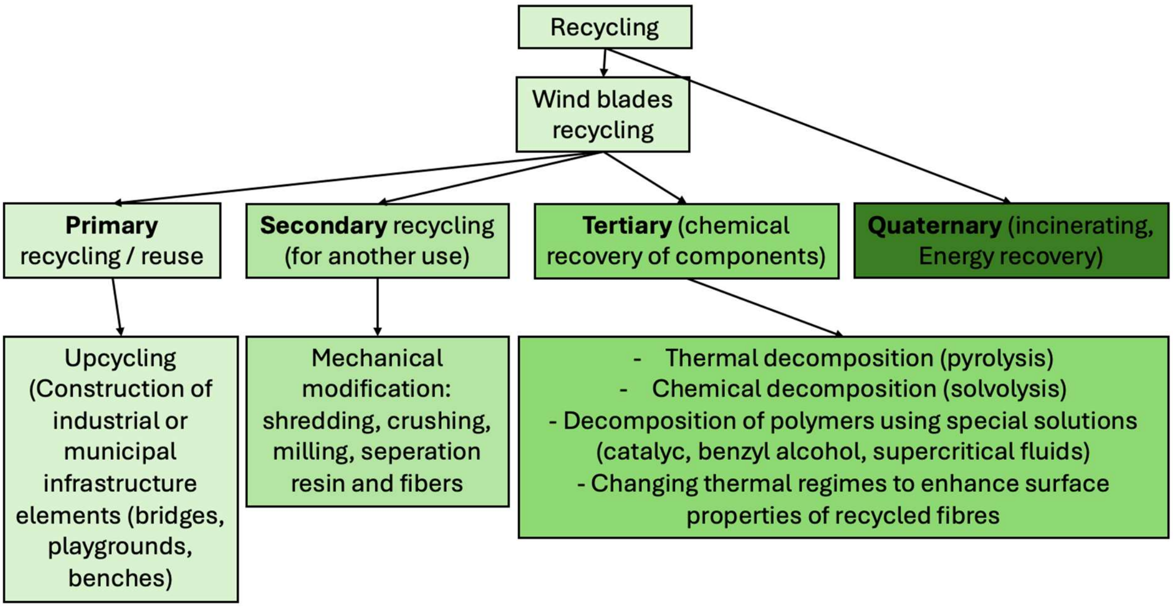

Figure 4.1.2. Possibilities recycling methods: Reuse, repurpose, decomposition, energy recovery.

An example of primary recycling is upcycling (Figure 4.1.3). Reusing blades can contribute to the construction of bridges, playgrounds, benches, bike shelters, and other infrastructure elements. However, this approach will not process all waste.

Figure 4.1.3. Wind blades upcycling.

Another example is mechanical treatment. The fibers can be shredded and used as fillers, for instance, in concrete mixtures. One ton of turbine waste can reduce CO_2 emissions by 110 kilograms and save 461 kilograms of raw materials compared to standard cement production. However, this approach wastes the structural properties of the material. Cut materials can also serve as fillers for vehicles or bicycles (reducing weight and lowering CO2 emissions) (Farina & Anctil, 2022).

Another example is pyrolysis. This process involves heating the material to a temperature of 400-700 degrees Celsius in a low-oxygen environment. This breaks down the resin into simpler substances, allowing the fibers to be recovered and reused. Research shows that after heating, the strength of the fibers can decrease by as much as 50%. Additionally, the pyrolysis process is energy-intensive and does not allow for resin recovery (Xu i in., 2023).

However, pyrolysis is being developed further. A Dutch team has developed a technology for extracting fibers from blades by briefly introducing oxygen into the process. Before oxygen is introduced, the resin and fibers are separated through oxygen-free pyrolysis. These recovered fibers can be used in automotive parts.

Fibers recovered using the two-stage technology demonstrated 19% better tensile strength and 43% better fracture toughness compared to fibers recovered through single-step high-temperature pyrolysis (Ginder & Ozcan, 2019).

Another method is microwave processing. In this process, glass fibers can lose about 25% of their strength. An ideal recycling process should enable the recovery of both fibers and resin to produce new products. At the same time, the strength of the fibers should be comparable to that of virgin fibers. A review of the literature suggests that the solvolysis process may hold potential for recycling wind blades.

In the solvolysis process, the polymer matrix of the composite is swelled using volatile, high-boiling, low-molecular-weight solvents or solvent mixtures. Depending on the type of resin used in the composite, a catalyst may also be required. This catalyst, aided by the loosened composite matrix, can more effectively penetrate deep into the material and facilitate its degradation, as shown schematically in Figure 4.1.4. The process occurs at an elevated temperature, restricted by the solvent’s boiling point, within a nitrogen-rich atmosphere at atmospheric pressure („Solvolysis and Oxidative Liquefaction of the End-of-Life Composite Wastes as an Element of the Circular Economy Assumptions”, 2024).

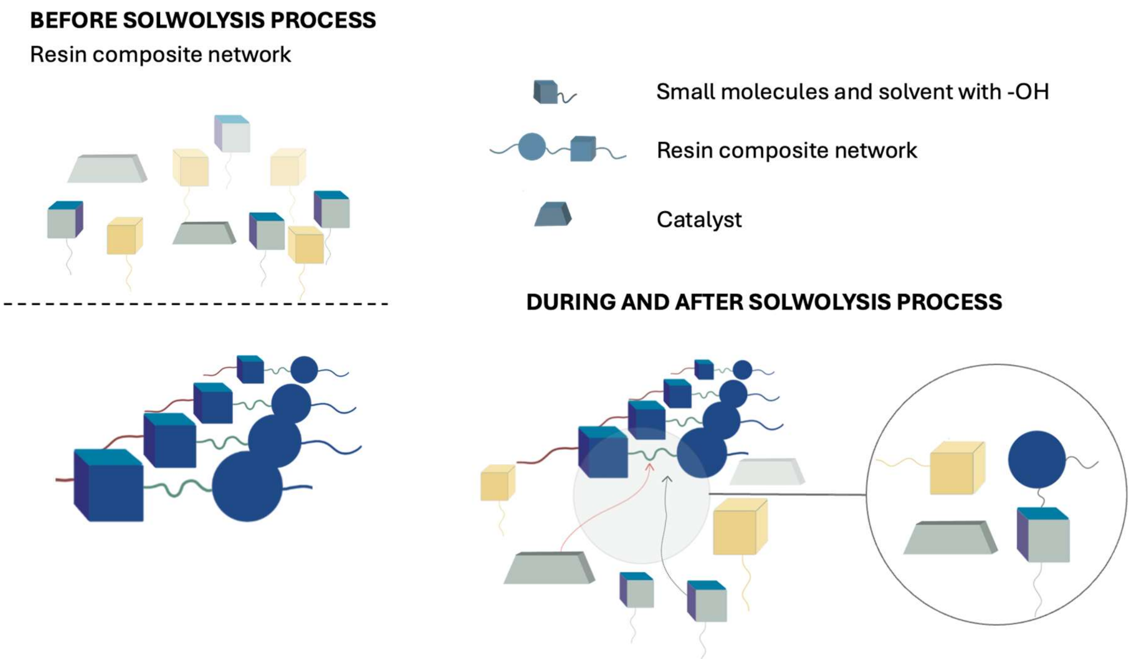

Figure 4.1.4. The solvolysis process entails a bond exchange reaction where hydroxy groups in the solvent interact with ester bonds within the resin-composite network.

Chemical recycling has the potential to provide cleaner fibers while preserving more strength due to the lower temperatures involved compared to pyrolysis. Various solutions can be employed to break down polymers, such as catalytic processes, nitric acid, ammonia, glycol, and ethanol. In solvolysis processes, the phenomenon of the critical temperature can be utilized. This is the temperature above which the difference in density between the gaseous and liquid states of a substance disappears, making it impossible to liquefy the gas despite increasing pressure.

Solvolysis processes can also be combined with other techniques, such as microwaves or pyrolysis. Microwave-assisted chemical recycling processes can be used to recover glass fibers from composite waste, with the recovered fibers retaining 93–99% of the strength of virgin fibers. The recovered glass fibers demonstrated 99% tensile strength, 93% Young's modulus, and 95% strain-to-failure compared to virgin fibers (Branfoot i in., 2023).

Different technologies consume varying amounts of materials, reagents, and energy needed for processing. This affects not only costs but also the environmental impact. The goal is to develop a method that is more efficient and effective across the entire lifecycle compared to primary production.

5 Labour Market and Skills Impact of Recovered Carbon Fibre Technologies

The development of recovered carbon fibre technologies represents a key component of the transition towards a circular economy and a more sustainable materials industry. With the increasing use of composite materials across sectors such as automotive, aerospace, wind energy, and construction, the volume of composite waste is growing significantly, creating both environmental challenges and new economic opportunities. rCF technologies respond to these challenges while simultaneously establishing a new segment of the labour market and generating demand for specialised skills and competencies.

The impact of recovered carbon fibre technologies on the labour market is multifaceted. On the one hand, it includes the creation of new jobs in areas such as composite waste collection and logistics, mechanical, chemical, and thermal recycling processes, quality control of secondary materials, and their reintegration into manufacturing value chains. On the other hand, these technologies are driving the transformation of existing occupational roles within the materials and manufacturing sectors, requiring workers to adapt their skill sets in response to new processes, standards, and business models.

A particularly important aspect is the growing demand for interdisciplinary skills that combine expertise in materials engineering, process technologies, automation, data analysis, and sustainability principles. The expansion of the rCF sector also increases the relevance of competencies related to life cycle assessment, material certification, regulatory compliance, and design for recycling. These skill requirements reflect the increasing complexity of circular material systems and the need for close integration between technological innovation and environmental performance.

Analysing the labour market and skills implications of recovered carbon fibre technologies is essential to ensuring the long-term competitiveness of the European materials and manufacturing industries. The effective alignment of education policies, vocational training programmes, and reskilling and upskilling initiatives can not only mitigate the risks associated with skills shortages but also enhance the socio-economic benefits of the transition towards sustainable materials. This chapter therefore focuses on identifying key employment trends, existing skills gaps, and potential pathways for skills development in the context of the growing importance of rCF technologies.

5.1 Mapping of technological activities and ESCO/ISCO classification

The labor market is undergoing profound transformation driven by technological advancements, green transition initiatives, and shifting global dynamics. These changes are reshaping job structures, leading to the decline of some roles while creating demand for new ones—particularly in digital, green, and service-oriented sectors. As a result, the competences required of the workforce are evolving rapidly, with a growing emphasis on digital literacy, adaptability, critical thinking, and continuous learning. This analysis is particularly relevant in the context of the carbon fibre recycling market, where labor dynamics and emerging skill requirements play a key role in evaluating the industry's development potential. It forms an integral part of the broader socio-economic analysis, providing essential insight into the human capital dimension of this evolving sector. Table 5.1 outlines technological processes divided into work packages (WP3, WP4, WP5) with a focus on: use cases/processes (*types of tasks such as design, installation, diagnostics, etc.*); technological actions (*specific activities, e.g. component repair*); potential jobs creation (*roles matched with ISCO/ESCO job classifications*); required skills (*technical and soft skills needed to perform the actions*)

Table 5.1. Potential job and required skills matrix for EuReComp.

WP number	Use Case / Process	Description of Technological Actions	Potential Jobs (ISCO/ESCO)	Required Skills
WP3	Extension of blade life cycle (repair with glass fibers)	Repair and reuse of composite elements (wind turbine blade)	Composite Repair Technician (ISCO 7233), Eco-design Designer (ISCO 2163), LCA/sLCA Specialist (ISCO 2149)	Laminates repair, design for recycling, handling manual and automatic tools, knowledge of composite materials, familiarity with ISO 14040/44 standards
WP4	T4.1.1 Sub- and supercritical water solvolysis (pilot scale)	Recycling of carbon fibers using water under sub- and supercritical conditions	Chemical Process Operator (ISCO 3133), Composite Recycling Engineer (ISCO 2145), Lab Technician (ISCO 3111)	Operation of high-pressure reactors, knowledge of solvolysis processes, chemical safety, quality analysis of recovered fibers, control of high-temperature processes
WP4	T4.1.2 Low-scale chemical-assisted solvolysis	Small-scale chemical recycling using chemical solvents	Lab Technician (ISCO 3111), Chemical Process Operator (ISCO 3133), Materials Specialist (ISCO 2145)	Work with solvents, process parameter control, waste analysis, basics of polymer chemistry, chemical safety practices
WP4	T4.1.3 Pilot-scale chemical-assisted solvolysis	Pilot-scale chemical recycling	Pilot Plant Chemical Operator (ISCO 3133), Process Engineer (ISCO 2146), Maintenance Technician (ISCO 3115)	Operation of semi-industrial facilities, chemical process control, carbon fiber quality assessment, emission and waste monitoring
WP4	T4.1.4 Plasma-enhanced solvolysis	Chemical recycling using plasma	Plasma Installation Operator (ISCO 3139), Materials Engineer (ISCO 2145), Recycling Specialist (ISCO 2149)	Operation of plasma systems, knowledge of high-temperature processes, workplace safety, post-process fiber analysis, plasma equipment calibration
WP5	Automotive Shaft Demonstrator	Production of automotive shaft from recovered fibers	Composite Forming Machine Operator (ISCO 7223), Composite Production Engineer (ISCO 2145), Quality Control Technician (ISCO 3119)	Composite part forming, quality control, production documentation, CAD/CAM for composites, mechanical testing of automotive parts
WP5	Formula Seat Demonstrator	Production of motorsport seat from recovered fibers	Lamination Technician (ISCO 7223), Composite Structures Assembler (ISCO 7214), Materials Engineer (ISCO 2145)	Manual and automatic lamination, resin handling, quality control, ergonomic component design, knowledge of motorsport safety standards
WP5	Steering Wheel Demonstrator	Production of steering wheel from recovered fibers	Composite Production Technician (ISCO 7223), CNC Machine Operator (ISCO 7223), Component Assembler (ISCO 7214)	CNC machining of composites, lamination of small parts, dimensional control, detail assembly, ergonomic finishing
WP5	Container Pontoon Demonstrator	Production of large-scale demonstrator (container pontoon)	Large Composite Structures Assembler (ISCO 7214), System Integration Engineer (ISCO 2145), Testing Technician (ISCO 3119)	Assembly of large panels, work with hybrid GF/PU panels, quality control, mechanical testing, documentation of assembly processes

Individuals from WP3 can work in wind turbine maintenance and repair, the composite manufacturing industry, materials laboratories, or design offices focused on eco-design and lifecycle assessment. The key skills are: laminate repair, design for recycling, operation of manual and automated tools, knowledge of composite materials, and familiarity with ISO 14040/44 standards.

WP4 include mainly advanced recycling of carbon fibers. This work package focuses on various solvolysis methods—sub- and supercritical water solvolysis, chemical-assisted solvolysis on both small and pilot scales, and plasma-enhanced solvolysis—to recycle carbon fibers from composite waste. Graduates or specialists involved in these processes can find employment as chemical process pperators, composite recycling engineers, laboratory technicians, process engineers, or maintenance technicians in chemical plants, research centers, or pilot-scale recycling facilities. They will possess skills in operating high-pressure and high-temperature reactors, handling chemical solvents, understanding polymer chemistry, managing process parameters, ensuring chemical and workplace safety, conducting fiber quality analysis, and calibrating plasma or semi-industrial equipment.

WP5 includes the production of several demonstrators using recycled composite fibers. For the automotive shaft demonstrator, possible roles include composite forming machine operator, composite production engineer, and quality control technician. The formula seat demonstrator enables employment as lamination technician, composite structures assembler, or materials engineer within motorsport industries. The steering wheel demonstrator provides opportunities for composite production technicians, cnc machine operators, and component assemblers, while the container pontoon demonstrator prepares professionals for roles such as large composite structures assembler, system integration engineer, and testing technician in the marine and heavy composite industries.

Participants developing competencies through these work packages can find employment primarily in renewable energy, chemical and materials industries, automotive and motorsport manufacturing, marine and aerospace engineering, and research and development institutions. Overall, these technological efforts contribute to the creation of green jobs that integrate technical expertise with sustainability principles, promoting innovation within the circular economy.

5.2 Full-Time Equivalent scenarios for carbon fibre recycling and demonstrators

As industries transition toward more sustainable and circular practices, the accurate assessment of workforce needs becomes a cornerstone of effective planning and socio-economic analysis. In the context of emerging sectors such as carbon fibre recycling, understanding the scale and nature of human resource requirements is vital for projecting economic impact, feasibility, and scalability. One of the most widely adopted methods for quantifying labor inputs in a standardized way is the Full-Time Equivalent (FTE) metric. FTE enables analysts and project planners to translate diverse working arrangements—whether full-time, part-time, or contractual—into a common unit that reflects total labor effort. This chapter introduces the concept of FTE, its calculation methodology, and its practical significance in project evaluation, budgeting, and workforce planning. It forms a foundational element of the broader socio-economic assessment of carbon fibre recycling value chains, particularly in comparing pilot- and industrial-scale scenarios across work packages WP3 to WP5. The following section outlines how FTE is computed and applied in this analysis.

FTE is a standard unit that measures the workload of an employed person in a way that makes workloads comparable across various contexts. It allows organizations to represent part-time and full-time employees in a unified manner. 1.0 FTE typically refers to one full-time worker**,** while a 0.5 FTE would mean a person working half the hours of a full-time schedule.

FTE is calculated by dividing the actual number of hours worked by the number of hours considered full-time (usually 40 hours per week in many countries) as is shown (1) and (2) (Suryadi i in., 2025):

FTE per Year = Total Hours Worked during a Year/ Total Working Hours per Year (1)

FTE per Month = Total Hours Worked during a Month/ Total Working Hours per Month (2)

FTE provides a consistent basis for evaluating staffing levels, regardless of how many hours employees actually work. This is especially helpful in organizations that have a mix of part-time, full-time, or contracted staff. Since FTEs can be used to estimate salary costs, benefit allocations, and operational expenses, they are essential in HR budgeting, project costing, and grant applications. In project planning, FTE is critical to determine the total human resource effort allocated to specific for examole work packages, track progress and costs across teams and justify the level of effort and roles. Organizations often use FTEs for productivity analysis, comparing how many FTEs are required to achieve specific outputs or KPIs. It also facilitates cross-company or international benchmarking. Table 5.2 shows the FTE scenarios for WP3-WP5 basis on the same assumptios (as actual and projected CFRP production, CFRP waste, and the number of employees needed in the years 2010–2040 globally). The table 5.2.1 compares pilot-scale vs industrial-scale implementation across several use cases from WP3 to WP5. The pilot scale is estimated based on discussions with partners and scaled from the laboratory scale.

Table 5.2.1. FTE scenarios for carbon fibre recycling and demonstrators.

WP number	Use Case / Process	Change (Pilot/ Industry)	Automation Level	Pilot – FTE	Industry – FTE	Example Pilot Team
WP3	Extension of blade life cycle (repair with glass fibers)	1 / 1 (1 shift per day (8 hours), low automation	Manual / Semi-automatic	5	15	2 chemical process operators 1 lab technician 1 process engineer

		(mostly manual)				
WP4	T4.1.1 Sub- and supercritical water solvolysis (pilot scale)	2 / 3	Semi-automatic	4	12	2 chemical process operators 1 lab technician 1 process engineer
WP4	T4.1.2 Low-scale chemical-assisted solvolysis	1 / 1	Manual / Laboratory	3	10	2 lab technicians 1 chemical process operator
WP4	T4.1.3 Pilot-scale chemical-assisted solvolysis	2 / 3	Semi-automatic	5	15	2 operators 1 process engineer 1 maintenance technician
WP4	T4.1.4 Plasma-enhanced solvolysis	2 / 3	Semi-automatic	4	12	2 plasma system operators 1 materials engineer 1 recycling specialist
WP5	Automotive Shaft Demonstrator	1 / 3	Semi-automatic	6	20	2 forming machine operators 2 quality technicians 2 composite assemblers
WP5	Formula Seat Demonstrator	1 / 2	Manual	6	20	2 lamination technicians 2 structure assemblers 1 materials engineer
WP5	Steering Wheel Demonstrator	1 / 3	Manual	5	18	2 composite technicians 2 CNC operators 1 detail assembler
WP5	Container Pontoon Demonstrator	2 / 3	Manual	8	25	4 large structure assemblers 2 system integration

						engineers 2 testing technicians
Description: *• Shifts (Pilot/Industrial) – How many shifts per day for pilot and full-scale operations.* *• Automation – Level of mechanization (manual/semi-automatic).* *• Pilot – FTE – How many full-time employees are required for small-scale operations.* *• Industrial – FTE – How many full-time employees are required for industrial-scale operations*						

FTE serves as a standardized measure to compare labor inputs across pilot and industrial scales, accounting for variations in part-time, full-time, and contractual employment. The methodology enables precise estimation of human resource needs for project execution, budgeting, and socio-economic evaluation of recycling processes. Table 2 illustrates how FTE values increase when transitioning from pilot to industrial operations, reflecting both the scale-up of production and higher process complexity.

Most processes described in the table—especially in WP4 and WP5—are semi-automatic, with some still relying on manual or laboratory-scale operations. As automation progresses, the number of required workers per process decreases proportionally, while overall production capacity and process efficiency improve. Automated systems allow for greater control, consistency, and quality in composite recycling and part manufacturing, particularly under conditions involving high temperatures and pressures.

From an environmental perspective, automation supports sustainability by optimizing resource use, reducing waste, and minimizing exposure of workers to hazardous substances or high-risk environments. This leads to cleaner, safer, and more energy-efficient processes, contributing to the circular economy principles of carbon fibre reuse. On the human side, automation reshapes the workforce structure: while it may reduce the demand for manual labor, it simultaneously increases the need for highly skilled technicians, engineers, and operators capable of maintaining, monitoring, and improving automated systems. Therefore, the shift toward semi-automatic and automated recycling lines enhances both environmental performance and occupational safety, while driving the upskilling of the labor force involved in advanced materials recovery and sustainable manufacturing.

6 Monetized Environmental Benefits of Circular Carbon Fibre Solutions

Quantifying environmental benefits in monetary terms is a critical component of a comprehensive socio-economic assessment of circular economy solutions, including carbon fibre recycling technologies. While the environmental advantages of recycled carbon fibre (rCF)—such as reduced greenhouse gas emissions, lower energy consumption, and decreased demand for virgin raw materials—are well established, their translation into economic values enables direct comparison with investment and operational costs. Monetisation also enhances the transparency of sustainability gains and supports evidence-based decision-making for policymakers, investors, and industrial stakeholders.

This section presents a methodological framework for monetising the key environmental benefits of circular carbon fibre solutions, with a particular focus on avoided CO_2 emissions and reduced consumption of virgin carbon fibre. The approach is based on standardized and widely accepted unit values derived from the EU Emissions Trading System (EU ETS) and prevailing market prices for carbon fibre materials. These monetised indicators form the basis for evaluating the environmental and economic value proposition of recycling technologies at pilot and industrial scales.

6.1 Key Assumptions and Reference Values

6.1.1 Carbon pricing (CO_2)

The EU Emissions Trading System (EU ETS) provides a market-based reference for the economic value of avoided CO_2 emissions. During the 2023–2025 period, EU ETS prices ranged approximately between €60 and €100 per tonne of CO_2, with an average price of around €85/t CO_2 in 2023 („Price of CO2 Emission Allowances EU ETS", b.d.)

For comparison, estimates of the Social Cost of Carbon (SCC) used in external cost assessments range from approximately €50 to €150 per tonne of CO_2, depending on model assumptions and discount rates (*Actual Social Cost of CO2 Emissions More Than Twice as High*, b.d.).

To ensure conservative and policy-aligned results, the calculations in this analysis apply a reference carbon price of €80–€100 per tonne of CO_2**,** closely aligned with recent EU ETS market values.

6.1.2 Material substitution (carbon fibre)

Virgin carbon fibre (vCF) prices typically range from €20 to €60 per kg, depending on fibre type (e.g. PAN-based or pitch-based), quality, production scale, and end-use sector. For industrial-scale applications, an average reference price of €30–€35 per kg is assumed. Recycled carbon fibre (rCF) prices are significantly lower, typically in the range of €5–€15 per kg (ltd, 2025).

6.1.3 Monetised Value of Avoided CO_2 Emissions

The economic value of emission reductions achieved through carbon fibre recycling is calculated as:

$$\text{Monetised CO}_2\text{ Benefit (€)} = \Delta\text{CO}_2\ (\text{t}) \times P_{\text{CO}_2}\ (€/t)$$

Where:

ΔCO_2= total avoided CO_2 emissions attributable to recycling (in tonnes), derived from life cycle assessment (LCA) results

P_{CO_2}= reference carbon price (€/t CO_2), based on EU ETS values (€80–€100/t)

This equation allows direct conversion of quantified emission savings into an economic indicator comparable with capital and operating expenditures.

6.1.4 Monetised Value of Avoided Virgin Carbon Fibre Production

The economic benefit associated with reduced demand for virgin carbon fibre is calculated as:

$$\text{Material Substitution Benefit (€)} = M_{\text{rCF}}\ (\text{kg}) \times P_{\text{vCF}}\ (€/kg)$$

Where:

M_{rCF}= mass of recycled carbon fibre effectively substituting virgin fibre (kg)

P_{vCF}= average market price of virgin carbon fibre (€/kg), assumed at €30–€35/kg

This indicator reflects the avoided resource extraction, energy use, and upstream emissions embedded in virgin carbon fibre production.

6.1.5 Aggregated Monetised Environmental Benefit

The total monetised environmental benefit of circular carbon fibre solutions is calculated as the sum of the two components:

$$\text{Total Environmental Benefit (€)} = \text{Monetised CO}_2\text{ Benefit} + \text{Material Substitution Benefit}$$

This aggregated value provides a transparent and policy-relevant metric for assessing the contribution of carbon fibre recycling technologies to climate mitigation and resource efficiency objectives. When compared against investment and operational costs, it enables an integrated assessment of the economic viability and societal value of circular carbon fibre demonstrators and full-scale industrial applications.

6.1.6 Monetised CO_2 Emission Reduction from Carbon Fibre Recycling – SUT example

This (SUT) illustrative example quantifies and monetises the climate benefit of recycling 1 kg of carbon fibre**,** based on life cycle assessment (LCA) results comparing virgin carbon fibre production with carbon fibre recycling.

6.1.6.1 System boundaries and emission factors

The following emission intensities are assumed:

- Virgin carbon fibre production:

$$E_{\mathrm{vCF}} = 76.3 \ \text{kg CO}_2\text{/kg CF}$$

- Carbon fibre recycling (rCF):

$$E_{\mathrm{rCF}} = 6.32 \ \text{kg CO}_2\text{/kg CF}$$

These values reflect cradle-to-gate greenhouse gas emissions associated with the respective production routes.

6.1.6.2 Avoided CO_2 emissions

The avoided emissions resulting from substituting virgin carbon fibre with recycled carbon fibre are calculated as:

$$\Delta\text{CO}_2 = E_{\mathrm{vCF}} - E_{\mathrm{rCF}}$$
$$\Delta\text{CO}_2 = 76.3 - 6.32 = 69.99 \ \text{kg CO}_2 \text{ per kg CF}$$

This means that recycling 1 kg of carbon fibre avoids 69.99 kg of CO_2 emissions compared to producing the same amount of virgin fibre.

Since carbon prices are expressed per tonne of CO_2, the avoided emissions are converted accordingly:

$$69.99 \ \text{kg CO}_2 = 0.06999 \ \text{t CO}_2$$

6.1.6.3 Monetisation using EU ETS reference values

In line with EU ETS market prices, a conservative reference range of **€80–€100** per tonne of CO_2 is applied (ltd, 2025).

The monetised climate benefit is calculated as:

$$\text{Monetised CO}_2 \text{ Benefit (€)} = \Delta\text{CO}_2 \text{ (t)} \times P_{\text{CO}_2}$$

Lower-bound estimate (€80/t CO_2):

$$0.06999 \times 80 = 5.60 \ \text{€}$$

Upper-bound estimate (€100/t CO_2):

$$0.06999 \times 100 = 7.00 \ \text{€}$$

6.1.6.4 Result and interpretation

Based on the assumed LCA emission factors, recycling 1 kg of carbon fibre generates a monetised climate benefit of approximately €5.6–€7.0**,** solely from avoided CO_2 emissions. This value represents the implicit economic benefit associated with reduced greenhouse gas emissions under current EU ETS price levels.

6.2 Monetised Climate Benefits of Different Carbon Fibre Recycling Pathways

To enable a consistent comparison of alternative carbon fibre recycling technologies, the climate benefits associated with each pathway were quantified and subsequently monetised using EU ETS-based carbon price assumptions. The analysis is grounded in life cycle assessment (LCA) results, where avoided greenhouse gas emissions are calculated per kilogram of recycled carbon fibre relative to the production of virgin carbon fibre. Table 6.2.1 and figure 6.2.1 shows monetised climate benefits of different carbon fibre recycling.

Table 6.2.1 Monetised climate benefits of different carbon fibre recycling.

	Avoided emissions, kg CO_2	Lower-bound estimate (€80/t CO_2)	Upper-bound estimate (€100/t CO_2):
T. 4.1.1 TUD	72.68	5.8144	7.268
T. 4.1.2 SUT	69.99	5.5992	6.999
T. 4.1.3 FRAU	11.84	0.9472	1.184
T. 4.1.4 UPAT	48.78	3.9024	4.878

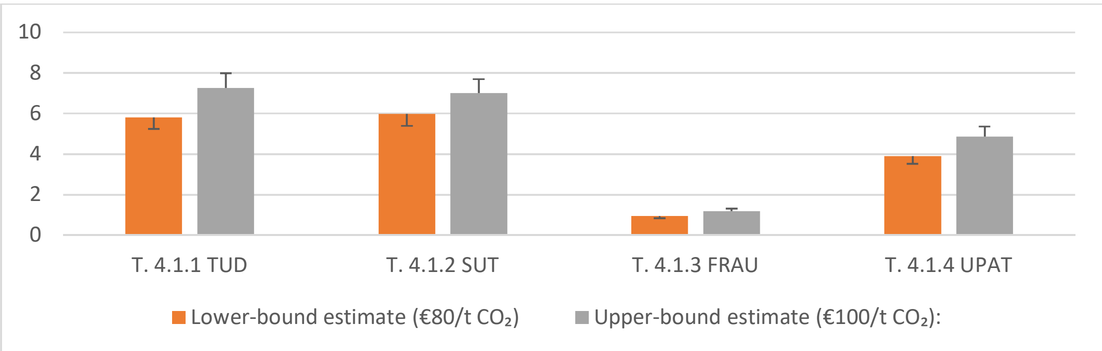

Figure 6.2.1. Monetised climate benefits of different carbon fibre recycling includes 10% error bars.

The highest monetised climate benefits are observed for T.4.1.2 SUT and T.4.1.1 TUD. Both pathways generate avoided-emission values close to €6 per kg of recycled carbon fibre under the

€80/t CO_2 scenario, increasing to approximately €7 per kg under the €100/t CO_2 scenario. This indicates a high level of climate efficiency relative to virgin carbon fibre production.

T.4.1.4 UPAT demonstrates moderate climate benefits, ranging from approximately €3.9 to €4.9 per kg. While lower than TUD and SUT, the results still represent a substantial carbon cost avoidance per unit of material processed. T.4.1.3 FRAU shows significantly lower monetised benefits (below €1.2 per kg), suggesting either lower avoided emissions or a smaller differential between virgin and recycled process emissions compared to the other pathways.

The chart includes 10% error bars, applied asymmetrically:

- Downward error margin for the lower-bound estimate
- Upward error margin for the upper-bound estimate

This approach reflects uncertainty in:

- LCA emission factors
- System boundary assumptions
- Carbon price volatility
- Process efficiency variability

The inclusion of ±10% uncertainty provides a conservative robustness check and illustrates the sensitivity of economic valuation to emission variability. Importantly, even when accounting for this uncertainty, the relative ranking of the technologies remains stable. This strengthens confidence in the comparative performance assessment.

The difference between the €80 and €100 scenarios shows a proportional increase (~25%) in monetised benefits, confirming direct linear dependency on carbon price assumptions.

Investment relevance:

At industrial scale (e.g., 1,000 tonnes/year), the monetised climate benefit would translate into:

- TUD: €5.8–7.3 million annually
- SUT: €6.0–7.0 million annually
- UPAT: €3.9–4.9 million annually
- FRAU: €0.95–1.18 million annually

Under sustained or increasing EU ETS prices, the economic attractiveness of higher-performing recycling pathways would strengthen further.

The figure 6.2.2 illustrates the projected annual monetised climate benefits associated with the recycling of post-consumer CFRP waste for four technological pathways (TUD, SUT, FRAU and UPAT) over the period 2010–2040, under two EU ETS carbon price scenarios (€80/t CO_2 and €100/t CO_2). The values are expressed in € million per year and assume that 100% of post-consumer CFRP waste generated in each year is recycled using the respective pathway.

Monetisation is based on pathway-specific avoided-emission intensities derived from life cycle assessment and scaled according to the projected growth of post-consumer waste volumes.

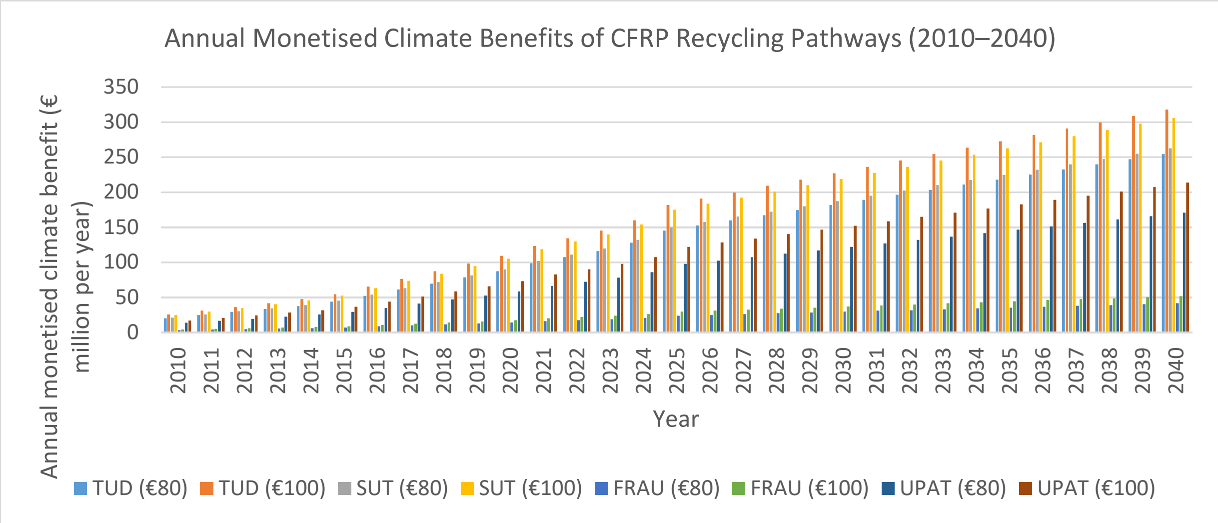

Figure 6.2.2. Annual Monetised Climate Benefits of CFRP Recycling Pathways (2010–2040)

Across the entire time horizon, all pathways exhibit a steady and near-linear increase in annual monetised climate benefits. This trend is driven by the continuous rise in post-consumer CFRP waste, which increases from 3,500 Mg in 2010 to 43,750 Mg in 2040. As avoided emissions scale proportionally with the volume of recycled material, the economic climate value also increases proportionally over time. The figure therefore clearly demonstrates the strong scaling effect associated with expanding circular deployment.

In comparative terms, the relative ranking of technologies remains stable throughout the period. SUT and TUD consistently deliver the highest monetised climate benefits, reflecting their higher avoided-emission intensities per unit of recycled material. By 2040, these pathways reach approximately €254–262 million per year under the €80/t scenario and exceed €300 million per year under the €100/t scenario. UPAT demonstrates intermediate performance, reaching approximately €171 million per year (€80/t) and €213 million per year (€100/t) by 2040. FRAU shows substantially lower monetised benefits across all years, remaining below €52 million per year even in the upper-bound scenario. The differences between pathways directly reflect their respective CO_2 avoidance efficiencies.

The gap between the €80/t and €100/t scenarios illustrates the linear sensitivity of monetised results to carbon price assumptions. Since the economic value is calculated as avoided CO_2 multiplied by the carbon price, increasing the price from €80 to €100 per tonne results in an approximate 25% increase in annual monetised climate benefits across all pathways and years. This confirms that the economic attractiveness of carbon fibre recycling strengthens significantly under higher ETS price trajectories.

Overall, the figure highlights the macroeconomic relevance of large-scale CFRP recycling. By 2040, the highest-performing pathways generate annual climate benefits exceeding €300 million, demonstrating that circular carbon fibre solutions represent not only an environmental mitigation strategy but also a substantial and growing economic climate value within the EU carbon pricing framework.

6.3 EU Job Market and the Workforce Implications of Circular Carbon Fibre Deployment

Understanding the dynamics of the European Union labour market is essential for assessing the socio-economic feasibility of emerging circular industrial value chains, including carbon fibre recycling. The EU is undergoing a structural transformation driven by decarbonisation targets under the European Green Deal, increasing carbon pricing through the EU Emissions Trading System (EU ETS), digitalisation, and strategic industrial autonomy objectives. These shifts are reshaping employment structures across manufacturing, materials processing, waste management, and advanced engineering sectors.

Over the past decade, the EU labour market has demonstrated moderate overall employment growth but significant sectoral reallocation. Traditional carbon-intensive industries face cost pressure due to rising ETS prices and energy costs, while demand is increasing in renewable energy, advanced materials, circular economy services, and environmental technologies. This structural rebalancing generates both displacement risks and new employment opportunities.

The deployment of circular carbon fibre (rCF) solutions intersects directly with several labour market megatrends:

1. Green Transition Employment Growth

The expansion of recycling infrastructure, advanced materials recovery, and secondary raw material markets contributes to job creation in:

- waste logistics and sorting,
- materials processing and chemical engineering,
- quality assurance and certification,
- industrial process optimisation,
- sustainability compliance and LCA analysis.

2. Demand for High-Skill Technical Profiles

Carbon fibre recycling is capital-intensive and technologically complex. It requires:

- materials scientists,
- chemical and process engineers,
- automation and robotics specialists,
- data-driven production optimisation experts,
- environmental compliance specialists.

This aligns with EU-wide evidence of increasing demand for STEM and advanced technical occupations, particularly within manufacturing and clean technology sectors.

3. Reskilling and Workforce Transition Potential

Regions historically dependent on energy-intensive production or conventional composites manufacturing may leverage rCF deployment as a transition pathway. Workers in polymer processing, composite manufacturing, and industrial thermal processes possess partially transferable skills that can be adapted to recycling operations through targeted reskilling programmes.

4. Regional Cohesion and Industrial Policy Relevance

The localisation of recycling facilities near composite-intensive sectors (automotive, aerospace, wind energy) creates regional employment clusters. This is particularly relevant for:

- Germany,
- France,
- Spain,
- Italy,
- Central and Eastern European manufacturing hubs.

Given the projected growth of post-consumer CFRP waste—from 3,500 Mg in 2010 to 43,750 Mg in 2040—the scale-up of recycling capacity implies substantial industrial activity expansion. Increased processing volumes translate into:

- higher demand for plant operators,
- engineering maintenance personnel,
- environmental reporting specialists,
- supply chain coordination roles.

Moreover, as demonstrated in previous sections, monetised climate benefits exceed €300 million annually for leading pathways by 2040. Such economic value strengthens the investment case and increases the probability of industrial-scale deployment, indirectly reinforcing employment creation potential.

The integration of circular carbon fibre solutions into the EU industrial ecosystem suggests several structural implications:

- A gradual shift from virgin carbon fibre production (high-emission, energy-intensive) toward lower-emission secondary material processing.
- Increased demand for hybrid skill profiles combining materials science and sustainability analytics.
- Greater importance of vocational education and training (VET) systems aligned with circular manufacturing.

- Enhanced labour market resilience through diversification of industrial activities.

Importantly, the employment effects of carbon fibre recycling are unlikely to be purely additive. They represent a reconfiguration of value chains, where economic activity shifts from primary resource extraction toward secondary resource recovery and advanced processing.

6.4 EU Job Market and Employment Implications of Circular Carbon Fibre Deployment

Understanding the dynamics of the European Union labour market is essential for assessing the socio-economic implications of scaling circular carbon fibre (rCF) technologies. The EU's transition towards climate neutrality under the European Green Deal, reinforced by the EU ETS and industrial decarbonisation policies, is reshaping sectoral employment structures and accelerating demand for green and technically advanced occupations.

According to Eurostat, employment in the environmental goods and services sector (EGSS)—commonly used as a proxy for "green jobs"—has grown steadily over the past decade. The sector employs approximately 4.5–5 million people across the EU, accounting for around 2–2.5% of total EU employment. Growth has been particularly strong in waste management, resource recovery, renewable energy, and environmental engineering services. This confirms that environmental transition policies are already generating measurable labour market effects.

Circular carbon fibre recycling aligns directly with the EGSS classification, particularly within:

- waste management and material recovery,
- secondary raw material processing,
- environmental technology manufacturing,
- industrial sustainability services.

To estimate potential job creation effects, employment intensity factors from advanced recycling and materials processing industries were used as benchmarks.

Studies of industrial recycling facilities in the EU indicate:

- Direct employment intensity:
  ~5–15 direct jobs per 1,000 tonnes (1,000 Mg) of material processed annually
  (including plant operators, technicians, engineers, quality control)
- Indirect and induced employment multiplier:
  1.5–2.5× direct employment
  (logistics, maintenance, equipment supply, certification, administration)

Given that carbon fibre recycling is technologically intensive and higher value-added than conventional waste recycling, a mid-range assumption of 10 direct jobs per 1,000 Mg is applied.

Thus:

$$\text{Direct jobs} = \frac{\text{Waste volume (Mg/year)}}{1000} \times 10$$
$$\text{Total jobs} = \text{Direct jobs} \times 2$$

(conservative multiplier of 2)

Using projected post-consumer CFRP waste volumes, direct jobs:

Direct jobs (2030):

$$\frac{31{,}250}{1000} \times 10 = 312 \text{ jobs}$$

Total jobs:

$$312 \times 2 = 624 \text{ jobs}$$

Direct jobs (2040):

$$\frac{43{,}750}{1000} \times 10 = 438 \text{ jobs}$$

Total jobs:

$$438 \times 2 = 876 \text{ jobs}$$

By 2040, large-scale deployment of circular CFRP recycling across the EU could support approximately:

- ~440 direct high-skill industrial jobs
- ~850–900 total jobs including indirect effects

These roles would predominantly require:

- chemical and process engineers,
- materials scientists,
- automation technicians,
- plant operators with advanced technical training,
- environmental compliance specialists,

- logistics and supply chain professionals.

Importantly, these are predominantly medium-to-high skill industrial jobs, aligning with EU labour market needs in advanced manufacturing and green technology sectors.

Given the high monetised climate benefits (exceeding €300 million annually under high-performing pathways by 2040), the sector demonstrates high economic value per employee, suggesting strong productivity potential.

7 Material Substitution and Strategic Autonomy in the Carbon Fibre Value Chain

7.1 Objective and scope

This report assesses the impact of carbon-fibre recycling and reclamation technologies on EU raw materials independence and supply-chain resilience, with a specific focus on virgin carbon fibre (vCF). The objective is to evaluate to what extent recycled carbon fibre (rCF) can reduce the EU's dependence on imports of virgin CF and thereby support EU strategic autonomy, in line with the objectives of the Critical Raw Materials Act (CRMA).

The analysis is conducted at EU level and focuses on carbon-fibre composite value chains relevant to key industrial sectors (automotive, aerospace, energy). It provides:

- quantitative data on EU imports of carbon fibre and key upstream feedstocks,
- an estimate of technically recoverable rCF from EU composite waste streams,
- a material balance comparing potential rCF recovery with current imports of vCF,
- an assessment of supply-risk reduction through substitution and diversification,
- identification of value-chain segments benefiting from rCF deployment, and
- a policy-oriented narrative aligned with CRMA and EU strategic autonomy.

7.2 EU import dependency for carbon fibre and upstream feedstocks

7.2.1 Imports of carbon fibre into the EU

Carbon fibre is not captured under a single dedicated Combined Nomenclature (CN) code; however, the HS/CN category HS 681510 (carbon fibres and articles of carbon fibres, for non-electrical purposes) is commonly used as a proxy for trade flows relevant to composite manufacturing.

According to UN Comtrade / World Bank WITS, for EU-27 (reporter: EUN):

- EU imports of HS 681510 in 2023: ≈ 13.1 kilotonnes
- Customs value: ≈ EUR 235 million (World Bank WITS/UN Comtrade, 2023)

These figures indicate that the EU currently depends on more than 10 kt per year of externally supplied carbon-fibre-based material, exposing downstream composite industries to external supply, price and geopolitical risks. Eurostat Comext remains the authoritative source for CN-level verification, but the order of magnitude is robust.

7.2.2 Upstream dependency: acrylonitrile and PAN precursor

More than 90% of global carbon fibre production is based on polyacrylonitrile (PAN) precursor, which itself depends on acrylonitrile as a petrochemical input (SGL Carbon, n.d.; Chen et al., 2023). Consequently, EU exposure to virgin carbon fibre supply is amplified by dependency on upstream chemical imports.

For HS 292610 (acrylonitrile), EU-27 imports in 2023 show a high degree of concentration (World Bank WITS/UN Comtrade, 2023):

- South Korea: ~56.6% of EU import mass
- Russia: ~21.6%
- United States: ~16.7%
- Other suppliers: <5% each

This concentration indicates structural upstream supply risk, driven by geopolitical exposure, energy price volatility and limited supplier diversification. Virgin CF production in Europe therefore remains indirectly exposed even where fibre conversion capacity exists within the EU.

7.3 EU composite waste generation and carbon-fibre recovery potential

7.3.1 CFRP waste generation in the EU

Published studies and sectoral assessments converge on the following estimates (Chen et al., 2023; EuCIA, 2023; WindEurope, 2023):

- Current CFRP waste generation in the EU: ≈ 120–150 kt/year
- Projected CFRP waste by 2030–2035: ≈ 250–300 kt/year, driven mainly by aerospace, wind energy and automotive end-of-life streams

7.3.2 Carbon-fibre content and recovery rates

Typical carbon-fibre mass fractions in CFRP range between 50% and 65%, depending on laminate architecture and application. Peer-reviewed and industrial studies report recoverable rCF yields of approximately 60% of CFRP mass for established thermal and chemical recycling routes (Chen et al., 2023).

7.4 Material balance: recovered rCF versus imported vCF

7.4.1 Material balance

Based on the available estimates, the European Union generates approximately 130 kt of CFRP waste per year, of which around 78 kt per year could be considered technically recoverable as recycled carbon fibres (rCF). For comparison, current EU imports of carbon fibre, used here as a proxy for external supply dependency, amount to approximately 13.1 kt per year. This implies that the potential volume of recoverable rCF is roughly six times higher than current EU imports of carbon fibre, resulting in an approximate rCF-to-import ratio of 6:1. These figures illustrate the significant, and currently underutilised, potential of composite waste streams to substitute primary carbon fibre imports and to strengthen material security within the EU.

By comparison EU imports of carbon fibre (HS 681510, 2023): ≈ 13.1 kt/year (World Bank WITS/UN Comtrade, 2023).

Key finding: Even if only ~17% of the technically recoverable rCF were redirected into applications substituting virgin carbon fibre, this would be sufficient to offset 100% of current EU imports of carbon-fibre-based material.

7.5 Supply-risk reduction and strategic relevance

7.5.1 Risk profile of virgin carbon fibre supply

EU supply risk for virgin carbon fibre arises from:

- high import dependency,
- strong concentration of upstream PAN/acrylonitrile suppliers,
- energy-intensive production exposed to price volatility,
- a limited number of global CF producers.

These characteristics are consistent with CRMA definitions of materials with high supply risk and strategic relevance, even if carbon fibre itself is not explicitly listed as a critical raw material (European Commission, 2024a).

7.5.2 Risk mitigation through recycled carbon fibre

Recycled carbon fibre reduces supply risk by:

- diversifying feedstock sources (EU-based EoL composites instead of imported chemicals),
- decoupling downstream users from upstream PAN supply chains,
- shortening and regionalising the value chain,
- buffering supply disruptions and price shocks.

From a resilience perspective, rCF acts as a secondary strategic raw material, enhancing robustness rather than fully replacing virgin CF in all applications.

7.6 Carbon-fibre value chain and circular loop (schematic description)

The carbon-fibre value chain is currently dominated by a linear, import-exposed model, in which critical upstream inputs are sourced largely from outside the EU and materials are predominantly lost at the end of their service life. In this status quo configuration, the chain starts with imported acrylonitrile, which is converted into a PAN precursor, then processed into virgin carbon fibre. The fibres are subsequently transformed into semi-products such as tows, fabrics and prepregs, which are used to manufacture composite components for various applications. After the use phase, these components are typically directed to disposal, resulting in the loss of high-value material and reinforcing the EU's dependency on external supplies of primary carbon fibre.

This linear configuration implies three structural weaknesses: (i) high exposure to import risks at the raw material and fibre production stages, (ii) continuous loss of embedded energy and material value at end-of-life, and (iii) limited feedback from downstream stages to upstream material supply. As a consequence, the system remains vulnerable to supply disruptions, price volatility and geopolitical risks, while at the same time generating growing volumes of composite waste.

In contrast, the circular, EU-resilient value chain introduces a recovery and reuse loop based on recycled carbon fibres (rCF). In this configuration, end-of-life CFRP components are collected and dismantled, followed by fibre reclamation processes that recover usable fibres. These recovered fibres are then converted into rCF, which is further processed into semi-products such as non-wovens, compounds or SMC feedstocks, and subsequently used to manufacture new composite components. These components re-enter the use phase, and at the end of their service life can again be directed into the recovery loop.

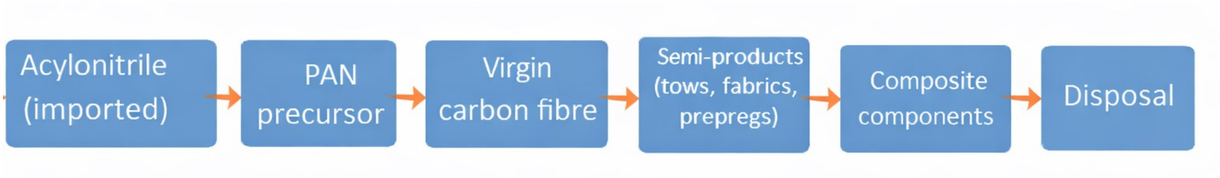

Figure 7.6.1. Linear, import-exposed value chain (status quo)

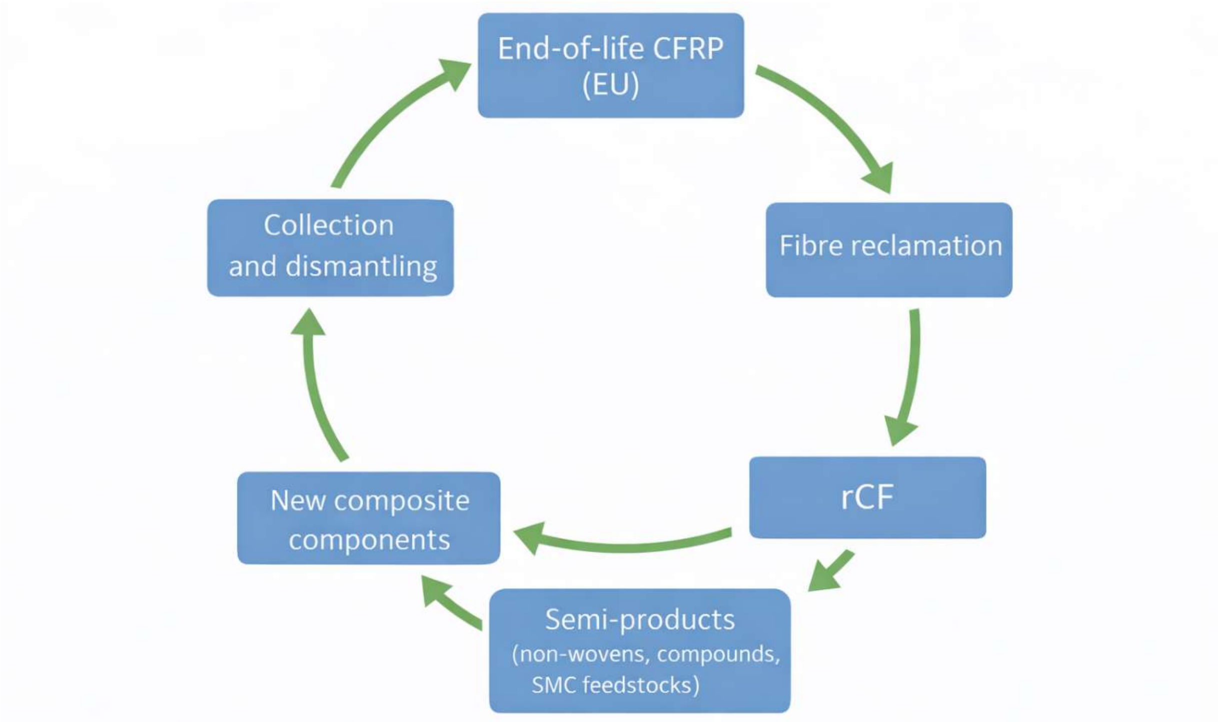

Figure 3.6.2. Circular, EU-resilient value chain (with rCF)

The introduction of this circular loop fundamentally changes the system logic. Instead of a one-way flow from imported feedstock to disposal, the value chain becomes partially closed, retaining material value within the EU and reducing dependency on virgin fibre imports. From a strategic perspective, this increases material resilience and supply security, while from an economic and environmental perspective it enables value retention, waste reduction and lower life-cycle impacts. The schematic comparison therefore illustrates the transition from a vulnerable, linear value chain towards a more robust and circular system in which rCF plays a central role as a secondary raw material for the European composites industry.

Positive effects along the chain:

- reduced demand for imported virgin CF,
- reduced exposure to acrylonitrile/PAN imports,
- increased EU value creation in recycling and semi-product manufacturing,
- improved supply diversification and strategic resilience.

7.7 Value-chain segments benefiting from rCF deployment

The large-scale deployment of recycled carbon fibres (rCF) has the potential to strengthen several key segments of the European carbon-fibre and composites value chain by redistributing value creation, reducing supply risks and enabling new industrial activities within the EU.

At the upstream end of the chain, waste management and dismantling activities in sectors such as aerospace, wind energy and automotive benefit from the transformation of end-of-life composite structures into higher-value material streams. Instead of being treated primarily as waste destined for disposal, composite components become a source of secondary raw materials, improving the economics of collection, sorting and dismantling operations and supporting the emergence of more specialised decommissioning and pre-processing services.

The recycling and material processing industries represent a second major beneficiary. The development of rCF markets requires industrial-scale fibre reclamation capacity, including thermal, chemical or hybrid processes, as well as downstream fibre conditioning and quality control. This creates new opportunities for EU-based recycling and processing companies to expand their technological capabilities, build new value chains and capture a larger share of the material value that is currently lost at end-of-life.

Further downstream, semi-product manufacturers producing non-wovens, compounds or moulding materials gain access to alternative fibre feedstocks that complement or partially substitute virgin carbon fibres. The availability of rCF enables product diversification, cost-risk management and the development of new material grades tailored to specific performance and price points, thereby increasing the flexibility and resilience of this segment.

Composite component manufacturers also benefit directly from rCF deployment through reduced exposure to imported virgin carbon fibre supply constraints. By integrating rCF into selected product lines and applications, manufacturers can mitigate risks related to price volatility, supply disruptions and geopolitical dependencies, while at the same time improving the environmental profile of their products.

Finally, strategic downstream sectors such as automotive, energy and transport benefit from improved continuity and security of material supply. In these sectors, where composite materials play an increasingly important role in lightweighting and energy efficiency, the availability of rCF contributes to stabilising supply chains and supports the long-term scalability of composite-based solutions within the European industrial system.

Taken together, these effects illustrate that rCF deployment does not only address waste management or environmental objectives, but also acts as a systemic industrial lever, strengthening multiple segments of the EU value chain and enhancing its overall resilience, competitiveness and strategic autonomy.

7.8 CRMA and EU strategic autonomy narrative

The Critical Raw Materials Act (CRMA) identifies recycling and secondary raw materials as key pillars of EU strategic autonomy, with targets for increased domestic capacity, supply diversification and reduced import dependency (European Commission, 2024a; European Commission, 2024b).

This analysis demonstrates that:

- carbon fibre exhibits a structural risk profile comparable to critical materials,
- the EU possesses a domestic secondary resource base (CFRP waste) that is several times larger than current imports of virgin carbon fibre,
- scaling rCF effectively transforms composite waste into a strategic resilience asset.

From a CRMA perspective, recycled carbon fibre directly supports:

- reduced external dependency,
- diversification of supply sources,
- increased value retention within the EU.

7.9 Conclusions

- The EU currently imports ≈13.1 kt/year of carbon-fibre-based material, while simultaneously generating >120 kt/year of CFRP waste.
- Technically recoverable rCF in the EU (≈78 kt/year) exceeds current import volumes by a factor of ~6.
- Partial substitution of imported vCF with rCF would already deliver substantial supply-risk reduction.
- rCF deployment strengthens multiple EU value-chain segments and supports industrial resilience.
- Recycled carbon fibre constitutes a quantifiable opportunity for EU strategic raw-materials independence, fully aligned with CRMA objectives.

8 Strategic Implications for Critical Raw Materials and EU Autonomy (CRMA Perspective)

8.1 Introduction: Material Resilience as a Strategic Challenge for the EU

The European Union's transition towards climate neutrality, advanced mobility, renewable energy systems and defence capabilities is increasingly constrained by material supply risks. High-performance composite materials—particularly carbon fibre reinforced polymers (CFRP)—are indispensable in sectors such as aerospace, automotive lightweighting, wind energy, hydrogen infrastructure and defence. However, the EU remains structurally dependent on imports of both carbon fibres and their upstream precursors, exposing critical value chains to geopolitical, economic and logistical disruptions (European Commission, 2023a).

Carbon fibres (CF) are energy-intensive to produce, rely on globally concentrated precursor supply chains (mainly polyacrylonitrile, PAN), and are currently classified as strategically important materials due to their role in enabling downstream clean-tech and industrial competitiveness (JRC, 2022). At the same time, growing volumes of composite waste—production scrap and end-of-life components—are emerging across Europe, especially from wind turbine blades, aerospace structures and automotive parts.

This creates a structural paradox: increasing material scarcity on the one hand, and growing stocks of underutilised composite waste on the other. Recycling of carbon fibres (rCF) offers a unique opportunity to transform this paradox into a material resilience strategy, directly aligned with the objectives of the Critical Raw Materials Act (CRMA) and EU strategic autonomy.

8.2 Carbon Fibre Use and Supply in the European Union

8.2.1 Consumption and Sectoral Demand

EU demand for carbon fibres has grown steadily over the last two decades and is estimated at 90–110 kt per year, representing roughly 25–30% of global demand (IEA, 2023; Witten et al., 2021). The main consuming sectors include:

- aerospace and defence (high-grade CF),
- wind energy (spar caps, blades),
- automotive and transport,
- pressure vessels and hydrogen storage,
- industrial equipment and construction reinforcement.

Demand growth is expected to accelerate further due to lightweighting requirements, electrification and renewable energy deployment (European Commission, 2023b).

8.2.2 Import Dependency and EU Production Capacity

Despite its strong downstream manufacturing base, the EU produces only a limited share of primary carbon fibres, with estimated production capacity of 30–35 kt/year, concentrated in a small number of facilities in Germany, France and the UK (Witten et al., 2021).

According to Eurostat trade statistics, more than 65–75% of carbon fibres and precursor materials consumed in the EU are imported, primarily from:

- Japan,
- the United States,
- China,
- South Korea.

This dependency is even higher for PAN precursors, which are derived from petrochemical value chains largely external to the EU (JRC, 2022). As a result, the EU is exposed to dual vulnerabilities: supply concentration and energy-intensive upstream processes.

8.3 EU-Scale Material Balance: Import versus Recovered Carbon Fibres

Based on conservative assumptions derived from industrial and academic sources (JRC, 2022; Witten et al., 2021):

- annual composite waste containing carbon fibres in the EU already exceeds 40–60 kt CF-equivalent, including production scrap and end-of-life products,
- by 2035, this volume could exceed 100 kt/year, driven mainly by wind energy and aerospace.

Assuming a realistic recovery rate of 50–60%, recycled carbon fibres could substitute 20–30 kt/year of imported primary CF by 2030. This corresponds to:

- 20–25% of current EU demand, or
- one third of today’s net imports.

From a CRMA perspective, this represents a material resilience lever comparable to opening new domestic mines, but without the environmental and social burdens.

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From a CRMA perspective, this represents a material resilience lever comparable to opening new domestic mines, but without the environmental and social burdens.

8.5 Substitution Potential and Supply Risk Reduction

Recycled carbon fibres are not a universal substitute for aerospace-grade virgin fibres, but they are fully suitable for:

- automotive structural and semi-structural parts,
- wind energy components,
- construction reinforcement,
- consumer and industrial goods.

This enables functional substitution, freeing high-grade virgin fibres for applications where they are strictly necessary. As highlighted by the European Commission, substitution and diversification are core pillars of the CRMA (European Commission, 2023a).

By reducing dependence on imported precursors and energy-intensive production steps, rCF deployment significantly lowers supply disruption risks, especially under scenarios of trade restrictions or geopolitical instability.

8.6 Value Chain Segments Benefiting from Carbon Fibre Recycling

Carbon fibre recycling redistributes value creation across the EU industrial ecosystem. Key beneficiaries include:

- Recycling and waste management companies, gaining access to high-value material streams,
- SMEs and composite processors, benefiting from lower-cost CF inputs,
- OEMs (automotive, wind, hydrogen), improving cost stability and ESG performance,
- Energy-intensive industries, reducing exposure to volatile energy markets,
- Regional economies, through localisation of recycling and re-manufacturing activities.

This strengthens industrial sovereignty not only at material level, but across the full composite value chain.

8.7 Contribution of the EURECOM Project to EU Raw Material Independence

The EURECOM project directly addresses the CRMA objectives by:

- developing scalable recycling routes for carbon fibre composites,
- enabling high-quality rCF reintegration into industrial applications,
- generating robust material flow and LCA evidence supporting policy uptake,
- fostering cross-sectoral value chain integration between recyclers, manufacturers and end-users.

By transforming composite waste into a secondary strategic raw material, EURECOM contributes to reducing import dependency, enhancing material circularity and reinforcing EU strategic autonomy—without increasing environmental pressure.

8.8 Conclusions

Recycling of carbon fibre composites represents a systemic opportunity for improving EU material resilience. Quantitative analysis demonstrates that recycled carbon fibres can substitute a substantial share of imports, reduce energy and emissions intensity, and strengthen domestic value chains. Within the CRMA framework, carbon fibre recycling should be recognised as a strategic pillar of raw material security, on par with primary resource diversification.

EURECOM provides a concrete, evidence-based pathway to operationalise this vision and to position the EU as a global leader in circular high-performance materials.

9 Social Acceptance and Implementation Barriers for Recovered Carbon Fibres

9.1 Introduction

This report synthesises evidence on perception, trust, and acceptance of recycled materials across three nested material categories:

- general recycled materials (secondary raw materials broadly),
- composite materials with emphasis on recycled fibre-reinforced polymers, and
- carbon fibre composites, focusing on recycled carbon fibre (rCF) and recycled carbon-fibre reinforced polymers (rCFRP).

The source base prioritises peer-reviewed academic literature, especially systematic and scoping reviews and empirical acceptance studies, followed by official EU and international policy and technical documents, then industry association reports and technical white papers, and finally reputable market analyses used cautiously due to methodological divergence (Polyportis et al., 2022; European Commission, 2022; OECD, 2022; National Physical Laboratory, 2025).

Examples of high-weight sources include the scoping review on consumer acceptance of products made from recycled materials (Polyportis et al., 2022), EU regulation and guidance on recycled plastics in food contact (European Commission, 2022), Eurostat and European Environment Agency waste indicators (Eurostat, 2024; EEA, 2024), and industry consultations on recycled composites and fibres conducted by the National Physical Laboratory (National Physical Laboratory, 2025).

A recurring barrier to adoption is that many stakeholders use the term “recycled” as shorthand for materially different realities. For analytical clarity, the following definitions are applied consistently:

Recycled materials (general) refer to secondary materials generated by processing waste streams into new usable inputs. A key practical distinction is post-consumer versus pre-consumer or post-industrial sources, as contamination risk, traceability, and regulatory constraints differ substantially between them (European Commission, 2022).

Composite materials are multi-constituent engineered materials, primarily fibre-reinforced polymers, in which fibres such as glass, carbon or natural fibres reinforce a polymer matrix. Their recyclability is more complex than for many commodity materials because fibre–matrix bonding and thermoset matrices complicate separation and consistent material recovery (Oliveux et al., 2015).

Recycled carbon fibre (rCF) and rCFRP denote carbon fibres recovered from manufacturing scrap or end-of-life CFRP parts via mechanical, thermal or chemical routes, subsequently remanufactured into discontinuous fibre formats such as chopped fibres or non-woven mats, or less commonly into aligned architectures. rCFRP refers to new composites reinforced with rCF (Witik et al., 2013).

9.2 A general mechanism: acceptance as "conditional trust under uncertainty"

Across all three categories, acceptance is rarely binary. It is more accurately described as conditional trust under uncertainty, in which both producers and buyers seek to reduce perceived technical, regulatory and reputational risks through signals such as standards, certification, traceability, testing data and credible sustainability claims (OECD, 2025; Ellen MacArthur Foundation, 2021).

This pattern is evident both in industrial consultations on recycled composite fibres, where concerns regarding traceability, contamination and confidence in mechanical performance dominate decision-making (National Physical Laboratory, 2025), and in consumer research, where quality cues and scepticism towards green claims shape purchase intentions (Magnier et al., 2019; Di Cicco et al., 2024).

Feedstock variability and process consistency drive the need for quality assurance and traceability. These factors, in turn, shape producer adoption decisions related to capability, cost and liability, as well as buyer acceptance decisions related to risk, value and trust. A structurally similar logic is identified in the Circular Plastics Alliance diagnosis for recycled plastics and in consultations on recycled composites, which emphasise stable supply, quality information, competitiveness, legacy substances and predictable investment frameworks (Circular Plastics Alliance, 2021; National Physical Laboratory, 2025).

9.3 General recycled materials

9.3.1 Global material context and relevance for acceptance

Global material consumption continues to grow, while overall circularity remains structurally low. According to global material flow analyses, the share of secondary materials in total material use has declined in recent years, despite increasing policy attention to circular economy principles (Circle Economy, 2024). This macro-level context is important for understanding acceptance, as it frames recycled materials not as marginal solutions but as increasingly necessary components of future material supply.

In the European context, waste generation and recycling rates indicate both the scale of available secondary raw materials and the limits of current systems. Eurostat data show that municipal waste generation in the European Union remains high, with recycling rates stagnating below policy targets, signalling that technical recycling capacity alone does not automatically translate into market uptake (Eurostat, 2024). The European Environment Agency similarly highlights structural bottlenecks related to quality of recycled outputs, market demand and cross-border consistency (EEA, 2024).

These trends imply that acceptance of recycled materials must be analysed not only at the level of individual attitudes, but also in relation to systemic conditions such as supply stability, regulatory enforcement and market design (European Commission, 2020).

9.3.2 How producers perceive recycled materials

From the producer perspective, recycled materials are increasingly viewed as strategically important inputs, particularly in the context of resource security, regulatory compliance and corporate sustainability strategies (European Commission, 2022; OECD, 2022). However, producer acceptance is highly conditional and depends on the ability to integrate recycled materials into existing production systems without compromising product performance, process reliability or legal compliance.

Industry consultations consistently identify quality variability as a primary concern. Differences in feedstock origin, contamination levels and processing routes lead to uncertainty regarding material properties, which in turn increases production risk and liability exposure (Reike et al., 2018; Allwood et al., 2019). As a result, producers tend to accept recycled materials more readily in applications with higher tolerance for property variation, while avoiding their use in safety-critical or tightly regulated products.

Supply stability represents a second key condition. Even where recycled materials meet technical specifications, inconsistent availability and limited volumes can undermine producer trust, as they complicate long-term production planning and investment decisions (OECD, 2022). Industry initiatives such as the Circular Plastics Alliance explicitly emphasise the need for predictable supply, sufficient quantities and transparent quality information as prerequisites for broader industrial uptake (Circular Plastics Alliance, 2021).

A further determinant of acceptance is regulatory clarity. Producers express higher confidence when recycled materials are covered by clear standards and harmonised regulatory frameworks, particularly with respect to product safety, chemical compliance and recycled-content accounting (European Commission, 2022). Conversely, regulatory ambiguity—such as uncertainty around mass-balance approaches or classification of chemically recycled materials—acts as a disincentive for adoption (European Commission, 2025).

9.3.3 How buyers perceive recycled materials

Buyer perception of recycled materials differs between consumer markets and professional procurement contexts, but follows a similar underlying logic based on risk and trust. Consumers generally express positive attitudes towards recycled materials, especially when environmental benefits are salient and aligned with personal values (Trudel and Cotte, 2009; European Commission, 2023). However, these attitudes do not automatically translate into purchasing behaviour.

Empirical studies repeatedly identify concerns related to durability, safety, sensory quality and aesthetic appearance as key barriers to acceptance (Magnier et al., 2019; Polyportis et al., 2022). When recycled materials are associated with inferior performance or ambiguous quality cues, buyer trust declines, even if environmental benefits are acknowledged.

Transparency plays a critical role in mediating acceptance. Buyers are more likely to accept recycled materials when information about origin, processing and quality control is clearly communicated and perceived as credible (Abbey et al., 2015). Conversely, scepticism towards environmental claims and fear of greenwashing undermine trust and can lead to rejection, even in cases where recycled materials perform equivalently to virgin alternatives (OECD, 2025).

Importantly, multiple studies document an attitude–behaviour gap: while buyers express support for recycled materials in surveys, actual purchasing decisions remain strongly influenced by price, perceived risk and brand trust (Polyportis et al., 2022). This gap highlights that acceptance is not solely a matter of awareness or values, but also of structural market conditions.

9.3.4 Conditions for acceptance of recycled materials

Across producer and buyer perspectives, acceptance of recycled materials converges around a set of recurring conditions. First, functional equivalence to virgin materials is essential, particularly in applications where performance failures carry significant consequences (Allwood et al., 2019). Second, traceability and quality assurance systems are required to reduce uncertainty and support trust (Reike et al., 2018).

Third, stable supply and competitive pricing influence both producer and buyer decisions, as volatility increases perceived risk and undermines confidence (OECD, 2022). Finally, regulatory consistency and enforcement play a crucial role in shaping acceptance, as they determine whether recycled materials are perceived as reliable, legitimate and future-proof inputs (European Commission, 2020).

9.4 Recycled composite materials

9.4.1 Specific challenges of composite materials in a recycling context

Composite materials, particularly fibre-reinforced polymers, pose distinct challenges in a recycling and acceptance context compared to mono-materials. Their heterogeneous structure, consisting of reinforcing fibres embedded in a polymer matrix, complicates separation, material recovery and quality control (Pickering, 2006; Oliveux et al., 2015). These technical characteristics have direct implications for how recycled composites are perceived by both producers and buyers.

Unlike metals or some plastics, recycled composites rarely re-enter material cycles in the same form or with equivalent performance. Instead, recycling processes typically result in downgraded material formats, such as shorter fibres, mixed fibre lengths or altered surface properties, which affect mechanical performance and predictability (Witik et al., 2013). As a consequence, acceptance of recycled composite materials is closely tied to application selection and risk management rather than to the general concept of recycling.

9.4.2 Producer perception of recycled composite materials

From the producer perspective, recycled composites are approached with considerable caution. Industrial actors emphasise that the anisotropic behaviour of fibre-reinforced composites makes small variations in fibre length, orientation or interfacial bonding particularly consequential for performance (Oliveux et al., 2015). Recycling processes that disrupt fibre continuity or surface chemistry therefore introduce uncertainty that must be carefully managed.

Empirical studies and industry consultations indicate that producers are willing to consider recycled composites primarily in applications where performance requirements are lower, safety margins are higher and certification constraints are less stringent (Job et al., 2016; Yang et al., 2021). Typical examples include non-structural components, interior parts and secondary elements, where recycled composites can offer acceptable performance without exposing manufacturers to disproportionate technical or legal risk.

Certification and regulatory acceptance emerge as central determinants of producer trust. In regulated sectors such as aerospace, automotive and energy, the absence of established qualification pathways for recycled composites acts as a major barrier to adoption (European Union Aviation Safety Agency, 2020). Producers report that even when recycled composites demonstrate satisfactory mechanical performance in laboratory testing, uncertainty regarding certification, liability and long-term behaviour can prevent their integration into commercial products.

Process repeatability and traceability are additional conditions for acceptance. Producers express greater confidence when recycled composite materials are derived from controlled, well-characterised waste streams and processed using standardised, reproducible methods (National Physical Laboratory, 2025). Conversely, mixed or poorly documented waste sources undermine trust and complicate quality assurance.

9.4.3 Buyer perception of recycled composite materials

From the buyer perspective, composite materials are often perceived as opaque or “black-box” materials, meaning that internal defects, damage or variability cannot be easily detected without specialised testing (Baxter et al., 2017). This perception is amplified in the case of recycled composites, where buyers may assume additional uncertainty regarding material history and processing.

As a result, buyer acceptance of recycled composite materials is strongly mediated by institutional trust. Buyers tend to rely on the reputation of manufacturers, the presence of certification and the provision of warranties rather than on direct assessment of material properties (Densley-Tingley et al., 2019). Acceptance is higher when recycled composites are integrated into products by established OEMs that assume responsibility for performance and safety.

Consumer-oriented studies suggest that recycled composites are more readily accepted in applications where users perceive limited personal risk and where environmental benefits are salient, such as sports equipment, furniture or interior components (Magnier et al., 2019). In contrast, acceptance decreases sharply in applications associated with safety, durability or long service life, particularly when information about testing and quality assurance is limited.

9.4.4 Conditions for acceptance of recycled composite materials

Across producer and buyer perspectives, acceptance of recycled composite materials converges around several key conditions. First, application-appropriate performance must be demonstrated through relevant testing, rather than through comparisons with virgin composites in absolute terms (Oliveux et al., 2015). Second, traceability of material origin and processing is essential for managing risk and supporting certification (National Physical Laboratory, 2025).

Third, regulatory clarity and the development of qualification frameworks are critical for enabling adoption in industrial contexts (European Union Aviation Safety Agency, 2020). Finally, transparent communication regarding limitations, appropriate use cases and expected performance plays an important role in shaping buyer trust and avoiding unrealistic expectations (Baxter et al., 2017).

9.5 Recycled carbon fibre (rCF) and recycled carbon-fibre reinforced polymers (rCFRP)

9.5.1 Specific characteristics of carbon fibre in a recycling context

Carbon fibre reinforced polymers represent a special case within the broader category of composite materials due to their exceptional mechanical performance, high cost and frequent use in safety-relevant applications. These characteristics make carbon fibre both an attractive target for recycling and a particularly sensitive material in terms of acceptance by producers and buyers (Pimenta and Pinho, 2011).

Unlike glass fibre composites, carbon fibre composites are typically used in applications where high stiffness-to-weight ratios, fatigue resistance and long service life are critical. Consequently, any uncertainty regarding fibre properties, damage history or processing effects has a disproportionate impact on perceived risk (Oliveux et al., 2015). Recycling processes that alter fibre length, surface chemistry or alignment therefore have direct implications for trust and acceptance.

Recovered carbon fibres are most commonly reintroduced into value chains in discontinuous forms, such as chopped fibres, milled fibres or non-woven mats, rather than as continuous fibres. While these formats enable material recovery and environmental benefits, they generally exhibit lower and more variable mechanical performance compared to virgin continuous fibres (Witik et al., 2013). This inherent performance shift underpins the hierarchical acceptance patterns observed for recycled carbon fibre.

9.5.2 Producer perception of recycled carbon fibre

From the producer perspective, acceptance of recycled carbon fibre is strongly conditional and structured around application criticality. Industrial actors generally distinguish between applications where recycled carbon fibre can be used without compromising safety or liability, and those where virgin material remains the default choice (Job et al., 2016; Oliveux et al., 2015).

Producers tend to accept recycled carbon fibre most readily in non-structural or semi-structural applications, such as housings, brackets, interior components or consumer products, where performance requirements are lower and variability can be tolerated (Wong et al., 2019). In contrast, use of recycled carbon fibre in primary load-bearing or fatigue-critical components is typically avoided due to certification constraints and uncertainty regarding long-term behaviour (Pimenta and Pinho, 2011).

A central determinant of producer trust is the availability of reliable characterisation data. Producers express greater willingness to use recycled carbon fibre when fibre properties are systematically measured, classified and linked to defined application envelopes (Witik et al., 2013). Qualification frameworks that translate recycled fibre characteristics into design-relevant parameters are therefore seen as essential enablers of broader adoption.

Supply-chain considerations further shape producer acceptance. Recycled carbon fibre is increasingly viewed as a potential means of improving resource security and reducing dependence on volatile virgin fibre markets. However, inconsistent supply volumes, lack of standardised grades and uncertainty regarding long-term availability remain significant barriers (Ellen MacArthur Foundation, 2021). Without predictable supply and quality, producers are reluctant to redesign products or processes around recycled carbon fibre.

9.5.3 Buyer perception of recycled carbon fibre

From the buyer perspective, recycled carbon fibre is rarely evaluated as a material in its own right. Instead, acceptance is mediated through product-level attributes, institutional trust and risk perception (Yang et al., 2021). Buyers typically rely on certification, brand reputation and warranty provisions rather than direct assessment of fibre origin or processing history.

Studies indicate that buyers do not inherently reject products containing recycled carbon fibre. Rather, concern arises when recycled content is associated with uncertainty regarding safety, durability or performance consistency (Witik et al., 2013; Wong et al., 2019). In applications where perceived personal or financial risk is low, such as sports equipment or consumer goods, acceptance of recycled carbon fibre is significantly higher.

Environmental benefits alone are generally insufficient to ensure acceptance in safety-critical or long-lifetime applications. However, when recycled carbon fibre is presented as technically validated, application-appropriate and supported by credible testing and certification, buyer acceptance increases substantially (Yang et al., 2021). This highlights the importance of framing recycled carbon fibre not as a direct substitute for virgin material, but as a distinct material category with defined and appropriate use cases.

9.5.4 Conditions for acceptance of recycled carbon fibre

Across producer and buyer perspectives, acceptance of recycled carbon fibre converges around a limited number of critical conditions. First, technical performance must be demonstrated in relation to specific applications, rather than through generic comparisons with virgin carbon fibre (Oliveux et al., 2015). Second, traceability of fibre origin, processing history and quality control is essential for managing risk and supporting trust (Ellen MacArthur Foundation, 2021).

Third, certification and regulatory alignment play a decisive role, particularly in highly regulated sectors. The absence of recognised qualification pathways for recycled carbon fibre remains one of the most significant barriers to broader adoption (European Union Aviation Safety Agency, 2020). Finally, transparent communication regarding limitations, appropriate applications and expected performance is necessary to avoid unrealistic expectations and erosion of trust (Wong et al., 2019).

9.6 Cross-cutting discussion: trust, risk and acceptance across material categories

9.6.1 Acceptance as a function of perceived risk and responsibility

Across recycled materials, recycled composites and recycled carbon fibre, acceptance by both producers and buyers follows a common underlying logic: acceptance increases as perceived risk decreases and as responsibility for that risk is clearly allocated. This pattern is consistent across material categories, despite differences in technical complexity and regulatory context (Allwood et al., 2019; OECD, 2022).

Producers evaluate recycled materials primarily through the lens of operational risk, liability and regulatory compliance. Buyers, in turn, assess acceptance through perceived product safety, reliability and trust in the institutions that stand behind the product. In both cases, acceptance is conditional rather than ideological, reflecting rational risk management rather than opposition to recycling as such (Reike et al., 2018).

As material complexity increases—from bulk recycled materials to recycled composites and recycled carbon fibre—the tolerance for uncertainty decreases. This results in progressively stricter requirements for evidence, certification and traceability, and a narrowing of acceptable application spaces (Oliveux et al., 2015; Pimenta and Pinho, 2011).

9.6.2 The role of standards, certification and traceability

Standards and certification emerge as central trust-building mechanisms across all material categories. For producers, standards reduce uncertainty by defining acceptable property ranges, testing methods and quality assurance procedures (European Commission, 2020). For buyers, certification functions as a signal that technical and safety risks have been assessed and managed by competent authorities (Densley-Tingley et al., 2019).

Traceability plays a complementary role by linking material properties to known origins and processes. In the case of recycled materials, traceability supports confidence in chemical compliance and consistency (European Commission, 2022). For recycled composites and carbon fibre, traceability becomes even more critical, as it underpins qualification, certification and liability management (National Physical Laboratory, 2025).

Where standards and traceability are absent or fragmented, acceptance is significantly reduced. Producers are reluctant to invest in recycled material integration without clear qualification pathways, while buyers respond to uncertainty by defaulting to virgin materials or established solutions (OECD, 2022).

9.6.3 Environmental value versus performance expectations

The literature consistently shows that environmental benefits alone are insufficient to ensure acceptance of recycled materials. While sustainability considerations positively influence attitudes, actual adoption decisions are dominated by performance expectations, reliability and risk perception (Trudel and Cotte, 2009; Polyportis et al., 2022).

This imbalance becomes more pronounced as material criticality increases. In the case of recycled carbon fibre, environmental arguments play a supporting role but cannot compensate for uncertainty regarding mechanical performance or durability in demanding applications (Witik et al., 2013; Wong et al., 2019). Acceptance is therefore highest when environmental benefits are aligned with clearly defined, technically appropriate use cases.

9.6.4 The importance of application-specific framing

A recurring theme across material categories is the importance of application-specific framing. Acceptance improves when recycled materials are presented not as universal substitutes for virgin materials, but as suitable solutions for specific functions and contexts (Allwood et al., 2019).

For recycled composites and recycled carbon fibre, this implies moving away from direct performance comparisons with virgin materials and towards design approaches that explicitly account for the properties and limitations of recycled inputs (Oliveux et al., 2015). Such framing reduces unrealistic expectations and supports more stable trust relationships between producers, buyers and regulators.

9.7 Implications for industry and buyers

9.7.1 Implications for industrial producers

The findings synthesised in this report indicate that increasing the uptake of recycled materials requires a shift from general promotion of recycling towards targeted risk-reduction strategies. For producers, this means prioritising the development of stable supply chains, reproducible processing routes and application-specific qualification frameworks (European Commission, 2020; OECD, 2022).

In the case of recycled composites and recycled carbon fibre, producers are encouraged to adopt design-for-recycling and design-for-secondary-materials approaches, in which material properties are treated as known design inputs rather than as degraded substitutes for virgin materials (Oliveux et al., 2015). Such approaches reduce uncertainty and support more predictable performance outcomes.

Engagement with standardisation bodies, certification authorities and regulators is identified as a critical lever for increasing acceptance. Producers that actively participate in qualification initiatives and pilot projects contribute to the creation of shared trust infrastructures, which benefit the wider market (European Union Aviation Safety Agency, 2020; National Physical Laboratory, 2025).

9.7.2 Implications for buyers and downstream users

For buyers, the report highlights the importance of transparent and credible information regarding material origin, processing and performance. Acceptance increases when recycled materials are accompanied by clear documentation, certification and warranties that shift responsibility for risk away from the buyer (Densley-Tingley et al., 2019).

In consumer-facing markets, communication strategies should avoid generic environmental claims and instead emphasise verified performance, appropriate use cases and tangible benefits. Overstated claims risk eroding trust and reinforcing scepticism towards recycled materials (OECD, 2025).

Professional buyers and public procurers can play an enabling role by incorporating recycled-material criteria into procurement specifications in a manner that is aligned with technical feasibility and certification requirements (European Commission, 2023). Such demand-side measures can stabilise markets and encourage investment in recycling infrastructure.

9.7.3 Limitations of the analysis

This report is based on a synthesis of existing literature and does not include new experimental data or original market surveys. Differences in methodological approaches across reviewed studies limit the comparability of quantitative findings, particularly with respect to acceptance levels and behavioural outcomes (Polyportis et al., 2022).

Furthermore, stated acceptance in surveys does not always translate into actual purchasing or adoption behaviour, especially in contexts where price, availability or institutional constraints intervene. The analysis therefore focuses on identifying structural patterns and conditions for acceptance rather than predicting specific market shares.

Finally, the rapidly evolving regulatory and technological landscape implies that some findings may require periodic reassessment as new standards, recycling technologies and market practices emerge.

9.8 Social Acceptance of Products Made from Recycled Carbon Fibres: Survey-Based Evidence – Buyer perspective

A dedicated survey was conducted among potential buyers and end users to assess acceptance of products made from recycled carbon fibres (rCF), including repaired and regenerated composite materials. The questionnaire addressed acceptance across selected application areas, perceived barriers and concerns, and the conditions required to build trust in such products. The survey collected responses from approximately 120 respondents representing key buyer groups, including consumers of sports and leisure products, users of transport-related products, customers of energy-related equipment, and professional users in technical and maintenance-oriented contexts. Results are reported as percentage distributions and ranges (without disclosing absolute sample sizes), in line with good scientific practice and to ensure comparability with the industry-oriented survey.

9.8.1 Acceptance across applications

The share of respondents indicating acceptance level is:

- Sports equipment (e.g. bicycle frames, rackets): approximately 79%
- Aircraft interior panels: approximately 77%
- Structural components of car seats: approximately 71%
- Segments of wind turbine blades: approximately 61%

These results show clearly higher acceptance for applications perceived as less critical in terms of direct safety risks, and more cautious attitudes towards structurally or safety-relevant components.

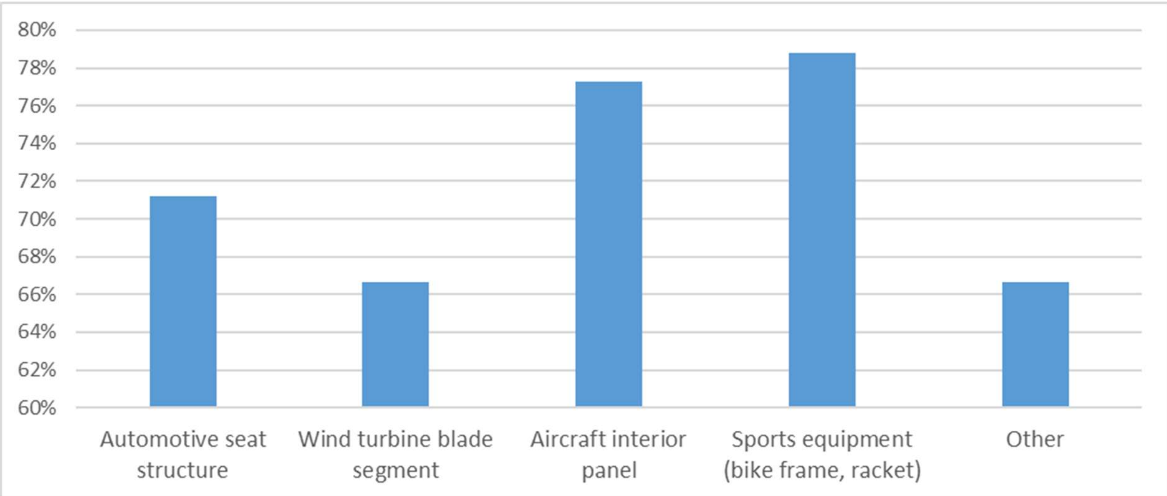

Figure 9.8.1.1. Relative acceptance of selected application areas for products made from recycled carbon fibres (rCF), based on survey results

9.8.2 Trust-building factors

The most important factors increasing trust in products made from rCF were identified as:

- Compliance with industry standards and regulations: rated as highly important by approximately 85–95% of respondents.

- Availability of test reports and quality assurance documentation: approximately 80–90%.
- Clear communication of environmental benefits (e.g. reduced carbon footprint): approximately 70–85%.
- Lower price compared to products made from virgin materials (without compromising quality): approximately 60–75%.
- This indicates that formal quality signals and verifiable evidence are more important than price alone in building buyer confidence.

9.8.3 Key concerns and barriers

Respondents indicated the following concerns as most significant (share rating each as high importance):

- Uncertainty regarding safety and performance: approximately 90–100%.
- Lack of guarantees and clearly defined standards: approximately 80%.
- Excessive price levels: approximately 70–82%.
- Insufficient transparency and information: approximately 73–80%.
- “Second-hand material” stigma: of relatively low importance (below 30%).

These results show that perceived risk and lack of formal assurances dominate over psychological stigma associated with recycled materials.

9.8.4 Results and interpretation

The survey indicates that acceptance of products manufactured from recycled carbon fibres is realistic and relatively high, but clearly conditional. Buyers do not reject the concept of secondary materials as such; instead, acceptance depends primarily on whether the final product meets expectations regarding safety, reliability, verified quality and predictable performance.

Acceptance increases as the perceived criticality of the application decreases. Consumer and semi-consumer products such as sports equipment reach the highest acceptance levels (~83%), while components associated with safety, liability or long-term responsibility (e.g. transport or energy infrastructure components) show lower acceptance levels (~58%). This pattern is consistent with established risk-perception mechanisms, where users evaluate products mainly through the lens of potential consequences of failure rather than environmental benefits alone.

9.8.5 Boundary conditions for acceptance

From an applied perspective, the results identify a minimum set of conditions for broad market acceptance of rCF-based products:

Standardisation and certification aligned with recognised norms.

- Performance evidence through test reports, durability data and environmental resistance assessments.

- Warranty schemes comparable to those for products made from virgin materials.
- Transparency and traceability, enabling understanding of material origin and processing routes.
- A clear value proposition, either through competitive pricing without undermining quality, or through documented environmental and functional benefits.

These conditions are particularly critical for applications with higher perceived risk.

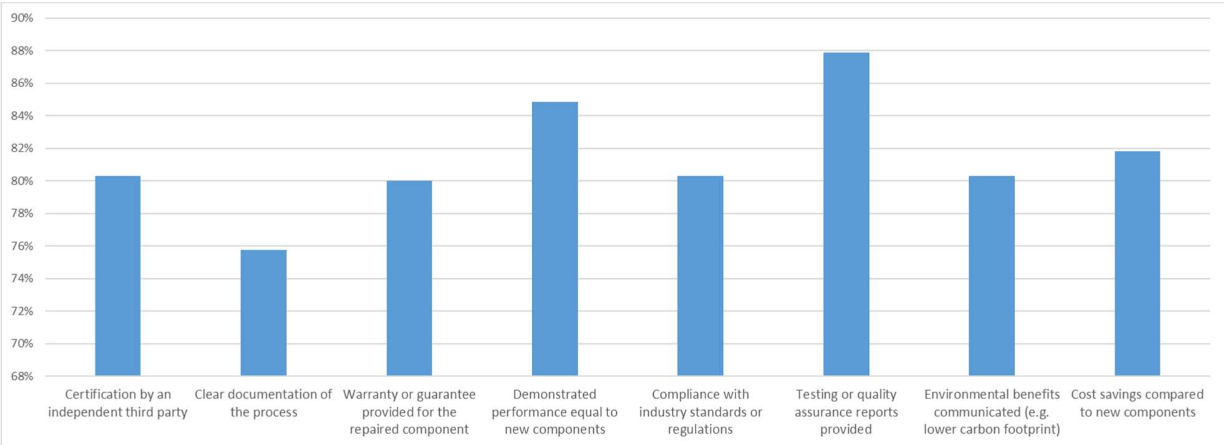

Figure 9.8.5.1. *Relative importance of trust-building factors for products made from recycled carbon fibres (rCF), based on survey results*

9.8.6 Key takeaways

Overall, the buyer survey demonstrates a high acceptance potential for products made from recycled carbon fibres, particularly in applications with lower perceived criticality. The principal barrier is perceived risk related to safety and reliability, not the use of secondary material itself. Acceptance increases substantially when standardisation, verified performance, transparency and warranty provisions are ensured.

Consequently, successful commercialisation of rCF-based products requires not only advances in recycling and repair technologies, but also the development of a comprehensive trust framework integrating quality assurance, traceability and evidence-based communication. Environmental benefits alone are insufficient to secure market uptake if concerns regarding safety and performance are not credibly addressed.

9.8.7 Implications for implementation and communication

The findings support a phased market-entry strategy, starting with high-acceptance segments (e.g. sports equipment or interior components) to build reputation and performance evidence, followed by medium-criticality applications supported by expanded quality documentation and traceability, and finally entry into highly regulated, safety-critical sectors once sufficient technological maturity and formal qualification have been achieved.

From a communication perspective, the results clearly indicate that emphasis should shift from abstract recycling narratives towards measurable indicators of quality, safety and reliability. Environmental benefits alone are not sufficient to offset safety concerns; they must be embedded in a broader trust infrastructure combining certification, testing, warranties and transparent information.

9.9 Social Acceptance of Products Made from Recycled Carbon Fibres:: Survey-Based Evidence – Industrial perspective

A dedicated survey was conducted among industry stakeholders to assess organisational acceptance of repaired composite products (rCP), including solutions based on recycled carbon fibres. The questionnaire covered perceived constraints, application suitability, willingness to adopt, motivating factors, and conditions for implementation. The survey collected responses from approximately 60 experts and decision-makers representing key industrial sectors, including automotive, aerospace, wind energy, rail and marine transport, construction, and composite manufacturing and engineering services. Results are reported as percentage ranges of responses, without disclosing absolute sample sizes, in line with good scientific practice and to ensure consistency with the consumer-oriented survey.

9.9.1 Key constraints and risk perception

The survey shows that technical and regulatory risks dominate industrial decision-making. The most frequently reported critical constraints are:

- Certification, standards and regulatory acceptance: major barrier for approximately 80–90% of respondents.
- Long-term durability and fatigue behaviour: critical for around 75–90%**.**
- Mechanical performance and consistency**:** strong constraint for approximately 70–85%**.**
- Supply chain stability and availability of rCP: moderate to strong constraint for about 60–75%**.**
- Cost-related uncertainty: secondary constraint for roughly 50–65**%**.

These results indicate that industry prioritises performance reliability and regulatory compliance over short-term cost advantages.

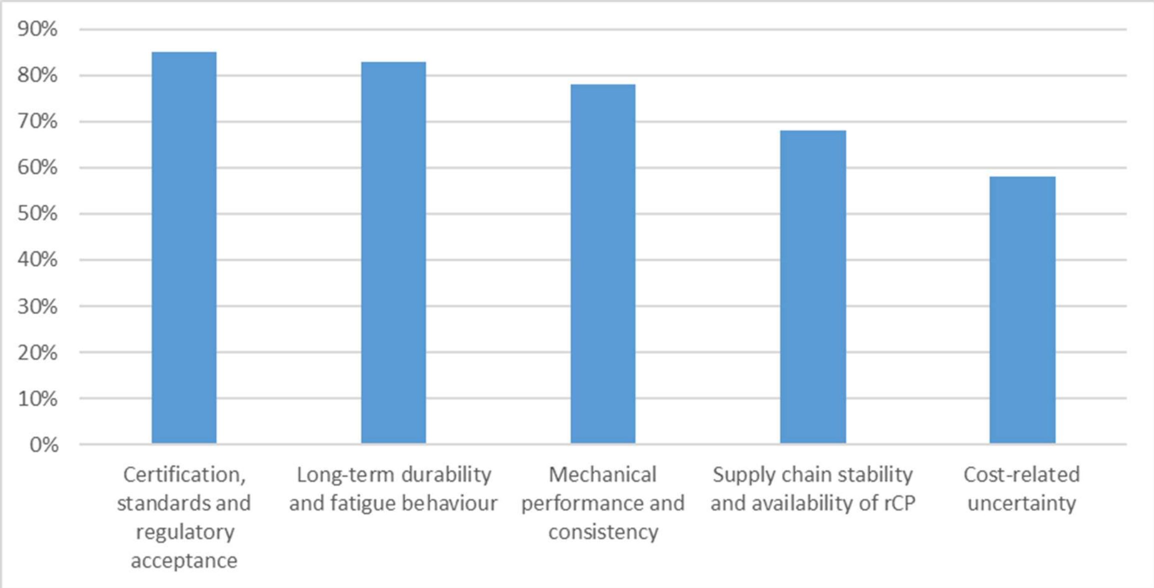

Figure 9.9.1.1. Relative importance of perceived barriers to the adoption of repaired composite products (rCP), based on industry survey results

9.9.2 Suitability of applications

Respondents assessed the suitability of rCP across application categories on a 1–7 scale. The share of respondents indicating high suitability (scores 5–7) is:

- Sports and leisure products: approximately 85–95%
- Non-structural components: approximately 80–90%
- Interior elements: approximately 75–85%
- Secondary aerospace components: approximately 50–65%
- Primary structural components: approximately 30–45%

This distribution shows a clear gradient driven by safety criticality and liability exposure: acceptance decreases as application criticality increases.

9.9.3 Willingness to adopt and to engage

Despite the identified constraints, a substantial share of respondents indicate openness to implementation:

- Organisations considering future use of rCP, provided conditions are met: approximately 65–80%.
- Organisations willing to participate in pilot projects, demonstrations or standardisation activities: approximately 60–75%.

This suggests that industry is not only a potential end user, but also a potential co-developer of rCP solutions.

9.9.4 Main drivers for adoption

The strongest motivating factors reported by respondents are:

- Reduced environmental footprint: strong motivator for approximately 80–90%.
- Improved access to materials and supply chain resilience: approximately 70–85%.
- Customer demand and green branding opportunities: approximately 65–80%.
- Regulatory pressure or incentives: significant for approximately 60–75%.
- Lower cost compared to virgin carbon fibre: moderate motivator for approximately 50–65%.

These figures show that strategic and environmental drivers are more important than pure cost reduction.

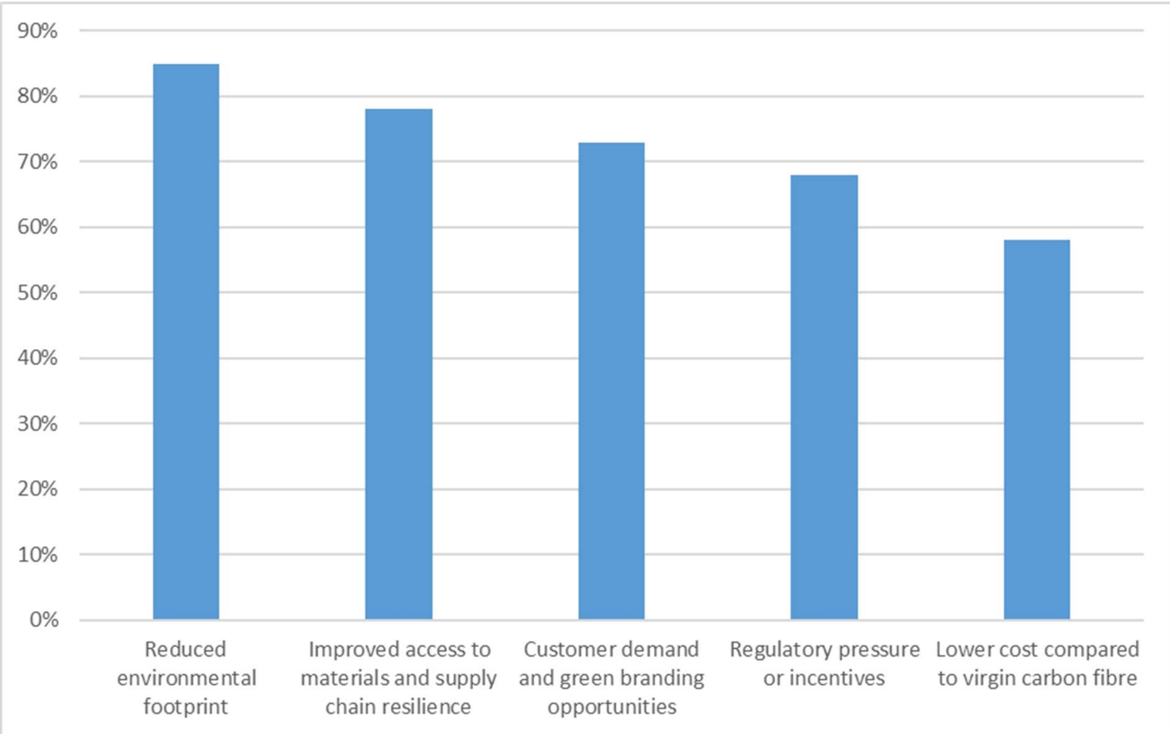

Figure 9.9.4.1. Relative importance of key motivating factors for the adoption of repaired composite products (rCP), based on industry survey results

9.9.5 Conditions for industrial acceptance

Across the sample, respondents consistently indicated that adoption of rCP would require:

- Verified and repeatable mechanical performance**,**
- Clearly defined standards, certification pathways and regulatory acceptance**,**
- Robust traceability systems covering material origin and repair processes**,**

- Availability of long-term durability and lifetime performance data**,**
- Demonstrated economic viability without compromising safety or quality**.**

9.9.6 Key takeaways

The industry stakeholder survey demonstrates that acceptance of repaired composite products is substantial but strongly conditional. While 65–80% of organisations are open to adoption in principle and 60–75% are willing to engage in pilots and standardisation, actual uptake is constrained by performance validation and regulatory requirements.

Acceptance varies strongly by application criticality, ranging from 85–95% high suitability in low-criticality products (e.g. sports and leisure goods) to only 30–45% in primary structural components. The dominant barriers are certification and regulatory acceptance (80–90%), long-term durability (75–90%), and performance consistency (70–85%), whereas cost plays a secondary role (50–65%).

The main drivers of adoption are strategic and environmental: reduced environmental footprint (80–90%) and improved supply chain resilience (70–85%) clearly outweigh pure cost considerations. This indicates that rCP is perceived primarily as a strategic sustainability solution rather than a low-cost substitute.

Overall, the results confirm a realistic pathway to market for repaired composite products, starting with low-criticality applications and progressing towards more demanding sectors as certification, standardisation, traceability and long-term performance evidence are established. Environmental benefits alone are insufficient to ensure industrial uptake; scalable adoption depends on embedding rCP within a robust technical and regulatory assurance framework.

9.10 Conclusions

In line with existing literature, the survey confirms a high potential for social acceptance of products made from recycled carbon fibres, especially in applications with lower perceived criticality. The principal barrier is not the use of secondary material itself, but perceived risk related to safety, reliability and long-term performance. Acceptance increases markedly when standardisation, verified quality, transparency and warranty provisions are ensured. Consequently, the successful commercialisation of rCF requires not only technological progress in recycling, but also the parallel development of a comprehensive trust framework supporting market confidence and informed purchasing decisions.

The analysis demonstrates that acceptance of recycled materials, recycled composites and recycled carbon fibre by producers and buyers is fundamentally conditional rather than absolute. Trust is shaped by perceived risk, responsibility allocation and the availability of credible mechanisms for quality assurance, certification and traceability (Reike et al., 2018; OECD, 2022).

For general recycled materials, acceptance is primarily constrained by quality variability, supply stability and regulatory clarity. In the case of composite materials, technical complexity and certification challenges further narrow the range of acceptable applications. Recycled carbon fibre represents the most sensitive category, where hierarchical acceptance patterns reflect the high performance demands and safety relevance of typical use cases (Pimenta and Pinho, 2011; Oliveux et al., 2015).

Across all material categories, environmental benefits alone are insufficient to ensure acceptance. Instead, successful uptake depends on aligning sustainability objectives with robust technical validation, application-specific framing and transparent governance structures. The findings suggest that the path towards wider use of recycled materials lies not in reducing performance expectations, but in building reliable trust infrastructures that enable informed, risk-aware decision-making by both producers and buyers.

10 Key Findings

Labour market and skills

- Scaling recycled carbon fibre (rCF) value chains from pilot to industrial level implies the creation of specialised jobs across recycling, materials processing, semi-product manufacturing and composite component production.
- Employment effects are concentrated in process operation, quality control, testing, certification, and traceability management functions, which require medium- and high-skilled technical profiles.
- The analysis indicates that skills availability, rather than technology readiness, will be a limiting factor for scaling, implying a need for targeted training aligned with industrial deployment scenarios.
- From an industrial policy perspective, rCF deployment shifts value creation from disposal to higher-value processing activities within the EU.

Monetised Climate Benefits of Carbon Fibre Recycling Pathways

- The highest monetised climate benefits are consistently delivered by T.4.1.2 (SUT) and T.4.1.1 (TUD).
- T.4.1.4 (UPAT) demonstrates moderate performance.
- T.4.1.3 (FRAU) shows substantially lower monetised benefits.
- The relative ranking remains stable across both carbon price scenarios (€80/t and €100/t CO_2) and under ±10% uncertainty assumptions**.**

This confirms structural performance differences between technologies rather than marginal variations.

Monetised Climate Value per kg of Recycled Carbon Fibre

Under EU ETS price assumptions:

- TUD: €5.8–7.3 per kg
- SUT: €5.6–7.0 per kg
- UPAT: €3.9–4.9 per kg
- FRAU: €0.95–1.18 per kg

  SUT and TUD generate approximately five to six times higher monetised benefits per kg than FRAU. The economic advantage directly reflects higher avoided-emission intensities relative to virgin carbon fibre production.

- Increasing the carbon price from €80/t to €100/t CO_2 results in an approximate 25% proportional increase in monetised benefits.
- Technologies with higher avoided-emission intensities benefit disproportionately in absolute terms under rising EU ETS prices.

- Higher carbon price trajectories significantly strengthen the investment case for high-performing recycling pathways.
- At a processing scale of 1,000 tonnes per year:
    - TUD: €5.8–7.3 million annually
    - SUT: €6.0–7.0 million annually
    - UPAT: €3.9–4.9 million annually
    - FRAU: €0.95–1.18 million annually

The performance gap between the highest- and lowest-performing pathways exceeds €6 million annually at identical scale, indicating major economic differentiation.

- With post-consumer CFRP waste increasing from 3,500 Mg (2010) to 43,750 Mg (2040):
    - Annual monetised climate benefits increase nearly linearly over time. By 2040:
        - TUD / SUT: ~€254–262 million/year (€80/t) / €300 million/year (€100/t)
        - UPAT: ~€171 million/year (€80/t) ~€213 million/year (€100/t)
        - FRAU: <€52 million/year even under the higher scenario
- High-performing pathways generate over €300 million annually by 2040, demonstrating macroeconomic relevance within the EU carbon pricing framework.
- The scaling effect significantly amplifies economic climate value over time.

EU Job Market and Workforce Implications

- The EU environmental goods and services sector (EGSS) employs approximately 4.5–5 million people.
- Circular carbon fibre recycling directly aligns with:
    - Waste management and recovery
    - Secondary raw materials processing
    - Environmental technology manufacturing
    - Industrial sustainability services
- The sector fits structurally within ongoing EU decarbonisation and industrial transition policies.
- Based on advanced recycling benchmarks:
    - ~10 direct jobs per 1,000 Mg processed annually
    - Total employment multiplier: ×2 (including indirect and induced effects)

This reflects the technologically intensive nature of carbon fibre recycling.

- Using projected post-consumer CFRP waste volumes:

  - 2030 (31,250 Mg): ~312 direct jobs/ ~624 total jobs
  - 2040 (43,750 Mg): ~438 direct jobs/ ~876 total jobs
- By 2040, EU-wide deployment could support approximately:
  - 440 direct high-skill industrial jobs
  - 850–900 total jobs including indirect effects
- With monetised climate benefits exceeding €300 million annually under leading pathways by 2040:
  - The sector demonstrates high economic value per employee.
  - Industrial deployment implies strong productivity and high value-added activity.
  - The economic case for investment strengthens in parallel with ETS price growth.

Environmental and economic performance

- Production of virgin carbon fibre is highly energy- and emission-intensive, while recycling routes deliver substantial savings in both energy use and CO_2 emissions per kilogram of fibre.
- When monetised using shadow pricing, the avoided emissions and material savings translate into a non-negligible societal value, which increases strongly with deployment scale.
- Scenario analysis shows that EU-level deployment yields several times higher total benefits than demonstration-scale implementation, confirming the importance of scale effects.
- Environmental performance therefore provides a strong economic rationale for circular carbon fibre systems, but does not by itself guarantee market uptake.

Material flows, volumes and substitution potential

- The EU currently imports approximately 13.1 kt/year of carbon fibre-related materials, while generating roughly 120–150 kt/year of CFRP waste.
- About 78 kt/year of this waste stream is technically recoverable as recycled carbon fibre, implying a potential rCF-to-import ratio of approximately 6:1.
- Substituting only around 17% of the technically recoverable rCF would be sufficient to offset 100% of current EU imports of carbon fibre.
- Even partial substitution therefore has a material strategic effect, reducing exposure to upstream supply risks related to PAN and acrylonitrile feedstocks.
- rCF is not a full replacement for aerospace-grade fibres, but is fully suitable for automotive, wind energy, construction, consumer and many industrial applications, enabling functional substitution at scale.

Value-chain impacts and strategic autonomy

- Current EU demand for carbon fibre is estimated at approximately 90–110 kt/year, while domestic primary production capacity is around 30–35 kt/year, implying an import dependency of roughly 65–75%.
- By 2030–2035, composite waste streams in the EU are expected to exceed 100 kt/year CF-equivalent, creating a stable secondary raw material base.
- Assuming realistic recovery rates of 50–60%, recycled carbon fibres could substitute approximately 20–30 kt/year of virgin fibre, corresponding to about 20–25% of current EU demand or roughly one third of net imports.
- This substitution potential is strategically comparable to opening new primary supply sources, but with significantly lower environmental and social costs.
- Multiple value-chain segments benefit, including waste management, recycling and processing, semi-product manufacturing, component production and strategic downstream sectors such as automotive, energy and transport.

Market and social acceptance and conditions for uptake

- Acceptance of rCF-based products is application-dependent and decreases with increasing safety criticality and regulatory exposure.
- For low-criticality applications such as sports and leisure products, acceptance reaches approximately 85–95%, while for non-structural and interior components it remains around 75–90%.
- For secondary aerospace components, acceptance drops to approximately 50–65%, and for primary structural components to around 30–45%.
- On the demand side, the main conditions for acceptance are compliance with standards and regulations (rated important by approximately 85–95%), availability of test reports and quality documentation (approximately 80–90%), and transparent performance evidence.
- The main barriers are uncertainty regarding safety and performance (approximately 90–100%), lack of guarantees and clearly defined standards (around 80%), and insufficient transparency (around 70–80%).
- Price effects are secondary: lower cost is considered important by approximately 50–65% of stakeholders, but cannot compensate for missing performance evidence or certification.
- Industrial uptake is therefore conditional upon the establishment of robust qualification frameworks, including standardisation, certification, traceability and warranty schemes comparable to those used for virgin-material products.

Overall synthesis

- The EU has a quantitatively significant secondary resource base for carbon fibres, with technically recoverable rCF volumes (~78 kt/year) far exceeding current import volumes (~13.1 kt/year).
- Even partial mobilisation of this resource can materially reduce import dependency and supply risk.

- The main constraints for large-scale deployment are not material availability or basic technical feasibility, but the speed at which quality assurance, certification, traceability and skills ecosystems can be established.
- Market acceptance is high in appropriate application segments but is strictly conditional on performance evidence and regulatory compliance.
- Recycled carbon fibre should therefore be positioned as a qualified engineering material embedded in robust technical and regulatory frameworks, not as a low-cost substitute for virgin fibres.

11 Conclusions

From a socio-economic perspective, the EURECOMP project addresses a structurally important mismatch in the European composites economy: the European Union currently imports approximately 13 kt/year of carbon fibre-based materials, while simultaneously generating more than 120 kt/year of CFRP waste, of which around 78 kt/year is technically recoverable as recycled carbon fibres. This imbalance demonstrates that material scarcity is not a physical constraint, but a systemic and organisational one. By developing, demonstrating and validating industrial routes for high-quality fibre recovery and reuse, EURECOMP directly targets this inefficiency and converts waste streams into a strategic secondary resource base.

The project's socio-economic value lies first in its contribution to material security and strategic autonomy. Even partial mobilisation of the recoverable rCF potential has the capacity to offset a substantial share of current imports. Substituting only around 17% of technically recoverable rCF would already be sufficient to replace 100% of current EU imports of carbon fibre. This makes EURECOMP highly relevant in the context of supply risk, price volatility and geopolitical exposure of upstream feedstocks such as PAN and acrylonitrile.

Second, EURECOMP generates value along multiple segments of the European value chain. It shifts economic activity from low-value disposal towards higher-value recycling, materials processing, semi-product manufacturing and component production. This supports industrial employment, creates demand for specialised technical skills, and strengthens EU-based industrial capabilities in recycling technologies, quality assurance, testing, certification and traceability systems.

Third, the project provides a quantified environmental-economic benefit. Recycling routes developed and assessed within EURECOMP deliver significant energy and CO_2 savings compared to virgin carbon fibre production. When monetised, these avoided impacts represent a non-negligible societal value, which increases strongly with scale and supports the economic rationale for EU-wide deployment of circular composite solutions.

Fourth, EURECOMP directly addresses the main market barrier to recycled carbon fibre: trust in performance, safety and reliability. The project's focus on process control, material characterisation, testing, qualification and application-specific validation responds precisely to the conditions under which both industrial users and buyers are willing to accept rCF-based products. Acceptance levels of 75–95% in low- and medium-criticality applications, and 50–65% in more demanding segments, show that the market is not closed, but conditional. EURECOMP provides the technical and organisational building blocks required to move from conditional acceptance to scalable market uptake.

Finally, from a policy perspective, EURECOMP operationalises key objectives of the EU Circular Economy Action Plan and the Critical Raw Materials framework by creating a credible, industrially anchored pathway for substituting imported primary raw materials with high-quality secondary resources. It demonstrates that recycled carbon fibre is not a niche waste-management option, but a strategic industrial material capable of strengthening competitiveness, resilience and sustainability of European manufacturing.

In summary, EURECOMP is socio-economically valuable because it simultaneously addresses material security, industrial competitiveness, employment and skills, environmental performance, and market acceptance barriers. By linking waste streams to strategic material supply through validated industrial solutions, the project provides a concrete and scalable model for how circular economy principles can be translated into measurable economic and societal benefits for the European Union.

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