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Discussion

Research and Development in Carbon Fibers and Advanced High-Performance Composites Supply Chain in Europe: A Roadmap for Challenges and the Industrial Uptake

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Abstract: Structural materials, typically based on metal, have been gradually substituted by high-performance composites based on carbon fibers, embedded in a polymer matrix, due to their potential to provide lighter, stronger, and more durable solutions. In the last decades, the composites industry has witnessed a sustained growth, especially due to diffusion of these materials in key markets, such as the construction, wind energy, aeronautics, and automobile sectors. Carbon fibers are, by far, the most widely used fiber in high-performance applications. This important technology has huge potential for the future and it is expected to have a significant impact in the manufacturing industry within Europe and, therefore, coordination and strategic roadmapping actions are required. To lead a further drive to develop the potential of composites into new sectors, it is important to establish strategic roadmapping actions, including the development of business and cost models, supply chains implementation, and development, suitability for high volume markets and addressing technology management. Europe already has a vibrant and competitive composites industry that is supported by several research centers, but for its positioning in a forefront position in this technology, further challenges are still required to be addressed.

Keywords: carbon; carbon fiber reinforced polymer composite (CFRP); circularity; composites; fibers; high performance; roadmap

1. Introduction

The potential of carbon fibers with regard to their thermomechanical properties is far from being exhausted in today's industry, since the highly complex mechanisms of structure formation in fiber production and the process parameter–structure–property relationships have so far only been investigated in the academic field [1]. With the targeted control of the properties from the molecular structure to the composite, completely new applications are conceivable in addition to the significant improvement of existing composite materials for lightweight applications. These include new crash-absorbing structures in automotive engineering [2], more efficient gas diffusion structures for fuel cells [3], adsorptive fibers for hydrogen high-pressure tanks, next-generation energy storage systems, cell-compatible fibers to replace nerve tracts in paraplegia, prosthetics with tailored properties to avoid stress shielding, and many more. In particular, low-cost carbon fibers (CFs) are particularly interesting as reinforcement structures for carbon concrete [4] or for wind turbine rotor blades [5], since ecological and financial aspects play a particularly important role in the CF quantities required there. However, basic research is needed to enable a large-scale application of multifunctional CF in resource-efficient intelligent construction methods.

This is precisely where new approaches come in, starting from the research and development of precursor materials and continuing to the spinning production processes, through targeted stabilization, carbonization, graphitization, and surface functionalization to conclude to the formation of the final composite materials [6]. This provides decisive insights along the entire process chain and the essential foundations for multifunctional materials and thus versatile constructions of the future with defined adjustable properties such as strength, stiffness, energy absorption capacity, ductility, and energy storage capacity as well as thermal and electrical conductivities with significantly improved resource efficiency.

The development of smart materials and intelligent structures with improved properties and functionalities will meet the current industrial challenges at the global level and the use of smart materials will allow improvements on the quality of life of society [7]. The development of components with damage sensing and self-healing properties generates products with higher benefit, lower maintenance, and increased security for the end-user, reducing the overall economic impact in this application. Weight reduction of structural components and consequent energy/fuel savings due to the use of lightweight carbon fiber reinforced polymer composite (CFRP) materials can be achieved through nanomodification. Moreover, the productivity and competitiveness of CFRP products will be enhanced with the nanomodification and contribute to its broader range of applications [8]. By this applied research and collaborations between academia and industry will be enhanced, so that the findings of each partner can serve as a basis that potentiates further innovations.

The European Commission (EC), according to the Paris Agreement [9], intends to reduce greenhouse gas emissions by 80% below 1990 levels in 2050 [10]. For that, the EC is strongly driving electrical systems to preferential positions, which in addition to the above-mentioned advantages show high efficiencies of energy conversion, low noise emission, high reliability, or low maintenance costs, among other benefices. However, the fact is that it is not only necessary to produce energy but also store it [11]. This challenge is becoming more critical nowadays due to the high and growing demand of energy created by the mobile electric technologies (portable electronics, ground and air vehicles, etc.), but also due to the necessity to support the closer future demands where massive electrification is expected in a fleet of air and ground vehicles.

There is an increasing drive to reduce greenhouse gas emissions and resource consumption arising from the manufacture and use of products across a wide range of industries. The current economy is seen as linear and inherently unsustainable, with a 'take–make–dispose' philosophy in which materials are extracted, manufactured into products, and discarded at the end of life. Composite materials are inherently difficult to recycle and often landfilled at the end of life. Recycling focuses on recovering fiber and discarded matrix phase, which is indeed at the last chain or the circle. The final step to consider for a full circularity is the repairing of CFRP structures during their operation and at the end of their life. The EC defines Agenda 2030 [10], which aims a circular and bioeconomy model aiming for sustainability by reducing waste and keeping resources at their highest value where possible (Figure 1).

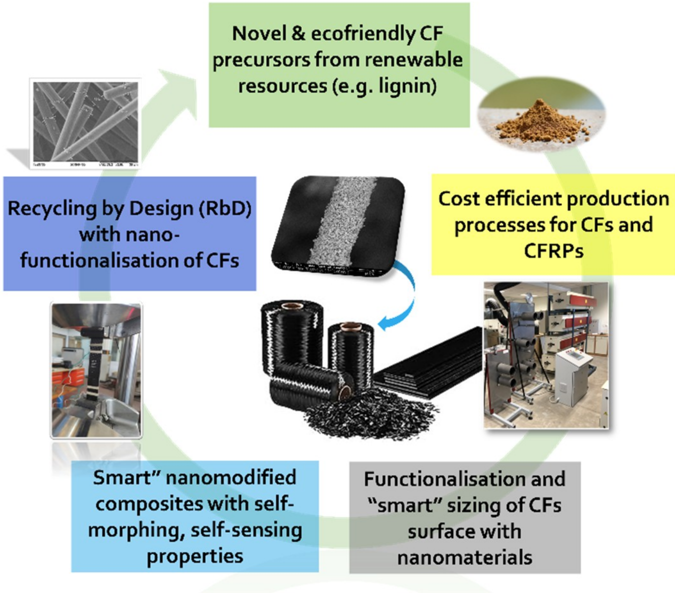

Figure 1. Composite material circular economy; from "green" fibers to nano-enhanced fibrous polymer composites.

2. Novel Materials and Optimized Processing

2.1. Carbon Fiber Conversion Technologies

Three different development directions have been identified for the carbon fiber conversion technologies:

- The improvement of carbon fiber properties by optimizing the carbon fiber conversion technologies;
- The generation of additional functionalities for carbon fibers;
- The reduction of energy consumption during the carbon fiber conversion while maintaining the CF properties.

More cost-effective CFs are particularly interesting for industries in which the use of carbon fibers is currently out of the question for economic or ecological reasons. For this reason, numerous recent studies have focused not only on the use of alternative, less expensive precursors instead of polyacrylonitrile (PAN) but also on reducing energy costs during CF conversion. In the field of furnace technology, recent work has shown that it is possible to reduce energy costs by up to 90% in some cases. In addition, alternative conversion technologies such as laser-, plasma-, or e-beam-based conversion are focused. With a profound comprehensive scientific penetration of the process steps of thermomechanical conversion or alternative conversion technologies for different precursors, in particular the currently enormously high-energy consumption and environmental pollution can be significantly reduced, and the process speeds increased. In this direction, the following challenges occur:

- Understanding the process parameter–structure–property relationships during thermomechanical conversion;
- Process influence on tailored CF properties for multifunctional applications;
- Mechanisms of crosslinking of precursor fibers within laser-, plasma-, and e-beam stabilization and their influence on the structural change during conversion to carbon fibers;
- Energy conditions for resource-efficient CF structure formation.

In order to overcome the aforementioned challenges, inter-laboratory comparisons of carbon fiber properties together with upscaling of existing academic carbon fiber lines and manufacturing of a significant amount of fibers to validate the potential of multifunctional fibers, need to be taken into account. By this, the growth of European fiber industries will be increased, since the product range and quality will be widened. This will help the initiation of completely new industries for CFs, with multifunctionality, that may lower also the environmental impact (from production to final use), deriving from more efficient products. The technological impact will offer a breakthrough of CF and CFRP in cost-sensitive sectors like wind energy or civil engineering.

2.2. Semi-Product Development and Supply Chain

Typically, the fibers are used in the form of semi-products, namely pre-impregnated (prepreg) sheets. A prepreg is the common term for a reinforcing fiber that has been pre-impregnated with a resin system that is in a partial curing stage. As a result, the prepreg is ready to layup without the addition of any other components. The reduced number of suppliers of specialty fibers and related semiproducts for high demand applications has, however, been pointed out as a major limitation for the competitiveness of European composites industry.

It is essential to create the ability to produce carbon fibers and carbon fiber semiproducts in Europe, enabling not only the space industry to have free access to these materials, but potentially boosting other sectors, that can benefit if lower costs would be attained. A larger supply network can increase materials' availability and more efficient manufacturing methods can reduce the price of specialty grade carbon fibers. This would contribute to improve Europe's worldwide competitiveness in the field of high-performance CFRP structures. Additionally, new semi-products types and forms are emerging, requiring also the capacity of having a sustainable value chain to make them accessible to the final composites' manufacturers. In fact, new reinforcement fabric structures, different material combinations and raw materials modification could be the route for boosting a successful European industry. For instance, preforms made by 3D weaving provide several important advantages in composite manufacturing, especially in fabricating thick composites, due to significant reduced timings, as one or only a few three-dimensional plies to conformable 2D fabrics are capable of replacing multiple layers of two-dimensional fabric plies [12].

From the point of view of prepreg properties, there is also a need for lower areal weight fabrics, enabling the possibility to further optimize mass savings based on the lay-up design. Increasing the range of prepreg semiproducts is also an interesting possibility; for instance, thermoplastic matrices are gaining interest, naturally a consequence of lower processing times required, recycling/reusing possibility, and longer shelf lives. The aerospace industry recognizes thermoplastic composites provide remarkable costs savings when produced at rates compared to traditional thermoset-based composites and advanced metals. These savings are especially significant on smaller parts, where final finishing work on parts formed from other materials can significantly increase per-part cost [13]. Carbon fiber manufacturers were required to update their portfolio, now offering the possibility to purchase fibers with thermoplastic-compatible sizing. Their conversion into semi-products and expansion of combination and products forms is also an important driver for future gains on composites performance.

Europe's worldwide competitiveness in the field of high-performance CFRPs is mainly connected to the carbon fiber-based semi-products manufacturing by European companies in European facilities, due to a low number of suppliers and limited R&D capacity. Moreover, alternatively, lower cost and more environmentally friendly carbon fiber precursors, new fiber structures such as preforms made by 3D weaving, exploiting different material combinations for enhanced properties, therefore increasing the range of commercially available semiproducts, are topics of interest for enhancing the European CFRP composites industry.

The challenges that appear in the field of composites semi-products are mainly related with the development of new semi-products, with the best performance to cost ratios and with lower environmental impact that can be quantified through life cycle analysis (LCA) of new material solutions. Additionally, new resin/fiber-matrix combinations need to be tested by manufacturing small demonstrators to validate the potential of new materials, in order to increase the range of semiproducts available and investigate new fiber/fabric architectures. By this, an increased technological readiness level (TRL) of novel semi-products for CFRP manufacturing can be achieved, by semi-products with high-performance materials (carbon fibers, polymeric matrices, and additional components, such as through the introduction of nanoparticles). Finally, the limited number of suppliers of carbon fiber semiproducts is another challenge that needs to be overcome, which can be achieved with the implementation of European industrial and R&D facilities.

These advancements, will give to Europe the ability to become independent in the manufacturing of semiproducts and thus, on CFRP products manufacturing, contributing to the growth of European composite industries, by increasing the semiproducts availability and product range. Access to new industry sectors will also be offered, if new material combinations are developed and commercialized. As for the environmental impacts, generally, the widespread use of carbon fiber-based composites as structural components leads to lower consumption (weight reduction of and consequent energy/fuel savings), consequently reducing CO/CO_2 emissions and representing lower fuel costs. Moreover, a lower environmental impact can be derived from more efficient products (from production to final use). Another hot point is the reduction of wastes, which can be achieved if thermoplastics replace thermosets, due to the potential of reusing/recycling possibilities.

2.3. Enhanced Process Throughput for High Volume Applications

Vehicle light-weighting is a particularly important approach due to the mass decompounding that might occur as reduced primary vehicle weight enables secondary mass reductions. Solutions to the high-volume manufacture of composite body structures without losing the skills and knowledge learned from steel production are highly needed. As may be agreed, 2015 marks the year that the material goes into serious high-volume production. The challenge with implementing carbon fiber composites is to make them cost effective for high volume production. Thus, the material must be modified so it can be robotically handled to avoid costly inefficiencies while utilizing existing processing equipment.

However, high volume production for the carbon fiber composite body structure in an automotive is not just a cost-effective production. The body structure interfaces with every other component on the car. There are still many cases that show the composite material structure being inferior to steel parts. For instance, when going into a composite solution one needs to think about how to recycle the really good stuff into something that is less good. One goes in with target costs' but the yield is not going to be 100% so one is going to have engineer scrap. On a current steel car, it has thirty different grades of steel. Every single part, or it seems like every single part, has been optimized for a particular grade of steel. The automotive body structure design has been evolving for the last 100 years and all of these really high-quality steel design manuals and steel processing design guidelines are impressive, really hard for composite materials to compete with.

The development of high-tech high-volume production of CFRP composite materials for the automotive industry needs the real composite expertise that can do exactly the same, or close enough to the automotive steel design manuals and the high strength steel application design guidelines. People working in the field of high-volume production for the carbon fiber composite body structure in an automotive have to understand how a car is designed and assembled today. The focus cannot be just on few pieces monocoque, consolidation of component, integration of components, or trying to build a vehicle that is one or two pieces. Due to the business target, a lot of budget is put into their own research department so to achieve the innovation or development at a much faster pace than academia orientated research. This will increase the difficulty to research high volume production of carbon fiber composite applications. Although the current high-volume application of CFRP composites focuses on the automotive industry, such application in other sectors, such as the aerospace and construction industry, should definitely not be excluded. In Table 1, the needs, research required, and the relevant impacts are listed.

Table 1. The needs, research required, and the relevant impacts for the enhanced process throughput for high volume applications.

The Needs	The Research Required	The Impacts
-Demonstration of a few production technologies for CFRP composite products corresponding to a production rate, such as 100,000–500,000 units/year or manufactured structure equivalent to 100–500 tonnes/year -Demonstration of an automated manufacturing process for a selected automotive and/or aircraft structural component with a production aforementioned -Identification and characterization of new composite materials with lower manufacture costs -Identification of appropriate manufacturing technologies for large load-bearing structural elements **Challenges** -Still high production costs including raw material cost especially carbon fibers, the current inadequacy for long automotive run lengths and limits in recycling techniques -Composites in cars have a low penetration rate because they are not significantly used in structural parts and their usage is limited to static load-resistant parts -Composites lack robust design and performance data and guidance, and thus more difficult to move through the design cycle compared to metal -Innovation-driven, highly dynamic, rapidly evolving manufacturing landscape in this area is difficult to codify, model, and simulate since the key players such as material and machinery developers and suppliers focus on their own business	-Great effort should be devoted to low-cost and bio-resourced carbon fiber and resin production -Development and optimization of design, forming simulation, and assembly: (1) Simplified tools are needed to reduce the lead time for design iteration; (2) Kinematic drape models are only suited to a first-order approximation and do not capture critical forming constraints. Finite element models incorporating contact demonstrate better correlation, but extensive validation is required; (3) Transition from welding processes to a combination of bonding and/or mechanical fasteners may be required. -Development and optimization of composite properties, producibility, CAE, material specs, and standards -Enhancement of recyclability and repairability of composite materials -Significantly reduce the composite manufacturing cost possibly by reducing raw materials especially carbon fiber cost and by reducing part production cost -Enhancing design and analysis of composite structures by developing the institutional culture and knowledge base and enhancing tool sets -Addressing life cycle factors by ensuing the life cycle value	**Societal Impact** -Increased number of business and industries that use lightweight solutions -Increased level of competence for the use of composites in different industrial sectors -Enhanced fuel use efficiency hence energy saving -Lowered greenhouse gas emissions **Technological Impact** -Increased skills of suppliers and networks in the field -Increased knowledge of rational composite manufacturing methods of lightweight parts -Increased speed of technology conversion regarding bio-resourced resin and carbon fibers -Improving automation of composite manufacturing -Improving processing and structural simulation **Economic Impact** -Lowered cost of resin and carbon fibers, especially those currently with high prices -Reduced energy consumption

2.4. Development of Structural Materials Driven by Enhanced Energy Management

One of the main restrictions in many engineering applications is the weight, especially sensitive when referred to air transportation. The high weight that current battery systems show is limiting its use with the major impact for instance in air vehicles. Normally, the energy storage systems consist of a large number of devices grouped and combined in one enclosure to facilitate the integration into the system or vehicle. The conventional approach is to minimize the mass of energy storage components through the optimization of individual subcomponents. Although mass savings are achieved following this way, there is not a drastic weight reduction and the own system continues contributing as additional weight in the final product without any other function and becoming structurally parasitic.

The disruptive concept of structural batteries, where a holistic approach is considered, and the structural and energy storage functions are treated as a whole, is gaining significant interest and catching the attention at many different sectors due to the multiple benefits that it could bring, particularly weight reduction and energy efficiency increase. The use of multifunctional materials performing two or more functions simultaneously would be the key to get it.

Currently, an exponentially growing tendency to replace metals by composite materials is observed in sectors such as air or ground transport. The reason for that lays in the high potential that composite materials have demonstrated regarding structural performance at a lower weight, when compared to metals, allowing to save mass in the overall product and consequently reducing the fuel consumption and, thus, the greenhouse gas emissions. For electrical vehicles, composite materials also expected to generate a very significant energy consumption reduction, through the overall weight reduction of the vehicle. In particular, CFRPs have become a mature technology that is gaining ground by the day. In addition to the structural performance role, carbon fiber can provide electrical characteristics that confer CFRP multifunctional properties allowing combining structural performance whilst storing electrical energy.

The field of structural power composites for structural energy storage seems to be promising and with a great potential to be explored in the near future. Development and characterization of multifunctional composite materials for structural energy storage applications is therefore required, while high integration or compatibility into existing systems as well as with associated manufacturing processes are highly recommended. Demonstration and testing in a relevant industrial environment should be carried on where possible; environmentally friendly production processes, possible second life applications, and materials that are easily available in Europe should be considered. To this way, several challenges occur, such as an increase of TRL of currently explored materials and greater gains in energy storage capacity using raw materials readily available and at affordable prices. Modeling at materials level is therefore required, to accelerate development process, while applied research should be performed using as reference existing target products and applications for their integration. This will result in the use of clean renewable energy, a reduction of greenhouse gas emission in order to reach established climate goals, improving in an indirect way the health of EU society. Low noise emissions shall be targeted, improving in an indirect way the health of EU society.

2.5. Nanomodification to Enable More Applications for Enhanced Mechanical Properties and Multifunctionalities

Nano-modification of polymeric matrices with different types of nanoparticles seems to be a promising route for developing CFRP composites with enhanced mechanical properties and multifunctionalities, since the incorporation of nano-reinforcements with different geometric shapes, features, and surface chemistry into polymers has demonstrated a huge potential to overcome mechanical robustness limitations, which are dominated by the brittle and insulate nature of thermosets especially through thickness direction [14–17].

Carbon nanotubes (CNTs), and more recently, graphite and its derivatives—graphene nanoplatelets (GnPs), graphene oxide (GO), and graphene (G)—have caught worldwide attention owing to their unusual properties [18–22]. A quick search on the Scopus database on August 2018 for the words "carbon nanotubes" (58,547 documents), "graphene" (102,573 documents), and combinations of CNTs with graphene (hybrid systems, 291 documents) shows a growing enthusiasm with the use of these nanomaterials (documents considered starting from 2015 to 2019). Several research work has been focused on the manufacturing of CFRP composites through the nano-modification of the polymeric matrix reveal that the properties imparted from these nano-reinforcements are severely restricted either by the dispersion level attained or by the interface established with the polymer [23,24]. The dispersion of carbon-based nanostructures is still a major challenge due to their tendency to form stable aggregates with strong cohesive strength, depending on particle morphology and surface chemistry [25,26] (Figure 2). The self-aggregation is promoted by intermolecular interactions, namely van der Waals forces, dipole–dipole interactions, or additional π-stacking between separated graphene layers [27]. Moreover, the chemical inertia of their surfaces hinders the formation of strong interfaces, restricting the load transfer ability from the matrix to the nanoreinforcements [28,29]. For those reasons, tailoring the surface of carbon-based nanostructures by either non-covalent or covalent strategies, as well as compatibilization with the polymeric matrix should be widely exploited in a view of extending the commercial interest and the range of properties that can be provided by introducing nanomaterials into CFRP products.

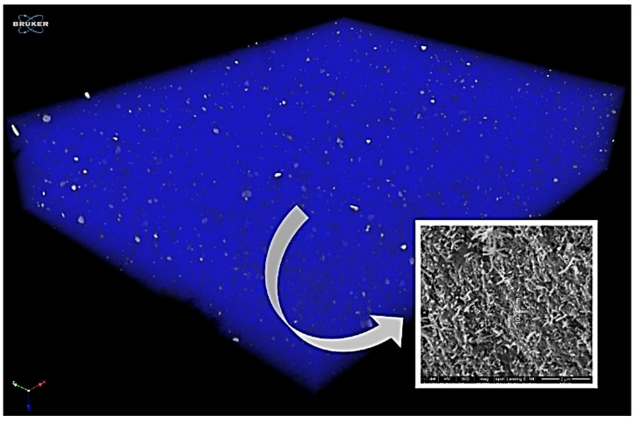

Figure 2. Micro-computed tomography image of carbon nanotube (CNT)-modified epoxy composite. The inset presents the CNT agglomerates.

Studies on this topic will allow the development of novel CFRPs composites, exhibiting enhanced mechanical performance and multifunctionality. Combinations of nanoparticles with different geometric shapes and tailored surfaces should be designed with specific functionalities, depending on the target applications of the final material. The inclusion of nanomaterials to provide smart materials for health monitoring and damage sensing of CFRP composites should also be developed.

The following challenges occur:

- Issues related to the poor dispersion and re-agglomeration phenomena of carbon-based nanostructures;
- Processability difficulties associated with a dramatic increase of the shear viscosity due to the incorporation of the nanostructures within polymeric matrices;
- Formation of weak interfaces between the nano-reinforcements and the matrix;
- Difficulties in transferring the remarkable properties of nanomaterials from the nanocomposite (nano-modified matrix) to composite level.

To improve the interfacial bonding established between nanomaterials and the matrix, novel routes that allow the incorporation of chemical functional groups with higher affinity to the matrix should be investigated, in comparison with the existing ones (Figure 3). Comparative studies between different types of nanostructures, including carbon-based, CNTs and GnPs, and other materials should be also carried out. This research should contemplate the evaluation of the mechanical, thermal, and electrical properties at the nanocomposite and composite level, aiming at selecting the most suitable formulations for the target applications. Novel matrix-oriented dispersion and nano-structuration strategies should be additionally investigated. The same principle can be applied in the covalent modification of nanoparticles. Research on this topic will comprise the development and implementation of synthetic routes to obtain the desired functionalized nanoparticles through covalent and non-covalent approaches. Cost–benefit analysis should be performed finally between the different possibilities considering the balance between performance gains with the materials availability and cost, as well as industrial implementation feasibility and cost.

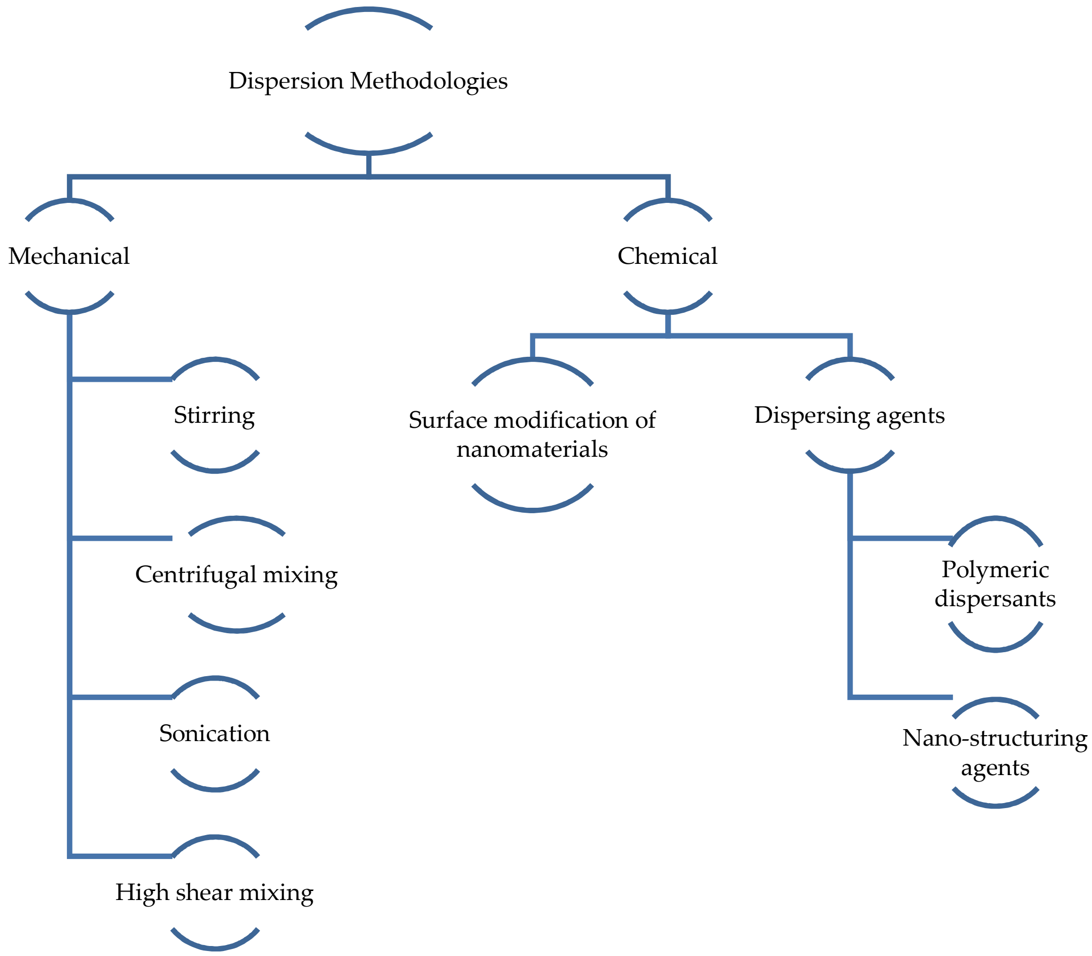

Figure 3. Methodologies to improve the dispersion or exfoliation of nanostructures into polymeric matrices.

2.6. Additive Manufacturing of CFRPs

By combining innovative 3D printing technologies with CFRPs, a wide range of opportunities for lightweight design and manufacturing of bioinspired components can be achieved [30,31]. Fused filament fabrication (FFF), an extrusion-based additive manufacturing (AM) technology, is widely used for the production of thermoplastic components because of its reliability, cost-effectiveness, dimensional stability, wide material customization, and simple fabrication process. In this context, one of the main goals is to advance FFF technology towards an alternative manufacturing method to support continuous CFs reinforcement of 3D printed structures [32]. This approach deploys the inherent advantages of the two technologies, in order to obtain competitive structural CFRPs for high performance and reliability applications [32], at even lower production costs, in a digital environment that allows design flexibility, in accordance with the requirements of a more and more dynamic market.

The state of the art of the FFF technology is based on the utilization of thermoplastics to produce the final product, while discontinuous micro-fillers are also added to improve the properties and performances of the 3D printed components. These approaches are not applicable for functional parts production and the components are mainly used as prototypes or conceptual models. In this respect, modification of FFF systems aims to the production of continuous CFRP composites. The research into methods of obtaining CFRP components through a 3D printing process is only at its beginning, featuring a low degree of know-how and technological maturity. The advantages of this approach will enable the application of this new manufacturing process to the market and to industrial implementation, by ensuring that the final 3D printed parts will present the needed level of performance [33,34]. Current research initiatives on the reinforcement of thermoplastic polymers by 3D printing of continuous CFs (Figure 4), targeting at enhanced properties and performances of the final 3D printed smart materials, are of high interest and rapid development especially in the USA, followed by Japan and China. The engagement of countries with high economic power, in these research activities, strongly suggests the potential of the new method and its innovative products.

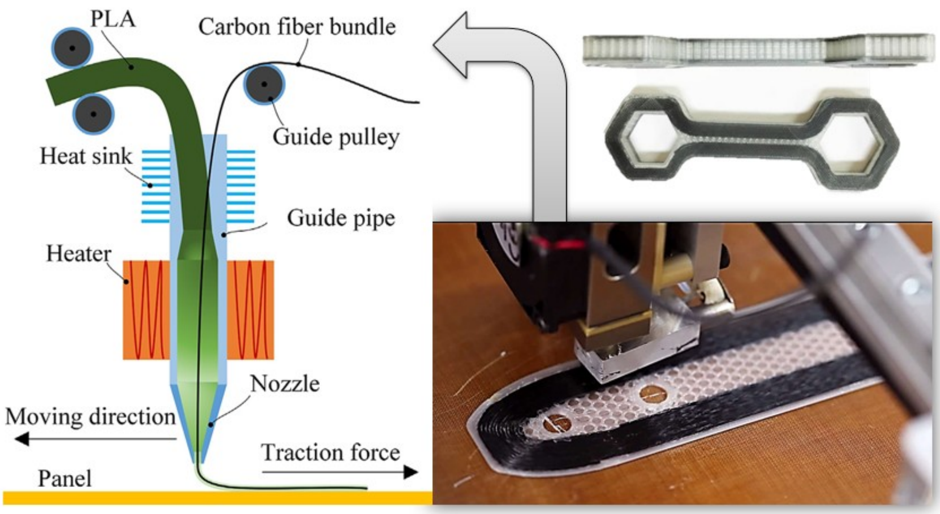

Figure 4. Continuous carbon fiber (CF) additive manufacturing for carbon fiber reinforced polymer composites (CFRPs) fabrication.

Additionally, the development of new sets of performant materials, along with the maturation of FFF-based 3D printing of continuous CFRP can pave the way towards the standard next-generation fabrication methodology of freeform composite components [35,36]. Competitive advantages of this manufacturing process involve high performance lightweight design with increased flexibility, cost-efficiency at low production rates, integration of the digital environment for design and manufacturing, and energy efficient production lines [37]. The expected economic impact arises from the inherent advantages of the digital AM, in terms of cheaper and more flexible production; easiness to adopt rapid changes in design according to market dynamics; low production rates while maintaining competitive costs; complete transformation of the production chain; advanced human-machine interaction [38]; reduced auxiliary systems and facilities needed for manufacturing, which in turn will translate into a positive impact on resources usage and environmental protection; reduced fuel consumption and NOx emissions due to improved lightweight characteristics of the material, which will also have a positive environment impact. Moreover, existing polymer-based 3D printing technologies are not applicable for functional parts production, hence innovative feedstock materials (specialty filaments, e.g., nanoenhanced) will enhance product performance and reliability.

2.7. High Performance REACH Compliant Matrices for Nanocomposites

Compliance with REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals) has an extremely significant influence on fiber reinforced polymer (FRP) composite and the related industry, since all components in FRP at different geometrical scales, including raw materials and chemicals for synthesis of these components as well as additives such as flame-retardant agents, will need to meet the REACH regulation. Polymer manufactures will have great obligation of withdrawing conventionally used chemicals for the base resin, hardener, and catalyst, which are not compliant with REACH, and more important, find suitable substitutes that have the same or better effect. Finding substitutes already means innovating.

Integration with nanomaterials is an efficient way for preparing high-performance or even multi-functional polymer matrices. This, however, will increase the challenge for the high-performance polymer matrices being compliant with REACH since there are already a lot of heated debate on nanomaterials regarding their significant influence on health, safety, and environment, not only related to the materials themselves, but also the process to produce, use, and recycle them and related materials.

The awareness of REACH compliance of polymers and nano-modified polymers from CFRP composites producers, manufacturers, and users including academia is not sufficient, which will certainly prevent the development, production, and commercialization of high-performance REACH compliant matrices for CFRP composites. Thus, polymer manufacturers who provide REACH compliant matrices and start using them in CFRP composites to facilitate the evaluation of the quality of the matrices, followed by the documentation of results with comparison to the composites using polymer matrices that are not compliant with REACH and are or will be banished from market need to be identified. The dependence of certain or specific products, for instance, in the aerospace and aircraft industry, on polymers that do not meet the REACH regulation, is very high, so the substitution process will take a very long time although it can eventually happen. However, comparable properties of CFRP composites will not be endued by using the polymers substituting those polymers or components such as the hardener and catalyst, which do not meet the REACH regulation. The compliance with the REACH regulation will reduce the cost from health damage of workers (less incidence of occupational diseases) and improve their well-being, preventing business risks, leading a better corporate reputation, while reducing risks/exposures of the general public. The better conditions will lead to positive incentives for innovation and more efficient chemicals risk communication.

To conclude, after closer ties with engineering, design, and manufacturing functions, REACH should provide one regulation for all (research groups/organizations/departments and companies), enabling this way the reduction of risk to the environment from substances of very high concern (SVHC) and helping the market uptake of the nanomodified CFRPs.

2.8. Occupational Health and Safety Practices in Composites Manufacturing Industry

Issues of occupational health and safety are inherent in the composites manufacturing industry due to the complexity of the production process, which combines mechanical, thermal, and chemical sub-processes, which is a reality for every industrial process. The society of plastics industry provides general guidelines for the safe handling and processing of epoxy resin systems [39]. An emerging risk according to the European Agency for Safety and Health at Work [40] is related to the use of nanomaterials in advanced polymer composites (e.g., carbon nanotubes, carbon nanofibers in polymer matrices, and nano-TiO_2 coatings in engineering polymers [41–43]). Workplace exposure to nanomaterials may occur in areas where nanomaterials are produced, handled, and processed or those where nano-enabled products are used by professionals [42–46], for example:

- Handling dry colloidal deposits and unprocessed nanoparticle powders;
- Spraying from engineering nanoparticle suspensions, solutions, and slurries (i.e., thermal spraying);
- Dry blending of manufactured nanomaterials (MNMs) into a matrix (e.g., polymer);

- Processing solid matrixes containing MNMs e.g., weave, knit, twist, cut, grind, and scrape;
- Cutting/grinding a matrix containing MNMs.

There is evidence from in vitro and in vivo toxicological studies that exposure to nanomaterials may cause various adverse health effects (genotoxicity, carcinogenicity, pulmonary effects, oxidative stress, and possibly mesothelioma) depending on their physicochemical characteristics such as morphology, surface chemistry, impurity content, bio-solubility, rigidity, and de-aggregation status [47]. The main concern is exposure to nanoparticles through the inhalation route, but skin penetration and ingestion are not less important. A risk management approach to the exposure of nanoparticles comprises the following elements: (i) Primary prevention—first priority, and(ii) classic principles of "hierarchy of control apply": Engineering control (enclosure, local, and general exhaust ventilation—care for design, use, and maintenance), efficacy of filtration medium regarding penetration of nanoparticles through the filtering material, respiratory protection, and protective clothing (air-tight non-woven textile) [46–49].

It is worth mentioning that studies in the bibliography indicate that enterprises with the best occupational safety and health practices are the most productive and the most economic, social, and environmentally friendly businesses [50]. Furthermore, the lack of occupational health and safety not only increases the company's costs, including medical expenses, operational costs, and compensations to society and individuals, but also destroys its business reputation and decreases its market shares [51].

Specific actions need to be taken, such as: Data curation of the existing scientific literature to identify the missing gaps that need to be filled in with experimental studies. New innovation projects initiation to study the replacement of some alternative materials to thermoset resins can be studied: A high temperature polymer such as polyaryletherketone (PAEK), polyethylenimine (PEI), or polyphenylene sulfide (PPS) and also new grades of liquid acrylic-based resins with implementation of safe by design principles. Research initiations could be for toxicological studies on carbon fibers modified by nanomaterials along with improvement of in vivo and in vitro studies.

In addition, regarding the implementation of nanomaterials in advanced composites, these paths of research activities may be applied:

- Validation of the in vitro methods and methods to determine physico-chemical properties as tools to determine health effects;
- Identification of the nanomaterials in the working place and description of exposure;
- Measurement (proper instrumentation) of exposures of nanomaterials and efficacy of protective measures.

Implementation of directions for the improvement of occupational health and safety conditions in the composites manufacturing industry requires a sufficiently broad perspective from the beginning in order to understand economic and technical feasibility, estimate life cycle environmental implications of processes and products, and minimize unanticipated negative impacts, thus societal benefit is being under consideration. Consequently, the occupational safety and health practices and their improvement directly addresses the employees in the composites manufacturing industry, while indirectly affecting society, technology, innovation, culture, economy, politics, and environment in the long term, proportionally to the applicability domain of composites.

3. Characterization and Modeling: From Experiment to Simulation and Vice Versa

3.1. Advanced Characterization Techniques, Including Standardization and Data

Composite material models can only be used for structural design if all material parameters can be experimentally determined and secured [52–54]. A distinction is made between parameter identification (for model calibration) and model validation (proof of prognostic capability). Due to the complex nature of composites, usually different direct and indirect measuring methods must be combined. The first integral part that has to be undertaken is multi-axial strength testing. In the recent past, statistical aspects of the strength analysis have been in the focus using a sensitivity analysis to reduce experimental uncertainties. Fracture tests have to be combined with experimental technologies to study the damage and failure phenomenology like micrograph analysis, crack density measurements, acoustic emission, ultrasonics, thermography, nanoindentation mapping, computed tomography, or even in situ computer tomography [55–57].

To validate non-linear, viscoelastic, or viscoplastic material behavior, adapted concepts are required that are able to quantify the different relevant phenomena like stiffness degradation, strength degradation, strain rate dependency, temperature dependency, and inelasticity. Experimental procedures with simultaneous and sequential load increase are proposed for that purpose in several studies. The quantification of strain rate dependent behavior is only possible with special test equipment. For different strain rate areas, servo-hydraulic high-speed test machines and Split-Hopkinson devices were developed. Delamination testing is of special interest as well, whereby devices to determine delamination initiation and delamination progress are distinguished. The validation of models for cyclic loading is even more complex since the fatigue behavior depends on the load type, the load sequence, the amplitude, the degree of multi-axiality, and many more effects. The existing experimental concepts are based on tube specimen testing and crack density measurements [58,59].

However, experimental composite characterization is still a very challenging research field and several problems remain unsolved. Statistical verified data for several materials must be generated (design-of-experiment) since many results are only available at academic institutions. Moreover, experimental techniques must currently consider more and more material uncertainties resulting from manufacturing process deviations. In this context, big data and virtual twin approaches are very promising [60,61]. This process should end in a unified European standardization of characterization techniques.

Suitable and reliable characterization methods for complex materials (textile composites) or complex loading scenarios (high cycle fatigue and low cycle fatigue, in-plane and out-of-plane vibration, and crash and impact) are still not available, especially on the structural level [62,63]. A particular boost with respect to increasing the engineering efficiency (lower cost to market) is expected by standardized advanced composite characterization methods and an increase of available material data. In this context, the aerospace industry, the automotive sector, and the wind energy industry are considered as growth drivers. Structures with a higher damage tolerance and an improvement of structural health monitoring (SHM) technologies may also be expected. The following challenges occur:

- Optimum composite data generation, storage, and dissemination processes (design data, manufacturing data, operation condition data, and diagnostic data);
- European standardization of composite testing methods;
- Development of novel characterization methods (e.g., in situ test methods) for complex materials and complex load scenarios.

In order to overcome the aforementioned challenges, strong linkage between academic and industrial tests houses with industry is necessary. At this scene, a European standardization network can be implemented, which can establish novel test methods, data-case characterization (virtual twins), and increase the availability of test data for Small Medium Enterprises (SMEs). By this, the application spectrum for CFs and CFRPs will be widened, due to reduced testing costs, and the development time will be shortened, due to the increased availability of material data and standardized procedures [64–66].

3.2. Multiscale, Multiphysics, High-Performance Computational Tools for Advanced Composites

As composite materials are complex systems in terms of structure and interactions (functional behavior) between different phases it is critical the understanding of the physics/chemistry involved in the problem [67]. The identification of material parameters is often a challenge and the development of comprehensive theoretical and mathematical treatment of the phenomena difficult to achieve, since the governing and constitutive equations need to be approximated with soundness and consistency.

Moreover, the representation of composite structures needs configurations with plenty of interaction sites and adequate computing resources, because of their complexity. In order to deal with multi-scale approaches (from atomistic scale to continuum) common assumptions should be developed used from all stakeholders. Approximations for strongly coupled scales, homogenization strategies, and heterogeneous multiscale techniques are also important. Especially for the case of composites of major importance, for the representation and the properties of interfaces, a common understanding is needed [68]. One of the most important issues regarding modeling and characterization of composite materials is the correlation between numerical and experimental procedures to determine the corresponding material parameters. For this, repositories of experimental data for validation of the model seem essential. Open access repositories for modeling data related to composite materials should also be established. Finally, for predictive modeling tools the investigation and adoption of appropriate descriptors dealing with materials properties is necessary [69].

The impact of materials modeling on the industrial sector relates to a number of aspects. The increased cost of developing a 21st century product, with all its specifications, requires a clever and targeted design procedure where a performance-based (back-engineering) functionality of the product is guaranteed. Here material modeling is an essential component, being already part of many business processes; yet, it can become a more crucial part if the economic advantage for the end-user is made clearer. The majority of managers (in SMEs) are not aware of the importance of proper modeling assisted materials selection and sourcing procedures and the improvements that can be achieved with respect to quality and functionality on one side and the costs on the other. Increased awareness of the modeling potential here, as well as of training opportunities and the availability of a materials modeling market place, will be important. Material modeling can help minimize expenses and time needed in achieving a functional and marketable end product, since virtual integration of processes will reduce costs. At this point, it is crucial to increase the modeling impact in the framework of Industry 4.0, and to develop process-to-end-user (material performance) workflows and toolsets. Virtual factory models would revolutionize manufacturing. This requires levels of IT expertise much beyond that of traditional modelers; partnerships are vital here for the upscaling of materials models to include databases towards the development of business decision making software tools.

Data science and machine learning ease the efficient mining and potential for further processing of large material data sets, resulting in the extraction and identification of high-value material knowledge, towards design, quality, and manufacturing. This is accomplished by using linkages of process–structure–property (PSP) information, with the main focus of data transformations to be in the forward direction, as depicted in Figure 5.

Figure 5. Process–structure–property (PSP) information flow.

As therefore high-value information requires to be linked with the manufacturing and product design routes, the main challenge is, starting from a proper data management plan, to design and build the needed databases stems (tackling challenging issues such as rich internal materials structures that span multiple length scales) [70]. Data science foresight in materials' advanced characterization mitigates the inherent risk to a large extent, not only by making decisions more concrete (e.g., in design and manufacturing), but also by capturing failures and successes; information from this is then useful and processable to and from other disciplines. For an effective mitigation plan based on data management is strongly based on the availability of data and the use of data-driven protocols, as the uncertainty associated with the information and knowledge used in making decisions (in materials development workflows) is then quantifiable [71,72].

Within this approach a complete automation of data capturing [73], data storing, modeling, and optimizing is achieved. Major penalties will be tackled, arising from the lack of predictive modeling and the uncertainty associated with current design and manufacturing methods in composites, impacting on production cost and the environmental footprint. This will overcome over-conservatism in design, resulting in low operational costs and greenhouse-gas emissions; it will also meet manufacturing quality requirements associated with 'defect-free' part production policies [70].

3.3. Hybrid Reinforced Composites and Multiscale Simulation

Hybrid reinforced composites and multiscale simulation: Virtual testing (e.g., mechanical behavior) of composite materials and structures is now emerging [74]. There is still room for improvement for instance in the multiscale modeling, however the feasibility to carry out high-fidelity tests of composite coupons and small components subjected to very different loading conditions, exists already. Future developments and challenges in the area of multiscale modeling of FRP are likely to be found in hybrid form (hybrid composites), with the incorporation of multifunctional properties and processing in the simulation strategy. As further use of FRP is hindered due to their limitations in other physical properties (properties provided by matrix, such as thermal and electrical conductivity, fire resistance, moisture absorption, permeability, etc.); this is overcome by the addition of nanosize fillers such as clays, carbon nanotubes, and nanofibers as well as graphene; through this, properties controlled by the matrix are added [75–81]. A new challenge therefore occurs: The incorporation of the functional properties in the multiscale simulation strategy [82]. From the nanometer scale, functional (and mechanical) properties of polymers can be computed by means of molecular dynamics (MD) simulations (e.g., matrix-reinforcement interfacial properties), where extension to larger volumes and longer times is assessed by coarse-graining Monte Carlo methods [83–85].

The next steps in the multiscale simulation of functional properties should benefit from the separation of length scales between individual plies, laminates, and components and follow the scheme developed to compute the structural properties [86]. Accurate prediction of the macroscopic properties also needs precise information about processing; apart from, for instance, voids and thermal residual stresses generated during matrix infiltration and curing to manufacture the component, the curing degree and/or molecular arrangement, as well as the interface energies associated with the presence of nanoparticles are also of major importance [87]. When rheological properties of the hybrid composite are known, it is possible to simulate the manufacturing routes of a component, namely consolidation of resin pre-impregnated plies (or a stack of commingled fabrics made from thermoplastic and reinforcing fibers) under the combined action of pressure and heat, and infiltration of a low-viscosity resin into a mold containing the stack of fiber fabrics (additionally, mold filling, resin flow through the stack of fiber fabrics as well as within each fiber bundle, generation and transfer of heat due to the chemical reactions, generated during curing, and the effect of the consolidation pressure, are considered). The challenge in developing an integrated design strategy for composites, involves design, test, and optimization in silico before they are actually manufactured.

4. Environmental and Economical Circularity

4.1. The European CFs and Advanced Composites Industry Today and Tomorrow

Due to excellent performance, the market demand for CFs strong and a high annual growth rate of around 10% is anticipated until 2020 [88,89]. The global CF demand amounted more than 70,000 tons in the last five years. Specifically, the demand from automotive lightweight grew faster, which attracted many companies to get involved in this field. SGL (Wiesbaden, Germany) and BMW (Munich, Germany) cooperated to make use of CF materials. Toyota used also Toray's CFs for Mirai fuel cell vehicles. Recently the global carbon fiber capacity totaled approximately 130,000 tons, mainly contributed by Japan, Europe, and the U.S. The predominant production companies are Toray, Teijin, Mitsubishi Rayon, Germany SGL, and Formosa Plastics, which share together 60% of the global carbon fiber capacity, as it can be seen in the following pie chart (Figure 6) [89,90].

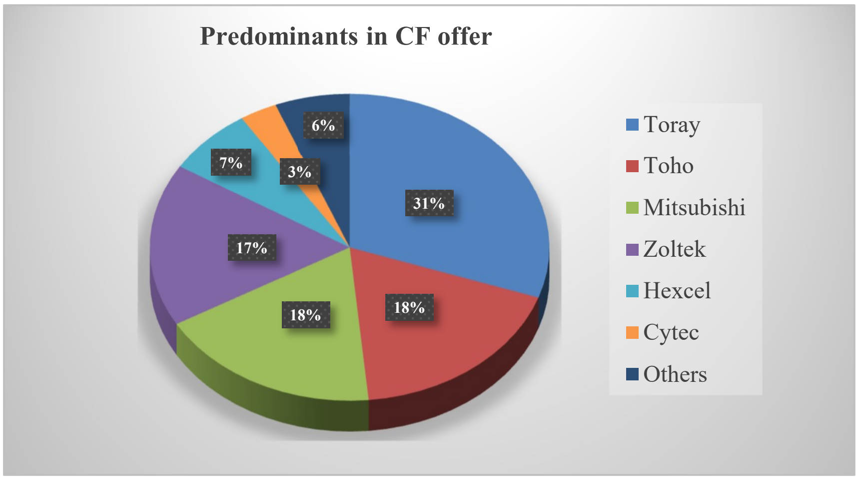

Figure 6. CF manufacturers worldwide.

The global carbon fiber market size, in terms of value, is projected to reach USD 3.51 billion by 2020, at a compound annual growth rate (CAGR) of 9.1% between 2015 and 2020. The global CFRP market is projected to reach USD 35.75 billion by 2020, at a CAGR of 12.07% between the period 2019–2024 [91]. This growth is fueled by the increasing production capacities of Boeing and Airbus, a rising demand of fuel-efficient vehicles, and growing application of CFRP in other application sectors such as constructions, rehabilitation, sporting goods, civil engineering, and wind energy globally [92].

According the aforementioned demands needs of economical circularity arise. This can be achieved both with the investigation of new precursors, as well as with sustainable recycling and cost-effective repairing. The following SWOT analysis (Table 2) summarizes opportunities that arise on the field, possible threats, and the major points of attention.

Table 2. SWOT analysis [93].

Strengths	**Weaknesses**
Good level of fundamental understanding and academic research Innovative manufacturing processes Wide-ranging of materials that can be used in many applications Good capability in specific areas (e.g., sports and leisure crafts) SMEs with flexible approaches	Shortage of trained staff and skilled engineers Limited knowledge of composites Shortage of design guides and design data Industry fragmented and lagging behind USA Low margins for composite industries Little applied R&D for composite industries Unstable primary material supply and costs Few suppliers and much raw material needed Small companies cannot influence specifiers Not defined/clear recycling routes for composites EU higher labor costs than foreign competitors
Opportunities	**Threats**
New markets in infrastructure, air and rail transport, offshore, lightweight products, and renewable energy Use of composites in new applications due to environmental regulations Stronger company/university links and the transfer of knowledge from academia to overcome some of the industry's problems Use of natural fibers Use of low-cost carbon materials Use of new processes and new materials	Low cost imports from cheaper countries Lack of design guidance and standard Environmental legislation and other regulations The lack of a clear recycling route, especially for thermosets Reduced research and development funding for new ideas and consequent technical stagnation Overselling of composites and the risk of high-profile failures The development of competitive technologies, such as titanium and high-strength steel

4.2. Alternative Precursors—Critical Non-Dependence

As a result of the foreseeable shortage of oil, sustainable alternatives to PAN to produce carbon fibers based on renewable raw materials are increasingly becoming the focus of scientific interest. The biopolymers lignin and cellulose, which have so far been little used in fiber form, have the highest potential in this context [94]. The research community has focused the last years on the exploitation of lignin and several European projects have already investigated alternative CF precursors from lignin (Figure 7).

Figure 7. Use of alternative precursors for CFs with different scientific prioritization: (i) Functionalized tailored CFs based on textile-grade polyacrylonitrile (PAN), polyolefins, and lignins [95]; (ii) CFs based on polyethylene for cost efficiency [96]; (iii) cost efficient CFs based on cellulose and lignin [97]; (iv) reduction of energy and greenhouse gases in the CF manufacturing process by using the LignoBoost technology [98,99]; and (v) biobased composites based on lignin precursors and biopolymers [100,101].

However, the scientific basis for the formation of CFs from alternative precursors is not yet available to a sufficient extent and the necessary continuity and the mechanisms of structure formation are not well understood. Accordingly, suitable process technologies are to be developed, scientifically investigated, implemented, and upscaled. The challenge is, among other things, to design natural raw precursor materials processable with new technologies in such a way that in future tailor-made CF for lightweight solutions in mass applications for structural materials can be produced in reproducible quality. To this end, new processing technologies are to be developed and modularized, ranging from precursor development, minimization of material-related defects and provision of stable spinning masses, precursor fiber production by means of solvent wet, melt, and dry spinning processes, and controlled pyrolysis to CF through to the formation of functionalized composite materials.

With a comprehensive understanding of the relationships between process parameters, inner material structure, and the properties, not only the stiffness and strength of carbon fibers can be significantly improved or specifically adjusted, but mechanical and functional material properties can also be combined in the future. For example, the use of PAN/lignin blends will make it possible to realize novel CF property combinations for the use of CF for structural batteries. In addition, thermal and electrical conductivities of CF can be efficiently adjusted by doping precursor materials with nanomaterials while maintaining or even increasing the mechanical properties due to defect healing processes, or even functionalize the surface of CFs with nanomaterials as a post-treatment. Lignin-based CF will especially be of interest for construction engineering and the usefulness of cotton fiber waste as a source of carbon fiber (CF) by pyrolysis is also evident. Carbon concrete composites (C^3) require a CF-based reinforcement at low costs.

To sum up, challenges relevant both with the precursor materials and the manufacturing processes should be overcome. Initially, the understanding of the influence of structural precursor characteristics (molecular weight, functional groups, and intramolecular cross-linking) on spinnability and properties of precursor fibers is necessary, together with the development of standardized precursor fragments for polymerization. Identification of lignin-related monomers as model lignin precursors for conversion by melt spinning and solvent spinning is also an option [102]. Finally, establishing upscaled precursor fiber manufacturing devices/equipment for wet spinning, dry spinning, and melt spinning for the right alternative precursors is a prerequisite. To confirm CFs quality, defect healing, and functionalization, a significant amount of fibers need to be manufactured, to validate the potential of alternative precursor materials with inter-laboratory comparisons to assess the precursor fiber properties.

Research activities that can be carried out towards the implementation of the above-mentioned actions are:

- Spinnable defect free or low defect precursors in reproducible quality;
- Process-independent precursor copolymers for melt and solvent spinning;
- Healing of defects through targeted doping of precursor systems;
- Mechanisms of structure formation of alternative precursor fibers in different spinning processes;
- Influencing the process for local defect healing or targeted porosity control;
- Modular and energy-efficient process chains.

The use of alternative precursors for sure will have positive results in the environment, economy and society. Lower environmental impact derives from green resources and this is a valuable contribution to the achievement of European climate objectives in accordance with the Paris Convention. Moreover, the non-dependence of raw materials will endow Europe the ability to become independent in the manufacturing of CFs, which will ensure the European technological leadership in the field of recycling in particular and in the green economy in general. The reduction also of costs for CFs and CFRPs manufacturing, due to the use of renewable precursors, will increase the acceptance of CFRP-based technical solutions, opening new markets and industrial sectors and by this a true circular economy can be established.

4.3. Recyclability of CFRPs and Reintegration of Recovered Materials into Manufacturing Processes

Due to the future changes in the guidelines for the disposal of CFRP, which no longer permit landfill or incineration in waste incineration plants, it will be necessary to invest in the development of new recycling technologies that permit the establishment of closed material cycles. Landfill and thermal recycling (pyrolysis) will not be possible in large quantities, which are especially critical in the automotive industry, due to legal regulations. The use of CFRP in hybrid lightweight structures additionally makes recycling more difficult due to the necessity of removing the structures. In the sorting process, the exact material classification according to matrix and fiber types is extremely important. The value retention can be significantly increased by specifying the material flows and considering the textile processing of the potentially recycled carbon fibers (rCF) since an associated textile handling and preparation has a strong influence on the achievable material properties of components made of rCF. In the future, developments will have to lead to a reduction in energy requirements in recycling and to an improvement in material quality and thus to the preservation of mechanical properties.

Currently, the most developed recycling technologies for CFRP are pyrolysis and solvolysis. High-performance rCF components are re-manufactured while preserving the recycled textile architecture. The dissolved matrix components are recycled as raw material of the chemical industry (stable aromatics) and integrated into chemical processes there. No waste products to be disposed are produced. Coupling pyrolysis and solvolysis (e.g., with supercritical water) may lead to a holistic recycling approach, if also the energy and resource efficiency are increased (e.g., by using waste heat from pyrolysis as an energy input for the solvolysis process).

The development of economical recycling technologies in the spirit of a true circular economy is an important prerequisite for maintaining and further expanding the already existing high CFRP competence in Europe. Recently a European H2020 Project started (Repair3D) [103], which investigates further recycling solutions for the reclamation of CFs from thermosets and thermoplastics, such as the use of magnetic nanoparticles. The clarification of the recycling issue of CFRP in Europe represents a clear economic location advantage for the development of this sector, which is expected to grow enormously in the future, for example in the field of electromobility.

The construction and commissioning of pilot plants for the integrated recycling of the entire portfolio of production waste and end-of-life components made from CFRP is of special interest for the European CFRP industry. Due to the high achievable market prices for rCF and the reduction of energy costs for their recovery, the profit forecast for European companies is very positive. The possibility of using solvolysis to recycle other materials, such as metals or rare earths from waste electronic equipment, etc., also represents further market potential. However, a coupling of different recycling technologies to a holistic recycling approach will require intensive research.

Two main industrial sectors are in the centre of reusability/recycling initiatives; automotive sector, due to legal regulations, and civil engineering, in which CF-based reinforcement is needed due to market growth rates of more than 20% after 2020. European industrial and R&D facilities need to be implemented and pilot plants for the aforementioned technologies to be established. Textile technologies should also be developed to manufacture reinforcing textile structures made of rCF and matrix systems, which can adapt the rCFs and foster CFRP recycling.

A holistic recycling strategy, including manufacturing, retail, (re)use and repair, recycling and redesign (Figure 8) will increase the acceptance of CFRP-based technical solutions and EU circular economy can be established. By this, European technological and economical leadership in the field of recycling in particular, and in the green economy in general, will be ensured over Asia and America. The improved European industrial manufacturing capacity for composites will increase product variety and customization and improve finally the value chain for CFRP composites.

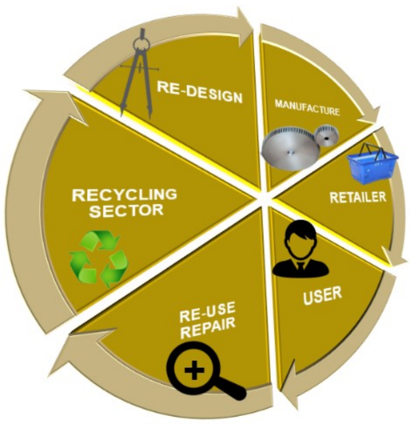

Figure 8. Circular economy and industrial symbiosis aim to create a more sustainable and resource-efficient way of supplying CF-based products to the market.

4.4. Cost Effective Repairing

CFRP composites often experience damage in the form of delamination and matrix crack even when little or no fiber breakage occurs. In principle it should be possible to repair this type of damage by completely infiltrating these cracks and/or re-bonding the delaminations with a repair resin or so-called adhesive. Such a solution, i.e., injection of a liquid repair resin into the damaged structure, has been first studied in the beginning of the 90s for repairing composite laminates [104]. In practice, the crack opening is often less than 5 µm while the delamination may extend for several centimeters. Thus, not only must the resin possess adequate thermal and mechanical properties, it must also have a relatively low viscosity and good surface wetting characteristics [105]. It has been shown that polymer infiltration enables to slow down and repair fatigue cracks in composites, as well as restore strength to the pristine composite.

The rapidly growing technology in the CFRP composite including the use of nanotechnology may provide more cost-effective repairing methods. For instance, CFRP composite tape or prepreg, nano-modified resins, and even nano-modified prepregs could be potential means. The repairability of structural and secondary composite components during the initial design phase should already be considered. The quality of the repair, compaction of the repair patch, and integrity of the bondline in adhesively bonded repairs becomes critical, driving a range of new technologies and pursuit of a standard repair technician certification.

One of the major issues in composite repair is time and labor. Manual repairs are time-consuming, and therefore, expensive. There are several automated repair technologies in development, including a fairly small mobile system by Airbus (previously EADS Innovation Works, Germany), the Inspection and Repair Preparation Cell (IPRC) in the U.S., and a system using resin infusion by the German Aerospace Center (DLR, Germany). For all these systems, automated functions include creation of 3D digitized images of the repair surface, nondestructive inspection and evaluation (NDI/NDE) of damage, removal of damaged material and preparation of the repair area, development of the repair materials, and assessment of the completed repair; all of them in order to reduce human error.

The scope of cost-effective repairing may first define the most targeted industrial sector(s) where CFRP composites are widely used or the use of CFRP composites is increasing, and repair will hold a much stronger position, especially from an economic point of view, over replacement. This means, the aerospace and aeronautic industry might be the priority followed by the automotive, marine, and sport industry. Secondly, a thorough survey in these sectors regarding the repair subjects including what type of defects, existing technologies to repairing, and the expectation of repairing technologies, as well as a cost estimation or more precisely, a life cycle analysis, should be performed. Manufacturing processes, material characterization, and the application of related measurement tools, protocols, and standards should be included.

Challenges of cost-effective repairing of CFRP composites are different in different industrial sectors; even in the same industry, the challenges can be very different corresponding to different parts to be repaired. To summarize, some general challenges include:

- Uncertainties surrounding the parts that are most-safety-critical parts of an object, such as an aircraft, which simply cannot be allowed to fail or be compromised, therefore, will have extremely high accuracy demand;
- Another challenge can be the lack of standards or limited standardization of composite materials and repair techniques, such as in wind energy and automotive repairs, especially the automotive situation is more nascent and critical;
- Without the appropriate standards and the low level of training and awareness of workers handling composites, difficulties arise regarding the detection and repair of composites damage.

As a result, development of accurate and efficient damage assessment techniques via non-destructive testing, such as ultrasonic techniques, thermography, and shearography, together with techniques for material or damaged parts removal by composite machining and surface preparation techniques is necessary. Moreover, repairing materials should be developed such as high performance and cost effect resins, prepregs, composite tape, etc. Design mechanisms, monitoring and automation of repairs, improvement of repairing accuracy, and standardization of composite repairing, need to be also the first priority. As a conclusion, the cost-effective repairing of composites will contribute to the circular economy and will offer environmental benefits, since more efficient use of resources (both man power and natural resources) will be utilized. Efficient technologies towards higher accuracy and automation will lead to reduced cost and energy of manufacturing whole pieces and manpower demanding and reduced landfill.

4.5. Life Cycle Assessment of Carbon Fiber Composite Products

The increasing demand for structures made of CFRP is enhancing the development of more eco-efficient manufacturing. Within eco-efficiency enhancement, both eco-logical and economic aspects are involved (Figure 9). On the one hand, global warming and the phenomenon of climate change have been associated with carbon dioxide (CO_2) as the primarily emitted greenhouse gas. Structures made of CFRP can lead to a significant reduction in e.g., vehicle empty weight. This weight reduction can decrease the CO_2 emissions up to 20% during operations [106]. On the other hand, the economic aspect is crucial in shaping the future of CFRP implementation in aerospace industry, whereas cost reduction is a main market driver.

Possible direct applications for the decision-makers should be sought, e.g., advanced technologies for reducing the fiber waste during cutting are needed, energy consumption within curing can be significantly reduced. In the composite industry, certifications and regulations should be considered in direct applications (aeronautics, automotive, etc.); the development of a holistic tool is crucial for supporting the decision making process.A gate-to-gate assessment of the carbon footprint and direct cost of manufacturing process is a cornerstone in performing a cradle-to-grave assessment. Efforts are required for data collection in an activity-based eco-efficiency assessment. Moreover, precise system boundary, unit process definition, and elementary flow allocations are crucial and effortful. Therefore, data collection can be enhanced through the implementation of smart measurement systems that reduces the Life Cycle Impact (LCI) efforts in eco-efficiency assessment.

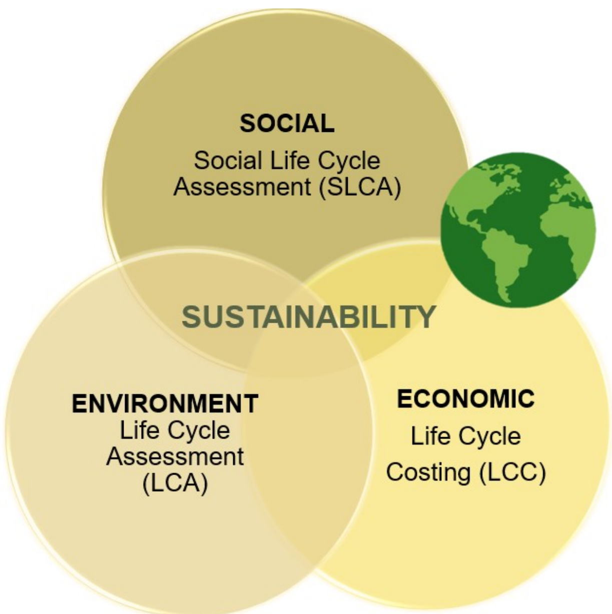

Figure 9. For the development of advanced composite CF-based materials for high value and high-performance applications, the assessment of environmental, social, and economic aspects is deemed necessary, in order to ensure their benefits from a sustainability perspective.

The total environmental impact of CFRPs is dominated by the carbon fiber production. Thus, technological improvements through the use of LCA as a decision making tool, such as the reduction of production waste, the recycling of cut-offs, and the use of renewable energies, will lead to environmental benefits. The reduction of the cut-offs and the use of renewable energy in carbon fiber production still offer the greatest potential to improve the environmental impacts of both, carbon fiber and CFRP parts. Taking into account that part size and thickness, which have the main impact on the weight specific process energy demand, are usually defined by the required performance, the highest process energy reduction potential lies in the curing time. A holistic approach, including the parametric unit process model, taking into account the dominant part features, and determining the impact per kg of output material should be used in future LCA studies of CFRP parts.

5. Conclusions

The relative maturity of composites take-up in sectors, such as aerospace, and the potential for significant growth in advancing markets, such as in the automotive and energy sectors, is on-going. The expansion of the CFRP market, for example, is driving large investments in advanced industrial facilities. Despite the promising features of CFRP based products, the penetration of processing technologies in some industries, with special focus on SMEs, is hindered by significant challenges. In volume-intensive industries, such as the automotive, poor economies scale and learning increase costs, keeping most applications in niche or premium markets. Coupled with a lack of awareness about composite applications, proper design standards, and an enduring metals-based design culture, CFRP technologies are limited for widespread utilization across sectors. Scattered knowledge about composites processing technologies affect the performance of supply chains, since the lead time for technology adoption, namely the acquisition of equipment and installations, may be less than the time needed to assimilate technical knowledge.

Novel business models for composite products and services need to be promoted, oriented primarily to SMEs, enacted by enhanced collaboration and information exchange among the actors in extended value chain, and enabled by a digital and intelligent infrastructure that supports cross-sectoral engagement and knowledge transfer. Development of knowledge, technologies, and tools to share and analyze relevant data and demands from users will fully enable collaborative engineering in the production network, allowing all actors to propose innovative solutions and improve their understanding of end users' requirements by composite manufacturers. Responsiveness and agility of supply networks will be also improved, orchestrated by a digital platform that enables interoperable information flows across the entire life cycle of the CFRP applications industry in Europe. According to this, product development especially for SMEs will be accelerated and contribute to the sustainability of the European CFRP supply chain through local sourcing and reutilization of CFRP products at their end-of-life, thus reducing the overall environmental footprint and at the same time supporting economic activity and job creation. Finally, it seems crucial to increase the cooperation between research institutes, academia, and the industry to help end-users in developing new innovative solutions and competitive products, implement cost-effective high-volume production processes, and reduce the time-to-market and life-cycle costs.

Several actions can be considered in order to achieve a common roadmap for composites. Initially, a database for all gathered data on CFRP should be created, together with data mining software to enable big-data analysis. In addition, a software-based platform that enables the emergence of new business models in the CFRP applications market needs to be created. As a centralized action, Industrial Liaison Offices need to foster the transfer of technologies developed in the CFRP field to outside industries and/or institutions and to support CFRP users (especially SMEs) in finding suitable tailored package for decision making, engineering, and manufacturing according to their specific needs. For this, the creation of a unique integrated platform entry-point for all the Industrial Liaison Offices is a prerequisite. According to the above-mentioned LCA and life cycle costing (LCC) tools, their implementation to facilitate cooperation and engage user involvement towards new business models is also important. Moreover, the implementation of knowledge management tools that facilitates seamless interoperability of information exchange across users in supply networks is important. Finally, development intelligent strategies that optimize supply network configurations, enabling responsiveness and agility in addressing market demands is the most crucial step to penetrate in new markets and achieve economical and environmental circularity.

The impacts of such an action are equally distributed to technological, economical, and societal fields. Specifically:

- A significant number of industries for CFRP composites sector will be attracted and new job profiles will be created;
- The implementation of open innovation networks across Europe will boost long-term innovation, identifying a common background in CFRP sector design, prototyping, production, and validation;
- CFRP processing technologies can be adopted in the wider industry and increase the product variety and customization;
- Industries will be benefitted from R&D partner assets and improve technological reputation and investor relationships;
- An improved European industrial manufacturing capacity for composites will be achieved and extended supply networks in the CFRP industry will be supported;
- Improvement of the processability and use of CFRP with a cost-reduction perspective, as well as synergies between industries will pave the way to high volume production;
- Tailored business models need to be created for the engineering of CFRP customized solutions, in order to increase the quality of products and revenues.

The ultimate goal is to reduce the time to market especially for high volume products with less costs and risk for companies and the environment.

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