Carbon-Fiber-Reinforced Polymers in Circular Economy

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Thermosetting Carbon-Fiber-Reinforced Polymers (CFRPs) are engineered composites made out of carbon fibers (CFs) as the reinforcement and epoxy resin as the polymer matrix, which acts as load transfer elements across fibers.Thermosets are commonly charachterized by their high performance and flexibility according to different combination of polymeric-based materials (e.g. epoxies, polyurethane, rubber) and carbon fibers type. CFRPs owns durable and heat-resistant features that make proper them for cars or electrical appliances. CFRPs cannot be easily recycled or broken down after use, because the chemical bonds holding them cannot be changed or reversed as for thermoplastic material. New technological solutions are emerging with specific focus on the circular economy context.

carbon fiber composites automotive ex ante LCA

1. General Framework of Thermosetting Carbon-Fiber-Reinforced Polymers (CFRPs)

Thermosetting Carbon-Fiber-Reinforced Polymers (CFRPs) are engineered composites made out of carbon fibers (CFs) as the reinforcement and epoxy resin as the polymer matrix [1], which acts as load transfer elements across fibers [2]. Among different types of resin (epoxy, phenolic, polyester, urethane and vinyl ester) [2], epoxy is the chosen resin when mechanical and resistance performance is required [3]. Indeed, CFRP composites are characterized by outstanding mechanical properties such as high stiffness, long life span, non-corrosive and high fatigue resistance [1][2][4]. Lightweight is an additional property of CFRP that can reduce, for instance, the overall weight of a vehicle up to 10% compared to steel and aluminum [5] with a reduction in fuel consumption or an increase in batteries duration for electric vehicles [6], resulting in a lower environmental impact during the use phase [7]. Indeed, CFRP composites are increasingly replacing other materials such as steel [8] and aluminum [9] in a wide range of sectors such as sports equipment, wind energy, aircraft, construction and automotive [4][10][11]. In recent decades, the global demand for CF increased from 16 kt to 72 kt [12], reaching 100 kt in 2019 [6]. Furthermore, the global demand for CF and CFRP is projected to reach, respectively, 117 kt and 194 kt in 2022, which portrays an annual compound growth rate, respectively, of 11.50% and 11.98% [13][14].

Although the undeniable potentialities of CFRPs, environmental and economic concerns on the spreading of CFRPs have been raised by many studies, including Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) studies. LCA and LCC are the main adopted tools, respectively, for the environmental and cost burdens assessment in the entire life cycle of a product or a service [15][16]. Both tools allow not only the calculation of the environmental and cost impacts but also the identification of the life cycle stages with the most relevant impact and the potential drivers to reduce the impact [17]. Based on those studies, current challenges on CFRP composites are mainly associated with its waste production and management [8][18]. Firstly, albeit mechanical, thermal and chemical recycling are potential technologies for CF recovery [10] currently in the market [19], landfill and incineration are still the main routes of CFRP waste management. However, they are both in contrast with the Circular Economy concept [14][20][21]. Secondly, recycling of thermosetting CFRP is difficult because of its intrinsic properties, which do not allow it to be remolded and reshaped once it is cured [3][4]. Moreover, even when CFs are recovered, the recycled CFs could have a lower quality than virgin CFs [22]. Thirdly, 40% of CFRP scraps are generated during the manufacturing of the product [14]. Finally, several types of damages may occur both during product manufacturing, for instance, porosity or undesired bodies in the matrix, and during the use phase, for instance, delamination, matrix crack and fiber–matrix debonding [23]. However, in the case of a damaged CFRP product, repairing techniques are limited. Hence, its entire substitution is the most widespread approach, resulting in a further increase in costs and resources [24]. Weak CFRP waste management combined with the surging demand for CFRP has been leading to a tremendous amount of waste. It is estimated that the global CFRP waste will reach 20 kt per year by 2025. Furthermore, taking into consideration that the monetary value of CF is around 26.5 euro/kg [25], from an economic and environmental perspective, a considerable amount of composite waste accumulated every year results in a loss of valuable and energy intensive materials [12][14].

Among possible options for reducing the environmental and cost impact of CFRP composites, repairing, recycling and using alternative bio-based materials have been identified on legislative, industrial and research levels. Firstly, at the legislative level, Council Directive on End-of-Life (EoL) Vehicles defined the target on vehicles to reuse and recycle up to 85% by 2015, which is currently under review by the European commission [26]. At the industrial level, repairing technologies could extend the product lifetime, minimizing resource depletion [27] and costs [28]. If repair is not possible, a potential reduction in the environmental impact still occurs through used CF recovery [14]. Finally, at the research level, extensive R&D activities have been conducted in the material field to develop a new type of composite that can be recovered and reused [29] or to substitute CFs and traditional matrices with bio-based materials [7][30].

2. CFRP in Life Cycle Assessment (LCA) on Composites

Nowadays, the Life cycle assessment (LCA) tool is adopted by companies in order to estimate the current environmental footprint among several environmental categories and as a decision support tool to reduce their environmental impact [31]. As a matter of fact, the International Organization of Standardization (ISO) developed standards on LCA in order to consolidate the methodology [32] and provide guidelines to LCA practitioners and companies willing to apply this technique [33]. The tool estimates the current environmental impact of a product through its entire life cycle, from the raw material extraction to its End-of-Life (EoL), analyzing the entire supply chain. Moreover, it provides possible indications on reducing the environmental impact and a range of results according to the developed scenarios. LCA is divided into four iterative steps, which are *Goal and scope definition*, *Life Cycle Inventory (LCI)*, *Life Cycle Impact Assessment (LCIA)* and *Interpretation* [33]. Regarding the LCI step, primary data are directly provided by companies; secondary data are available from datasets and literature [34].

Although the LCA tool is mainly applied to existing technologies [31][35][36], a preliminary environmental assessment of emerging technology further enhances the knowledge of this technology from an environmental point of view [37], improving its design and further developing the product on an industrial scale [38]. As a consequence, this could attempt at obtaining a product in the market with as little environmental impact as possible [35]. This is the case of the ex ante LCA. It simulates the environmental impact of an emerging technology on an industrial level, for instance, a technology developed at laboratory, in order to (1) estimate its environmental impact among possible scenarios in case it will be developed on an industrial scale [31][39] and (2) compare it with existing technologies that provide the same or similar service [40]. Difficulties and challenges have emerged in developing an ex ante LCA mainly regarding the data collection [41] and scenario selection due to the absence of data, differences between industrial and laboratory scale and uncertainties on future scenarios of development [42] and large-scale technology diffusion on the market [43]. Indeed, the ex ante methodology is applied in order to solve the following two main issues related to primary data from a laboratory: (1) scale-up from consumption to industrial scale [42][44] and (2) unavailable primary data [42][45]. On one hand, technologies used as well as consumption of energy and materials on a laboratory scale are different from the ones at the industrial level. As a matter of fact, the consumption of raw materials and energy can be much higher on a laboratory scale than the one on the industrial scale [42][46]. On the other hand, data on energy and auxiliary materials consumption are usually not available at the laboratory scale [42], and hence, calculations are needed in order to compute the LCI. Efforts on establishing a methodology through which an ex ante LCA can be performed has been made by different authors [40]. Cucurachi et al. [31] identified five types of ex ante LCAs in order to uniform the present literature on this topic, provided a definition of 'emerging technology' and outlined the main challenges of performing ex ante LCAs. Moni et al. [42] focused on the challenges to perform LCA of emerging technologies, identifying possible pathways and recommendations in order to overcome those limits. Piccino et al. [46] provided an operational methodology of an ex ante LCA through which data on a laboratory scale can be transformed to industrial-scale data. However, few LCAs directly applied ex ante methodology in real case studies.

Concerning the application of LCA to composites, many studies can be found in the literature. LCAs on glass fiber polymers [47][48] and carbon fiber polymers [49][50][51] as well as thermoplastic [52][53] and thermosetting composites [5][52] among different applications, for instance, automotive [8][49][54], aviation [7][55] and construction [48][56][57] sectors. More recent comparative LCAs on CFRP waste management included mechanical, chemical and thermal recycling as alternatives to landfills and incineration [58]. Meng et al. [12] analyzed recycling technologies of CF, concluding that all recycling routes could achieve environmental benefits in terms of Global Warming Potential (GWP) and Primary Energy Demand.

3. CFRP in Economic Sustainability of Composites EoL

The economic assessment of a new project or a technology under different system configurations is of paramount importance to attain competitive edge since it helps business management to compare the profitability of the new business under a wide range of scenarios. To increase the competitive advantage of a product, the Life cycle cost (LCC) analysis is a proper tool that is used to compare the profitability of the new business under a broad range of hypotheses [16][59][60]. The U.S. military first introduced the LCC concept in the 1960s [61]. The idea was then used by different industries, such as energy, transportation, healthcare, etc., to assess a project's economic sustainability and helped investors compare the cost-effectiveness of alternative business decisions [16]. LCC analysis starts with the cost breakdown structure (CBS) and revenue breakdown structure (RBS) of a product or a new project. This approach measures and calculates the costs and revenues of the product at its different stages of life. Then costs and revenues are discounted using the discount rate. The discount rate represents the rate of inflation at the time when the financial model is performed [61]. From a higher-level standpoint, the LCC procedure aggregates all the discounted cash flows incurred over a project's entire life span. These discounted cash flows can be used to identify the profitability of the new project based on financial indicators such as net present value (NPV) and discounted payback period [62]. Although economic assessment and LCC are widely applied in different sectors, a very limited number of studies have investigated the economic sustainability of composites EoL solutions in the literature. Many studies on composites have evaluated the economic sustainability of products during the manufacturing and use phase. For example, Witik et al. [58] investigated the financial sustainability of CF composite products using diverse manufacturing processes (autoclave vs. out-of-autoclave). Delogu et al. [25] carried out a comparative analysis to evaluate the economic performance of CFRP during the manufacturing process compared to the use phase. Strogonov [63] analyzed the cost reduction of products made out of composites compared to steel products during the manufacturing process. However, very few studies have focused on evaluating the economic performance for the EoL of composite waste. In this regard, for example, Castella et al. [64] assessed the economic sustainability of a composite product in the automotive industry during different value chain stages: raw material fabrication, manufacturing, use phase and the end of life. It was found that using hybrid composites instead of steel can lower the lifecycle cost by 16%. La Rosa et al. [59] also focused on the economic performance of carbon fiber (CF)-thermoset composite during manufacturing and solvolysis recycling. The finding of this research proved that the chemical recycling is not economically sustainable. However, research on this topic is still lacking. In a broader sense, it can be argued that most studies on composite EoL were focused on the technical performance of recycling technologies [1][4][10][65]. Among these studies concentrating on the closing loop techniques, a few have briefly evaluated the economic impacts of recycling technologies. For example, Karuppannan Gopalraj and Kärki [10] carried out an extensive literature review on the technical aspects of the mechanical recycling, thermal recycling and chemical recycling and briefly pointed out that thermal and chemical recycling can be economically sustainable under certain conditions. Finally, it can be stated that although within the circular economy paradigm, repair is defined as one of the most effective approaches to address waste [66] and composite repair has been proven technically feasible [67], the economic assessment on this topic is still missing.

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