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Economic and environmental assessment of recovery and disposal pathways for CFRP waste management

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ABSTRACT

The high cost and energy intensity of virgin carbon fibre manufacturing constitute a challenge to recover substantial value from carbon fibre reinforced polymers (CFRP). The objective of this study is to assess the environmental and financial viability of several waste management processes for CFRP. Life cycle costing and environmental assessment models are developed to quantify the financial and environmental impacts of waste treatment pathways comparing a panel of recycling techniques that are now available (grinding, pyrolysis, microwave and supercritical water) and that can be used to substitute different grades of both carbon and glass fibres by recycled carbon fibres at competitive prices compared to landfill and incineration. GWP assessment promotes recycling activities by recovery of carbon fibre due to the high avoided impacts from substitution of virgin fibre, thus highlighting the high interest of recycling over conventional production for environmental purpose. Fibre recovery rate and recycling capacity are pivotal to decrease the unit cost of recycled fibre as well as GWP impacts. The advantages and drawbacks of each technique are analysed through economic and environmental indicators, to better understand the network configuration for optimisation purpose of waste management pathway in a holistic viewpoint.

1. Introduction

Due to their low density and high performance of physico-chemical properties, Carbon Fibre Reinforced Polymer Composites (CFRP) are increasingly used in structural applications to replace more conventional materials (steel, aluminium, alloys…) for the design of lighter products. According to Black (2012), the global demand of carbon fibres was expected to exceed production capacity in 2015 and if growth remains at this rate, a huge amount of waste will be generated. The benefits of CFRP recycling are threefold: first, it is necessary to limit the accumulation of waste second, recycling could be a fibre supply solution in order to meet future demand (Black, 2012) and third, recycling could be expected as a less energy-intensive operation with lower environmental impact than the traditional way to produce virgin CFRP, due to the bypass of some operation steps. Carbon fibre manufacturing is an energy intensive process (183–286 MJ/kg of carbon fibre, (Song et al., 2009)) that transforms the precursors with poorly ordered structure into a nearly perfect graphite structure in carbon fibre (CF) and generates environment and human health impacts due to emissions from the oxidation and carbonization furnaces, such as HCN, NH_3, NO_x… (Grzanka, 2014).

Composites recycling is a difficult process due to the heterogeneous nature of the matrix and the reinforcement, especially in the case of thermoset composite (Pickering, 2006). Only few commercial recycling operations for main stream composite materials are available due to technological and economic constraints. The utilisation of recycled carbon fibres (RCF) in industry generates some challenges due to their lower quality than virgin carbon fibres (VCF) (McConnell, 2010) and variability affecting many factors such as, length distribution, surface quality (adhesion of fibre and matrix), as well as their origin (different grades of fibres are found at various composite scraps from different manufacturers) (Oliveux et al., 2015a). This explains why the lack of

Abbreviations: BMC, bulk moulding compound; CEPCI, chemical engineering plant cost index; CF, carbon fibre; CFC, carbon fibre composite; CFRP, carbon fibre reinforced polymer; D, depreciation; FRP, fibre reinforced polymer; FU, functional unit; GF, glass fibre; GFRP, glass fibre reinforced polymer; GHG, green house gas; GLARE, glass laminate aluminium reinforced epoxy; GWP, global warming potential; GWPA, GWP impact of substituted products; GWPP, GWP impact of process; GWPTOT, GWP total of the system; LCA, life cycle assessment; LCC, life cycle cost; LP, linear programming; MFA, material flow analysis; MILP, mixed integer linear programming; NPV, net present value; OC, operation cost per mass unit of waste; PAN, polyacrylonitrile; RCF, recycled carbon fibre; RGF, recycled glass fibre; SCW, supercritical water; SMC, sheet moulding compound; TC, total annual costs; TRL, technology readiness level; UCF, average unit cost per mass unit of recovered fibre; UCW, average unit cost per mass unit of waste; VCF, virgin carbon fibre; VGF, virgin glass fibre

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markets, high recycling cost, and lower quality of the recyclates versus virgin materials still currently constitute major commercialisation barriers for composite recycling (Yang et al., 2012).

Current waste policies served as an incentive to develop composite recycling solutions, including general policies (The European Directive on Landfill of Waste (Directive 1999/31/EC, 1999)) and application-specific legislation (e.g., the End-of-life Vehicle (Directive 2000/53/EC, 2000)).

In parallel, several recycling technologies have been developed for composite materials over the past decades. In particular, the recycling of thermoset composites is receiving a lot of attention due to the technical difficulties to separate the thermoset matrix from the reinforcement materials (Yang et al., 2012). Different recycling techniques of FRP have been studied and developed in order to improve the recycling yield and the properties of the recovered fibre by three main types of techniques: (1) Mechanical techniques in which fibre and matrix are separated by shredding (grinding technique) (Pannkoke et al., 1998; Kouparitsas et al., 2002; Ogi et al., 2005, 2007, Palmer et al., 2009, 2010; Howarth et al., 2014) or high voltage pressure (electrodynamic fragmentation) (Müller, 2013; Mativenga et al., 2016) without chemical reactions; (2) Thermal techniques in which matrix is decomposed by heat (conventional pyrolysis, fluidised bed) (Fenwick, 1996; Kennerley et al., 1998; Pickering et al., 2000; Yip et al., 2001; Cunliffe et al., 2003; Gosau et al., 2006; Jiang et al., 2008; Meyer et al., 2009; López et al., 2012, 2013) or microwave radiation (microwave) (Lester et al., 2004; Akesson et al., 2013; Obunai et al., 2015) into heat or residual liquid; and (3) Solvolysis techniques in which matrix is decomposed by chemical reactions in water or in other organic liquids at atmospheric pressure or supercritical conditions (Allred et al., 2001; Hyde et al., 2006; Piñero-Hernanz et al., 2008a,b; Jiang et al., 2009; Nakagawa et al., 2009; Yuyan et al., 2009; Bai et al., 2010; Kamimura et al., 2010; Feraboli et al., 2012; Knight et al., 2012; Morin et al., 2012; Onwudili et al., 2013; Oliveux et al., 2013, 2015b; Okajima et al., 2014; Yildirir et al., 2014). Other recycling solutions can be found such as electrochemical (Sun et al., 2015) and biotechnological (Hohenstein Institute, 2015) techniques but they are less mature than other ones for CF recovery.

Life cycle assessment of FRP/CFRP has also received a lot of attention in order to study the environmental benefits of these composites that can be gained from the use of more conventional materials (Takahashi et al., 2002; Duflou et al., 2009; Suzuki and Takahashi, 2005; Song et al., 2009; Das, 2011; Witik et al., 2011, 2012). However, these studies focused mostly on the production and utilisation phases of such materials. The step of waste treatment is poorly studied and generally limited to one technique, e.g. recycling by microwave (Suzuki and Takahashi, 2005; Das, 2011) or recovery energy by incineration (Witik et al., 2011).

The literature analysis reveals that the majority of works reported are devoted to the development of a specific CFRP recycling process or to a specific recycling pathway. As highlighted in (Job et al., 2016), the challenge is now to develop appropriate business models, integrating with existing waste management supply chains and with associated capital investment, to enable commercialisation of what is technically proven. The proposed works aim at considering the whole waste management supply chain model in order to compare the potential benefit of each recovery pathway not only from an environmental viewpoint but also from an economic one.

For this purpose, the independent assessment of each pathway through its inputs and outputs under economic and environmental which is the prerequiste for system modelling is carried out in this study to identify the typical features, as well as the advantages and weaknesses of each recycling/recovery pathway. The composite waste treatment technologies that have been identified in the dedicated literature whatever their technology readiness level (TRL), i.e. landfill, incineration, co-incineration, mechanical recycling, pyrolysis, microwave and supercritical water, are all assessed in this study with economic and environmental indicators in an exhaustive and complementary way. Various indicators which represent the different viewpoints of the involved stakeholders will also be discussed.

This paper is organized as follows. First, a brief literature review on the Life Cycle perspective situates (see Section 2) the research focus within the scope of CFRP recycling/recovery pathways. The methods and tools that will be used throughout this study for the development of the framework for CFRP waste management and the assessment of economic and environmental will be addressed in Section 3. The analysis and results are presented in detail in Section 4. Finally, Section 5 will conclude this study on CFRP waste management and offer perspective for CFRP waste supply chain deployment and optimisation.

2. Literature review on life cycle perspective of CFRP recycling pathways

The literature analysis reveals that some articles have discussed the environmental impacts of transitioning from conventional materials to FRPs, as determined by Life Cycle Cost (LCC) and Life Cycle Assessment (LCA). The work reported in Hedlund-öström (2005) that applied LCC and LCA is focused on waste treatments of End-of-life CFRP and other composites involving grinding, fluidised bed and incineration. As LCC and LCA of waste treatment phase depend on the recovered products, not surprisingly, the choice of the replaced material between virgin carbon fibre (VCF) and virgin glass fibre (VGF) is particularly significant for result interpretation. Incineration may have a higher advantage than recycling if the recycled carbon fibre is used to replace low value material, such as glass fibre. In reality, the characteristics of the recycling process may impact the quality of recovered fibre output, besides the type of origin fibre in waste. The studies on CFRP recycling techniques have thus reinforced the need of in-depth investigations on the structure of CFRP waste treatment (Hedlund-Åström, 2005; Witik et al., 2013; Li et al., 2016)

Witik et al. (2013) studied the environmental impacts (climate change, resources, ecosystem quality and human health) of three waste treatment options, i.e., pyrolysis, incineration and landfilling. A quantitative model for the determination of equivalent quantities of VCF and VGF, which are replaced by RCF to achieve mechanical performance equivalent to virgin material in Sheet Moulding Compound (SMC) through the tensile modulus. However, the utilisation of RCF in polymer matrix is a complex process depending on numerous criteria apart from the tensile modulus. Although the market of RCF has not been mature due to the uncertainty of their mechanical properties compared to VCF, their potential applications are numerous, not only in reinforcement purpose (Bulk Moulding Compound (BMC), Sheet Moulding Compound (SMC), thermoplastic composites, concrete…), but also in other applications which do not depend much on mechanical properties of materials such as electrical and electronic products, e.g. electromagnetic shield (Wong et al., 2010).

Li et al. (2016) carried out a study on LCC and environmental assessment (GWP, energy use, final disposal waste) for End-of-life CFRP in automotive with three options (landfilling, incineration and mechanical recycling) within regulations of UK and EU. In this hypothetical case, a landfill tax can be viewed as a useful tool to shift CFRP waste from landfill to incineration because of the low GWP impacts and energy use in landfilling. Recycling benefits depend on the displacement factors of VCF by recycled fibre and on the recycling rate in order to balance the energy-intensive recycling process. However, grinding process in mechanical recycling degrades fibres on reducing their length and cannot separate cleanly fibre and matrix from the composite (Kouparitsas et al., 2002; Palmer et al., 2009). Increasing recovery rates can improve environmental and financial performance of the mechanical recycling pathway: in the base case, only 40% of CF present in CFRP waste is assumed to be recoverable. Considering higher recovery rates is hypothetical for (Li et al., 2016).

An alternative to LCA and LCC is cost–benefit analysis (CBA) (Leu