Journal of Cleaner Production 127 (2016) 451–460

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Environmental and financial performance of mechanical recycling of carbon fibre reinforced polymers and comparison with conventional disposal routes

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A R T I C L E I N F O

Article history:
Received 15 October 2015
Received in revised form
11 March 2016
Accepted 13 March 2016
Available online 8 April 2016

Keywords:
Life cycle assessment
Life cycle cost
Composite waste treatment
Carbon fibre recycling

A B S T R A C T

Recovering value from carbon fibre reinforced polymers waste can help to address the high cost and environmental burden of producing carbon fibres, but there is limited understanding of the cost and environmental implications of potential recycling technologies. The objective of this study is to assess the environmental and financial viability of mechanical recycling of carbon fibre composite waste. Life cycle costing and environmental assessment models are developed to quantify the financial and environmental impacts of alternative composite waste treatment routes, comparing landfilling, incineration with energy recovery, and mechanical recycling in a UK context. Current Landfill Tax results in incineration becoming the lowest cost composite waste treatment option; however, incineration is associated with high greenhouse gas emissions as carbon released from composite waste during combustion exceeds CO_2 emissions savings from displacing UK electricity and/or heat generation, resulting in a net greenhouse gas emissions source. Mechanical recycling and fibre reuse to displace virgin glass fibre can provide the greatest greenhouse gas emissions reductions of the treatment routes considered (−378 kg CO_2 eq./t composite waste), provided residual recyclates are landfilled rather than incinerated. However, this pathway is found to be unfeasible due to its high cost, which exceeds £2500/t composite waste ($3750/t composite waste). The financial performance of mechanical recycling is impaired by the high costs of dismantling and recycling processes; low carbon fibre recovery rate; and low value of likely markets. To be viable, carbon fibre recycling processes must achieve near-100% fibre recover rates and minimise the degradation of fibre mechanical properties to enable higher value applications (e.g., virgin carbon fibre displacement). On-going development of carbon fibre recovery technologies and composite manufacturing techniques using recycled carbon fibres leading to improved material properties is therefore critical to ensuring financial viability and environmental benefit of carbon fibre reinforced polymer recycling.

1. Introduction

Carbon fibre reinforced polymer (CFRP) is already a common lightweight material in aerospace applications and is expected to be increasingly used in automotive applications into the future. For transport applications, fuel savings can be achieved when CFRP is used in place of heavier materials such as steel and aluminium, with studies reporting energy savings of greater than 5 GJ per kg of steel displaced in automotive applications (Das, 2011; Duflou et al., 2009). In the past ten years, CF's annual demand worldwide has increased from approximately 16,000 to 72,000 tonnes and is expected to reach 140,000 tonnes/yr by 2020 in estimation (Witten et al., 2014). Correspondingly, CFRP wastes from manufacturing processes and end of life products are expected to increase. Virgin carbon fibre (vCF) is an energy-intensive and costly material, and therefore recycling of CFRP wastes could recover substantial financial value while contributing to waste mitigation objectives. To ensure that recycling strategies contribute to this aim, it is necessary to understand their environmental impacts and financial viability.

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http://dx.doi.org/10.1016/j.jclepro.2016.03.139
0959-6526/

Recycling of CFRP wastes is encouraged by the high cost and energy intensity of vCF production. Manufacture of vCF costs 20–40 £/kg in the UK (Pimenta and Pinho, 2011) and directly consumes about 183–286 MJ per kg, which is roughly 10 times more energy-intensive than glass fibre production (Howarth et al., 2014) and approximately 14 times more energy-intensive than conventional steel (Das, 2011). Greenhouse gas emissions associated with vCF production have been estimated previously at 31 kg CO_2 eq per kg, which is 10 times more than conventional steel at 3 kg CO_2 eq per kg production (Das, 2011). Recovering CF from CFRP wastes could help to compensate for these production impacts.

Existing waste mitigation policies further encourage value recovery from CFRP wastes. The landfill tax scheme in the UK is a financial disincentive applied to landfilling to encourage the diversion of wastes to alternative treatment processes by applying a charge to waste entering landfill (EC, 2012). The End of Life Vehicle Directive (EC, 2000) is relevant to automotive applications of CFRPs and mandates material recovery of end of life vehicles with objectives of reducing waste and improving environmental performance when automotive vehicles enter into end of life. A recycling target of 85% and a total recovery of 95% (including incineration) are newly initiated from 2015, allowing only 5% of a vehicle to be deposited into landfill and no more than 10% entering energy recovery. Developing viable CFRP recycling and recovery technologies is essential for future lightweight automobiles to comply with this legislation.

While there are numerous drivers supporting the recycling of automotive wastes, common difficulties in cost-effectively recovering non-metal material from automotive components result in a financial and environmental burden associated with such wastes. Currently, non-metal materials in the automotive sector – and particularly plastics – maintain low recycling rates in Europe, with the bulk of this material remaining in automotive shredder residue that is combusted for energy recovered or landfilled (Sakai et al., 2014; Santini et al., 2011). In contrast, metals used in transport applications, such as steel, are easily recovered at high recycling rates (Graedel et al., 2011). Vehicle lightweighting is a driver for increasing utilisation of plastics in future cars and risks impairing vehicle material recycling rates due to financial and technical barriers to recovering post-shredder plastic residues (Passarini et al., 2012). To increase the plastics recycling rate, labour- and cost-intensive dismantling is required to separate and collect material prior to shredding. Reviewing literature to date, large scale of plastic components dismantled to recycling is limited by the lack of a viable recycling network and uncertain markets for recovered materials (Chen et al., 2015; Duval and MacLean, 2007; Shapiro and Johannessen, 2015). Despite economic constraints, numerous studies have found environmental benefits to be realised from automotive plastic recycling, including reductions in energy consumption, greenhouse gas emissions, and non-renewable resource depletion (Ciacci et al., 2010; Duval and MacLean, 2007).

It is anticipated that CFRP waste from automobiles would face similar barriers to plastics, while its mixed-material nature may create additional technical and economic barriers to successful material recovery. Material recovery from CFRP wastes is complicated by the cross-linked matrix structure (typically epoxy resin), absence of standard composition, and difficulty characterising waste materials to optimise recovery processes (Pickering, 2006; Witik et al., 2013). A number of CFRP recycling methods have been successfully trialled including mechanical recycling, pyrolysis and fluidised bed processes (Pickering, 2006). However, the uncertain economic viability of recycling processes and availability of markets for recycled material are two key barriers to the implementation of CFRP recycling. Recycled carbon fibres (rCF) from mechanical recycling processes typically exhibit reduced mechanical properties and reduction in fibre length, thereby forcing these materials to lower-value applications than virgin carbon fibres (vCF) (Palmer et al., 2010). More advanced techniques such as pyrolysis and fluidised bed, which thermochemically decompose the cross-linked matrix material, can recovery clean and high quality rCF, but are expected to exhibit higher process costs and greater energy intensity than mechanical recycling. Moreover, reuse of rCF from pyrolysis and fluidised bed is not straightforward due to the fluffy nature of the rCF and surface properties that can impair binding with polymeric matrix materials (Oliveux et al., 2015; Pimenta and Pinho, 2011). As a consequence, CFRP may enter conventional waste treatment routes, including landfill and incineration, where minimal value can be recovered.

In order to assess the environmental and financial impact of waste treatment systems, life cycle assessment (LCA) (ISO, 2006) and life cycle cost (LCC) methods (Fabrycky and Blanchard, 1991) can be applied. LCA and LCC methods have been broadly applied to waste treatment systems, including investigations of end-of-life vehicles (Alonso et al., 2007; Duval and MacLean, 2007) and a wide range of other post-consumer products including plastics (Simões et al., 2013), home appliances (Kim et al., 2009), and general municipal solid waste management (Zhao et al., 2011). While these studies generally agree that recycling and other reutilisation scenarios can achieve environmental benefits (in terms of energy use, greenhouse gas emissions, resource depletion, *etc.*), financial viability is very dependent on specific cases and parameters such as total recycling cost and markets/value of recovered materials. Prior studies specific to CFRP waste recycling include an evaluation of the energy consumption associated with mechanical recycling (Howarth et al., 2014). Witik et al. (2013) conducted a life cycle study of a pyrolysis-based CFRP recycling process to assess environmental impacts; while this study lacked accurate data as to the energy requirements of the CFRP recycling process, it expanded on existing LCA studies investigating the production and use phases of CFRP products (Das, 2011; Timmis et al., 2015; Witik et al., 2011) to include CFRP end-of-life. However, to our knowledge no previous study has combined LCA and LCC methods to assess both the financial and environmental impacts of CFRP waste treatment.

This paper develops LCA and LCC models to quantify the financial and environmental (global warming potential, primary energy use, landfill waste generation) impacts of mechanical CFRP waste recycling. We compare mechanical recycling with conventional treatments (landfill, incineration) to address trade-offs between treatment options and assess the potential impacts of current waste treatment regulations in the UK and EU. A case study is conducted considering automotive CFRP waste.

2. Methods

This study assesses the environmental impact and financial performance of waste CFRP treatments when carbon fibre-based composite materials in end of life vehicles are disposed of. We consider three possible end of life treatments of waste CFRP materials: landfilling, incineration with energy recovery; and mechanical recycling to recover materials for use as fibre reinforcement and/or filler material. Trade-offs between the alternative treatment routes are assessed in the context of current waste regulations in the UK and EU.

Life cycle inventory (LCI) models are developed to quantify environmental impacts associated with the waste CFRP treatments. The functional unit for the analysis is one tonne waste CFRP entering the waste treatment processes. Global warming potential (GWP), primary energy use, and landfill waste generation are