CARBON FIBRE COMPOSITE WASTE: A COMPARATIVE ASSESSMENT OF RECYCLING AND ENERGY RECOVERY

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Abstract
The increasing use of CFRPs across a variety of industries will result in larger volumes of CFRP waste, which require environmentally appropriate treatment methods. Recent focus has been on the development of recycling processes in order to re-use carbon fibres from waste. However, work, which quantifies the benefits of such an approach against alternatives, is scarce. In this work LCA methodology is used to compare recycling via the pyrolysis process and incineration with energy recovery as potential end of life treatments for CFRP waste. Re-use of resulting recyclate was found to determine which option was environmentally preferable. Recycling was preferable to incineration if reuse of the recovered fibres displaced primary production of carbon fibres. Incineration with energy recovery was found to be preferable if potential applications displaced glass fibre production.

1 Introduction
The use of carbon fibre reinforced polymer (CFRP) materials is steadily increasing across a range of industries. Worldwide demand for carbon fibres (CF) is rising and annual production volumes are expected to rise from 40,000 tonnes in 2011 to 140,000 tonnes by 2020 [1]. Increased use of these materials today will inevitably lead to increased quantities of waste as the applications in which these fibres reside reach the end of their useful lives. Based on current industry demand estimates, and applying representative residence times for each industry, we estimate that annually, by 2020 there will be approximately 36,000 tonnes of CFRP resident in End of Life (EoL) waste with a further 26,000 tonnes being generated from production processes.

Until now fibre reinforced polymer (FRP) waste in Europe has predominantly been disposed of in landfills, with the remainder being incinerated. However, attitudes towards waste treatment have changed to favour waste avoidance, minimisation and recycling. These principles now form the basis of the Waste Framework Directive [2] which lists five possibilities for waste treatment in order of preference: (i) prevention or reduction, (ii) reuse, (iii) recycling, (iv) recovery and (v) disposal. It is now a requirement that this hierarchy be applied to waste treatment in the EU and compliance is encouraged by other directives such as the Landfill of Waste Directive [3] and the End of Life Vehicles Directive (ELV) which imposes strict limits on the disposal of vehicles, requiring that 85% of a vehicle be reused or recycled by 2015 [4]. Such restrictions clearly present a challenge for the composites industry, where continued growth, particularly within the automotive industry could be hindered by the lack of possibilities for waste treatment and recycling.

Waste treatment research has, until now, primarily focused upon recycling. A number of approaches have been reported which enable the separation of carbon fibres from their matrices, although the furthest advances towards commercialisation have been made with pyrolysis [5,6]. Other topics supporting this area of research include characterisation of recyclate, remanufacturing, and mechanical analysis [7]. Although crucial for understanding how environmental burdens from the disposal of these materials can be minimised, work assessing the environmental effects of recycling is scarce.

Reports from industry suggest that reclaiming CF via pyrolysis requires less than 5% of the energy required to produce virgin fibres [6]. However, this comparison does not provide a robust indication of environmental benefit. An assessment of the benefits must include other recycling related impacts such as: transportation, pre-treatments, process emissions and impacts from other resulting waste. Material re-use must also be considered since material production avoided through the recirculation of recovered material defines the potential environmental benefit. The sum of these impacts must then be compared to those from alternative waste treatment and new material production to determine if recycling is beneficial and to what extent. Life cycle assessment (LCA) enables such comparisons to be made. The use of this methodology is well established within other industries for assessing environmental impacts of products and services; it is also the most widely applied quantitative method for comparing different waste treatment options and determining the most environmentally favourable [8]. Studies assessing alternative EoL pathways for composites are rare, but vital for the industry, for targeting impact reduction strategies and for selecting and developing environmentally appropriate methods of waste treatment.

The aim of this study is to take an important step towards developing work in this area by using LCA methodology to assess two possible end-of-life pathways for CFRP waste: modern incineration with energy recovery and fibre reclamation via pyrolysis. Recycled CF (RCF) has the potential to be used in applications as a replacement for both virgin carbon (CF) and glass fibres (GF). Both of these pathways are studied to determine how re-use affects environmental gains. An analysis of the sensitivity of impact reduction to energy consumption of the pyrolysis process is also made.

2 Methods

2.1 Life Cycle Assessment (LCA)

LCA is an internationally standardised methodology for assessing environmental impacts attributed to the lifecycle of a product or service. The procedure for LCA is part of the ISO 14000 environmental management series, ISO 14040 more specifically describes the principles and framework of the approach [9,10]. The approach enables a holistic assessment of environmental burdens associated with a specific system of study, thus allowing relative contributions from each process or life cycle phase within to be identified, thus enabling improvement strategies to be targeted more effectively. LCA studies are carried out in four stages:

Goal and scope definition: during this stage the aim and purpose of the study are defined with the boundaries of the system to be assessed. A unit of comparison or functional unit (FU) is also defined to which impacts are allocated.

Life cycle inventory analysis: inventory analysis involves the collection of data and calculation of the inputs and outputs of the system of study. Energy, raw material and waste products are quantified along with emissions and other environmentally relevant aspects.

Impact assessment: during this phase the life cycle inventory (LCI) results i.e. emissions, waste products, resources etc, which were determined in the inventory analysis are translated into potential environmental impacts.

Interpretation: here the results from the impact assessment are summarised, conclusions are drawn and recommendations made against the original study goals.

3 Goal and scope definition

The goal of this study is to compare modern incineration with energy recovery to recycling via pyrolysis to identify the environmentally favourable option for the treatment of CFRP waste. Possibilities for using RCF are reported to exist in applications, which currently use GF and CF materials [7]. Both options are studied to determine the effects of material reuse on recycling benefit. The FU is 1 kg of CFRP waste treated. The ability of RCF to displace primary production of CF and GF is calculated based on mechanical performance when used within a short fibre composite beam. Applied force, width and length are fixed; beam thickness is adjusted to obtain equal deflections for all. Beam weights for equivalent deflections are obtained using equation 1. It should be noted that recycled fibres are reported to have lower strength [7], however this is not taken into account in this study. The commercial LCA software Simapro has been used to make the assessment [11]. Impact assessment is carried out with the IMPACT 2002+ [12].

$$\frac{W_1}{W_2} = \sqrt[3]{\frac{E_2}{E_1}}\frac{\rho_1}{\rho_2} \quad (1)$$

where :

W_1=Weight of beam 1
W_2 =Weight of beam 2
E_1 =Tensile modulus of beam 1
E_2 =Tensile modulus of beam 2
ρ_1 =Density of beam 1
ρ_2 =Density of beam 2

The incineration and recycling situations compared for each material replacement scenario are shown in figures 1a and b. Figure 1a shows a situation where no recycling occurs: two product systems are included, both use virgin fibre material to produce composite products which are incinerated after use. Figure 1b shows the recycling situation, where CFRP waste from the first product system is recycled and reused within the second product system. Virgin GF and CF production are avoided for scenarios 1 and 2 respectively along with the incineration process for the first product system. CFRP waste is assumed to be only recycled once.

Scenario 1: (RCF replacing glass fibre)
(Incineration of CFRP + new GF production) vs. (recycling + avoided GF production)

Scenario 2: (RCF replacing carbon fibre)
(Incineration of CFRP + new CF production) vs. (recycling + avoided CF production)

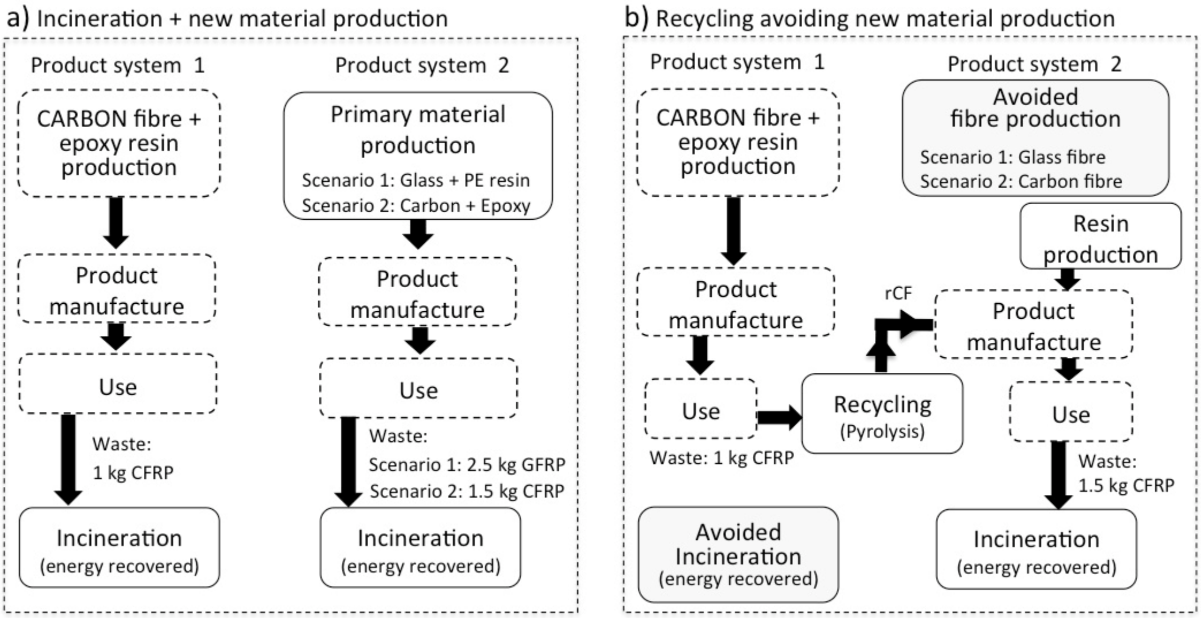

Figure 1a. Shows the incineration system where no recycling occurs and new material is produced as an input to the second product system. **Figure 1b.** Shows the recycling alterative where CFRP waste material is diverted from the incineration process towards recycling and then re-used to displace the virgin material requirement of the secondary product system.

4 Inventory and assumptions

4.1 Materials

A summary of material properties used in this study is shown in Table 1. The CFRP waste is assumed to be composed of only CF and epoxy matrix. Material data for the RCF composite has been selected from literature reporting recovery and re-use of CF via pyrolysis.

Material	***Density* (g/cm^3)**	***E* *(GPa)***	***Matrix* *(Wt%)***	**Fibre *(Wt%)***	**Filler *(Wt%)***
Waste material (CFRP)	1.60	-	35	65	-
RCF composite [13]	1.34	25	57	43	0
SMC (GF) [14]	1.90	11	30	30	40
SMC (CF) [15]	1.55	40	34	66	0

Table 1. Summary of material data used for bending stiffness equivalence and avoided material production calculations.

4.2 Technology descriptions - Incineration

Incineration is a thermal waste treatment process, which converts waste material into flue gas, ash and heat. Modern incinerator technology is assumed for this analysis such as that detailed in Ref [16], which enables embodied energy to be released and harvested. The processes included in this assessment are shown schematically in Figure 2a. We assume that a proportion of the energy recovered is used within the incinerator facility, with the remainder used to obtain both heat and electrical energy. Unburned remains, or bottom ash, are collected and transported to landfill. Flue gas is treated for fly ash separation and washed to remove other harmful components. Energy and ash content of the CFRP waste materials are given in Table 2, with equivalent avoided fuels. The LCI inventory describing efficiency and all relevant emissions from the incinerator has been obtained from Ref [16].

4.3 Technology description – Pyrolysis

Recycling by pyrolysis is assumed as it is reported to be the most commercially developed method for recovering carbon fibres. Assumptions made for this study are based upon the technical specifications of a commercial process [17]. The schematic diagram in Figure 2b shows the processes included. CFRP waste is first reduced in size and fed through a continuous fibre reclamation process comprising of a furnace with multiple zones, heated by electrical elements. Energy requirements for the reclamation of 1 kg of CF have been assumed to be 10% of that required to produce CF. Outputs from the process are: reclaimed carbon fibres, emissions to air and ash resulting from the combustion of the matrix material, which is sent to a landfill. Emissions from a waste incineration process have been applied according the amount of matrix material removed.

	Heating value	***Ash content***	***Avoided heating oil***	***Avoided electricity***
CFRP waste	32 MJ/kg	8 %	7.03 MJ	3.48 MJ
GFRP waste	10 MJ/kg	70 %	2.2 MJ	1.1 MJ

Table 2. Heating values and ash contents of composite material waste and fuel and electricity avoided from energy reclamation during incineration [16,18].

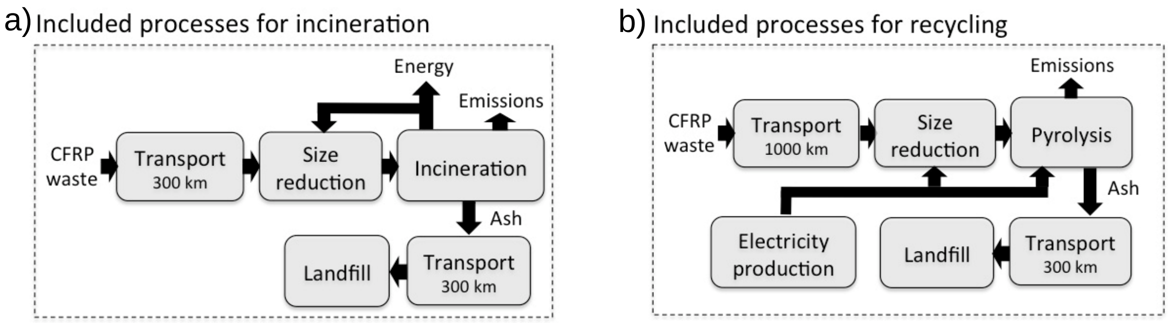

Figure 2a and b. Show the processes included for the incineration and recycling scenarios respectively.

5 Results and Discussion

Potential environmental damage for each scenario has been estimated with using the four following end point categories:

Climate Change: Contributions from green house gasses are converted to kg of CO2 equivalents (eq).

Resources: Determines the effects on resource extraction and non-renewable energy use. (MJ primary).

Human Health: measured in Disability Adjusted Life Years (DALY).

Ecosystem Quality: Damage to ecosystems is expressed in Potentially Disappeared Fraction (PDF) of ecosystem over an area and specific time frame (PDF/m2/yr).

5.1 Scenario 1: (RCF replacing glass fibre)

Figure 3a shows the results of the comparison between incineration with energy recovery and recycling with subsequent re-use of RCF to offset glass fibre production. In this case recycling CFRP waste is less preferable to incineration in three of the four damage categories considered. Damage in the ecosystem quality category was reduced. The change of resin type in the secondary product (polyester to epoxy) influenced this result as epoxy resin was identified to have lower impacts in this category compared with polyester. Figure 3b shows contributions to total impacts in the climate change category from the two alternative waste treatments. Impacts from the production of energy used in the pyrolysis process were higher than impacts from the production of virgin glass fibres, thus resulting in an overall increase in impacts.

5.2 Scenario 2: (RCF replacing carbon fibre)

Figure 4a shows the results the comparison with material re-use scenario 2. In this case recycling CFRP waste results in lower impacts than incineration with energy recovery in all impact categories. Figure 4b shows the principal contributions to climate change impacts for both waste treatment options. Recycling is preferable as the relatively large impacts from primary CF production are avoided.

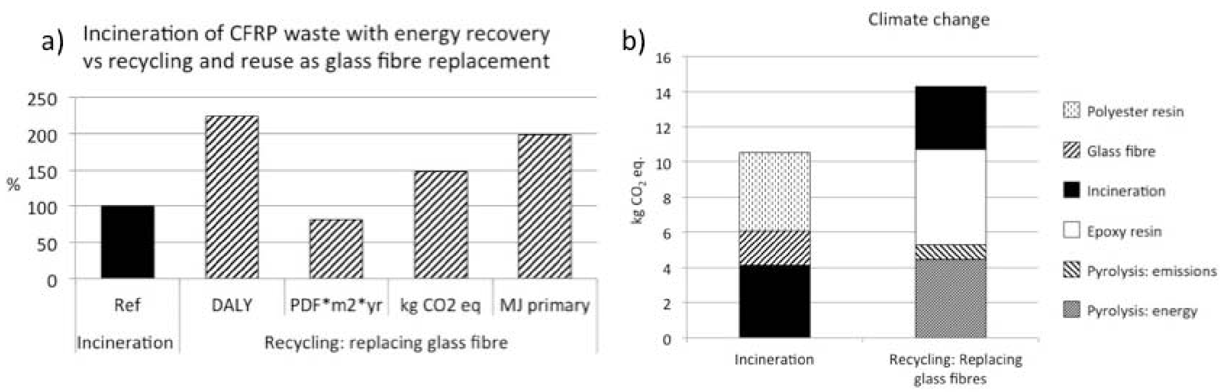

Figure 3a. Shows the results of the comparison between incineration and recycling with re-use Scenario 1(GF replacement). **Figure 3b.** Contribution of materials and processes in the climate change impact category (only contributions above 5% shown)

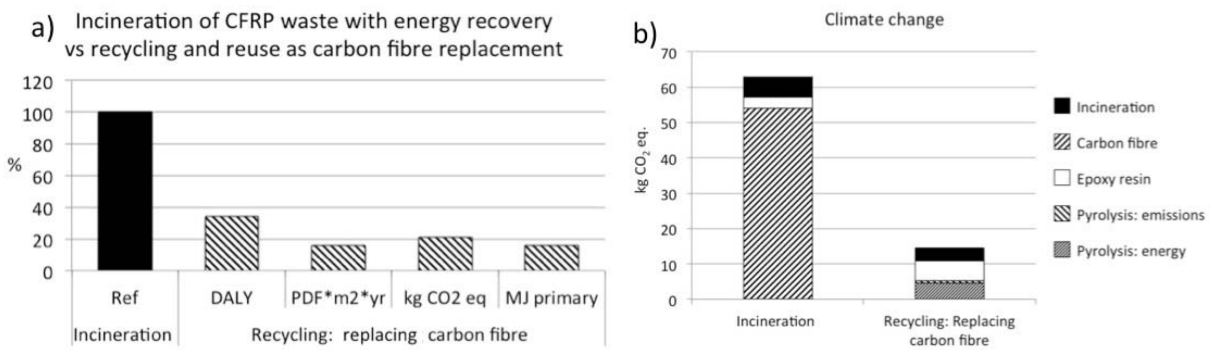

Figure 4a. Results of the comparison between incineration and recycling with re-use Scenario 2(CF replacement). **Figure 4b**. Contribution of materials and processes in the climate change impact category (showing only contributions above 5%)

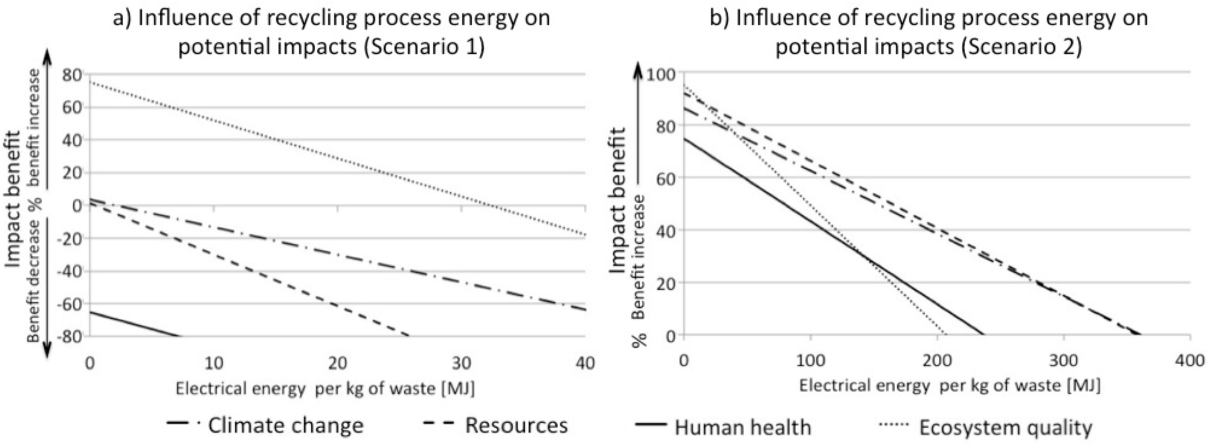

Figure 5a and 5b. Effects of pyrolysis process energy consumption on the environmental benefit of recycling for scenarios 1 and 2 respectively.

5.3 Process energy

Figures 5a and b show the effect of pyrolysis process energy demand on impact change for the glass and carbon replacement scenarios respectively. As reliable energy consumption data was not available, maximum allowable energy was computed per kg of waste treated. In the CF replacement scenario ecosystem quality was the first damage category which limited energy consumption, setting a maximum value just over 200 MJ/kg. Reducing energy consumption for the glass replacement scenario only reduced impacts on ecosystem quality.

6 Conclusions

The results of this work have shown that recycling CFRP waste can be environmentally preferable to incineration with energy recovery if the recovered material is used to offset virgin CF production. It is also shown that the potential re-use of RCF will strongly influence the benefits gained. Re-use of RCF in applications which could displace the production of GF or other low impact materials may lead to higher impacts than if incineration is used to recover energy. This suggests that growth of potential markets for these materials should be targeted towards applications where higher impact materials can be displaced to ensure environmental gains are made.

The work also shows that the application of LCA is key for increasing understanding related to the environmental performance of these materials and that such work is key for selecting potential applications and waste disposal strategies which are environmentally appropriate.

Acknowledgements

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