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Official URL: <https://doi.org/10.1016/B978-0-444-63576-1.50029-7>

To cite this version:

Vo Dong, Phuong Anh  and Azzaro-Pantel, Catherine  and Boix, Marianne  and Jacquemin, Leslie and Domenech, Serge  *Modelling of Environmental Impacts and Economic Benefits of Fibre Reinforced Polymers Composite Recycling Pathways*. (2015) *Computer Aided Chemical Engineering*, 37. 2009-2014. ISSN 1570-7946

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Modelling of Environmental Impacts and Economic Benefits of Fibre Reinforced Polymers Composite Recycling Pathways

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Abstract

In the last few years, composites have been used increasingly in different applications (aerospace, automobile, industry, sports...). Both environmental and economic factors have driven the development of recycling pathways for the increasing amount of fibre reinforced polymer (FRP) scrap generated. A recycling system for FRP has to be designed to recover and reuse the fibre and matrix content of the scrap. The objective of this paper is to model and compare the different routes of end-of-life FRP from both environmental and economic viewpoint combining Life Cycle Assessment and Cost-Benefit Analysis. More precisely, mechanical recycling, pyrolysis and fluidized bed are investigated and compared to low value end-of-life solutions (incineration, co-incineration and landfill) both for Glass and Carbon FRPs. Pyrolysis turns out to be an attractive recycling solution for CFRP that satisfies both environmental and economic benefit while co-incineration seems more promising for GFRP.

Keywords: composite recycling, fibre reinforced polymers, waste management, environmental impacts, economic benefits

1. Introduction

Fibre reinforced polymers (FRP) are composite material made of polymer matrix reinforced with fibres. Due to their low density, FRP are increasingly used in structural applications to replace more conventional materials (steel, aluminium, alloys...) in order to design lighter products especially in the aeronautics sector. Despite all advantages associated with FRP, the increasing use generates also an increasing amount of FRP waste. Common sources of waste include out-of-date preregs, manufacturing cut-offs, testing materials, production tools and end-of-life (EoL) components. The global demand of carbon fibres is expected to exceed production capacity in 2015 if growth remains at this rate and recycling could be a fibre supply solution in order to meet future demand (Black, 2012). However, the complex composition of FRP makes recycling more complex than typical thermoplastic recycling. Unlike thermoplastics, the thermoset FRP scrap cannot be melted down and remoulded, as is often done in plastic recycling. Most of the FRP waste is currently landfilled or incinerated but these solutions are far from being satisfactory from environmental, legislation and economic viewpoints (Yang et al., 2012).

The aim of this study is to use process systems engineering methods to model and compare the recycling pathways of Carbon Fibre Reinforced Polymers (CFRP) and Glass

Fibre Reinforced Polymers (GFRP). Unlike glass fibres that are generally ten times cheaper due to their simple fabrication by fusion, carbon fibres are high-value added products because of their high technical properties and complex production. Despite differences in fibre nature, the recycling techniques of these thermoset composites exhibit similar principles. Due to high durability of polymer matrix, the technologies like torrefaction and fast pyrolysis cannot be applied to FRP. The analysis of the relevant literature highlights that if technical solutions are readily available, they are developed at different scales of process maturity, i.e., industrial scale for mechanical recycling and pyrolysis, pilot and laboratory scales for fluidized bed and chemical recycling (Yang et al., 2012). More precisely, mechanical recycling, pyrolysis and fluidized bed are investigated and compared to low value EoL solutions (incineration, co-incineration and landfill) through a combined use of a Life Cycle Assessment (LCA) and a Cost-Benefit Analysis. The inventory, data collection will be described together with the evaluation of the economic and environmental impacts for the selected scenarios.

2. A methodological framework for recycling pathway evaluation

2.1. FRP recycling pathways

The recycling pathway alternatives considered in this work and the system boundaries are summarized in Figure 1. The recycling units are assumed to be located in France. The composite waste is cut on the dismantling site and then transported either to the landfill site or to any other recovery facility. All the different recycling technologies are assumed to be available to treat the FRP. The typical features of each process will be shortly presented together with the analysis.

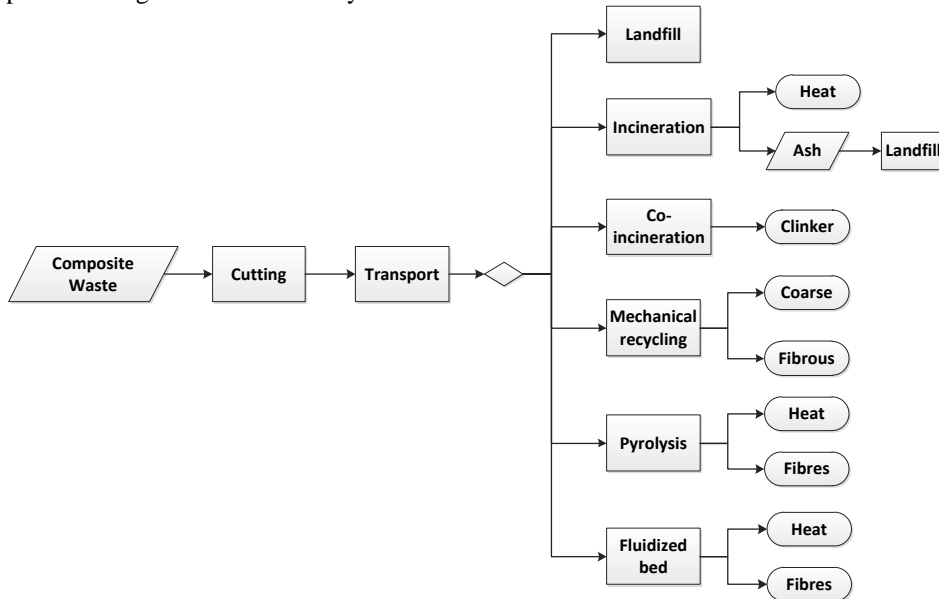


Figure 1: Recycling pathway alternatives and system boundaries

2.2. Life Cycle Assessment

The functional unit (FU) defined for this study is 1 kg of cured FRP waste to be treated by one of the proposed technology. A product life cycle consists in four individual phases: raw material extraction, production, utilization and EoL. Within the limits of this study,

only the environmental impacts of the EoL activities of the composite are assessed. Data on the energy requirements and emissions of the recovered product from the different waste scenarios were collected to analyse the influence of these paths. The calculations are based on elementary environmental impacts coupled with the LCA software SimaPro 7.3. Although LCA is identified as a multicriteria environmental management tool, the analysis is limited in this work to climate change impacts (CCI), evaluated on a kg CO₂ eq. basis performed by the ReCiPe Midpoint (H) v.1.06 assessment method.

2.3. Cost-benefit analysis

Cost-benefit analysis (CBA) is a simple method in which all expenses and incomes of an activity are considered to a cash balance (Farel et al., 2013). Its principle is summarized in Eq. (1).

$$CBA = \sum Benefits - \sum Costs \quad (1)$$

This allows determining whether an activity can promote economic profits or which solutions generate the most profit. This method is applied in this preliminary study to analyse the differences of economic benefits among the pathways of EoL composites. In this context, CBA is simplified and the total expenses are mainly based on the price of the process energy requirement and on the average cost of transport. The benefit of the recovery centres comes from the sale of recycled materials to the manufactures as raw materials and the savings of energy, i.e. “avoided energy”, which is released from the production process.

3. Modelling FRP recycling processes and inventory data

3.1. General assumptions

Due to the lack of FRP specific data for recycling, the system is modelled by a “black-box” approach, i.e. changes in waste composition during the treatment are not considered, but only fixed input-output data of the system are studied in this preliminary study. In each process, input-output data are estimated both from typical operating conditions of the considered processed obtained from a literature survey and on the basis of the information available, from SimaPro database. Data were also collected from the European Environment Agency (EEA) and Eurostat. The cost of electricity from French average power mix (with 78 % rate from nuclear energy according to SimaPro 7.3) is fixed at 0.085 €/kWh (Eurostat, 2014). The composite waste is supposed to be a continuous fibre reinforced thermoset resin and composed of 60 vol% in fibre and 40 vol% of resin. No contaminant, metallic insert, flame retardant agent, hazardous substance and filler is considered in the composition of FRP waste. In this study, FRP waste is classified as a non-hazardous waste. In each scenario, the composite is firstly shredded with an amount of energy of 0.0025 MJ/kg (Witik et al., 2013) and then transported over a distance of 100 km from the site of dismantling to the site of treatment by a 40-ton truck with an average cost in Western Europe of 0.14 €/t.km (Schade et al., 2006). The avoided impacts and the prices of the recovered products are summarized in the Table 1.

Table 1: Prices and avoided impacts of the recovered products (Witik et al., 2011; Duflou et al., 2012; Job, 2013; SimaPro databases)

	Carbon fibre	Glass fibre	CaCO ₃
Price (€/kg)	12	1.6	0.25
Climate change Impacts (kg CO ₂ eq/kg)	22.4	2.6	0.0132

3.2. Recycling alternatives

3.2.1. Landfill

The environmental impacts of landfill are assessed by the model of “sanitary landfill of mixed plastics” extracted from SimaPro databases because composite material specific data were not available. The total charge of landfill in France is about 80.5 €/t according to EEA (2013).

3.2.2. Incineration

Incineration is a thermal process, which allows recovering energy in heat resulting of waste combustion. The heat can be used directly or converted into electricity. In this scenario, the heat from the process is converted to electricity with an efficiency of 35 % and the process is assumed to be auto-thermal. The emissions of 1 kg FRP from combustion are presented in Table 2. The ash by-product is landfilled as an inert waste.

Table 2: The outputs of 1 kg FRP incineration (Hedlund-Åström, 2005; Job, 2013)

	Ash (wt%)	CO2 emission (kg)	Net heat of combustion (MJ)
CFRP waste	9.65	3.39	31.7
GFRP waste	75	0.61	12

3.2.3. Co-incineration

Although incineration and co-incineration are both based on combustion of waste, co-incineration allows material recovery besides energy recovery. Indeed, in co-incineration, waste is used as a substituted fuel involved in clinker fabrication.

3.2.4. Mechanical recycling

The principle of this technique is to separate fibres from matrix by a grinding process. However, the obtained product is a mixture of polymer and fibres composed of two fractions, i.e., a coarse one, which is rich in matrix and a fibrous part, rich in fibre. Because of the reduction of mechanical properties, the products are generally used for low value-added applications like filler in concrete (Job, 2013). In this scenario, the necessary energy for the process is estimated at 0.27 MJ/kg of composite, the yield is supposed to be 100 %, i.e. all of FRP waste is recovered. In the case of CFRP, according to Palmer et al. (2010), 24 % of composite waste can be used to replace the equivalent quantity of glass fibre in SMC without important degradation of mechanical properties; the remaining is used as calcium carbonate. In the case of GFRP, all products obtained from grinding composite are considered to replace calcium carbonate.

3.2.5. Pyrolysis

Pyrolysis is a thermal recycling process that decomposes the matrix at around 400 to 600 °C according to its thermal properties to recover fibres. The main characteristic of this process is the thermal decomposition in an inert environment or in a controlled atmosphere with a low proportion of oxygen to avoid the oxidation of fibres. A rapid gasification might be needed after the principal step to clean the fibres from char of resin decomposition. Gas fraction produced from the decomposition of matrix can be condensed to be reused as a fuel or burned to recover heat. In this study, the pyrolysis is assumed as the combustion of the matrix. The total energy used in pyrolysis which is estimated at about 30 MJ/kg composite (Witik et al., 2013). This recycling pathway is the most developed until now (Yang et al., 2012). The recovery rate of fibre is considered to be 95 % in this study. The recycled fibres are supposed to be used as reinforcement in composite, such as for SRIM (Structural Reaction Injection Molding).

3.2.6. Fluidized bed

In this process, the sand is fluidized by the hot air flow at a temperature of 450-550 °C with a velocity of 0.4-1.1 m/s. In these conditions, the organic matrix is volatilized and the fibres are thus released. The fibres are sent out of the bed by gas flow. After the fibres are recovered, the gas passes through a secondary combustion chamber where the polymer is completely decomposed. This technique is still at both development stage and pilot scale (Yang et al., 2012). The needs for electricity are estimated at 15.5 kWh/kg of composite and the fibre yield is fixed at 67.5 % in this scenario from the conditions of laboratory test of Pickering et al. (2000). As for the pyrolysis process, the recycled fibres from this technique are used as reinforcement in composite, such as for SRIM.

4. Results and Discussion

4.1. Case 1: CFRP waste treatments

The Climate Change Impacts and the CBA of six EoL scenarios of CFRP are presented in Figure 2 (a). In this case, the material recovery is the most important factor of CFRP waste management because of the high value of carbon fibre in market and reduction of the important avoided impacts by replacement of virgin carbon fibre. All of the recycling techniques studied in this work generate more profits and have less the environmental impacts than the energy recovery techniques (incineration, co-incineration). Composite combustion and landfill of ash are not only penalized from the economic viewpoint since they do not lead material recovery but the resulting emissions also contribute to the total positive Climate Change Impacts of these pathways. At this stage, pyrolysis remains the best solution for recycling CFRP wastes. Indeed, it leads to the best economical profit and generates a low environmental impact. This is probably due to the highest maturity of this technology for carbon fibre recovery compared to other processes.

4.2. Case 2: GFRP waste treatments

In this case (see Figure 2 (b)), the choice of the technology is not as clear as for CFRP if pyrolysis remains a good alternative regarding the economic term. Co-incineration is a better competitor from an environmental point of view. It can also be emphasized that the profit of GFRP pyrolysis is lower than the one of CFRP pyrolysis due to the lowest added value of glass fibre compared to carbon fibre. More generally, the low value of glass fibres influences the environmental benefits of GFRP waste management.

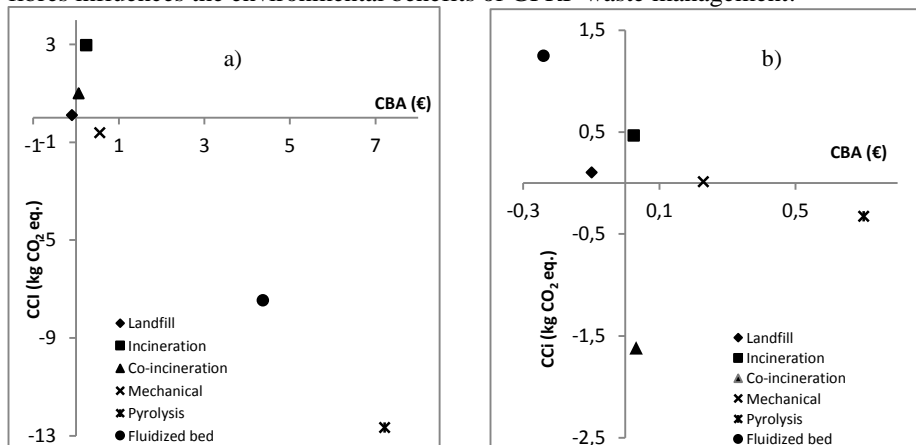


Figure 2: Evaluation of EoL pathways, (a) for CFRP, (b) for GFRP.

A process such as fluidized bed will not present the same advantage for CFRP and GFRP. This technique is outperformed by landfill pathway for GFRP. Since glass fibre is incombustible, the material recovery after combustion in co-incineration seems more promising than the incineration pathway.

5. Conclusions and Perspectives

This study proposed a model of the overall system of FRP waste pathways and an evaluation of environmental and economic impacts of each alternative. The results show the importance of the value of the recovered products and of the maturity of techniques on waste management. For CFRP, pyrolysis is an attractive recycling solution that satisfies both environmental and economic benefit. However, for GFRP wastes, it is not so obvious: mechanical recycling and co-incineration are possible alternatives. A weak point for GFRP waste recycling is the low value of the recovered product that may impact the total benefits.

This model will be then extended to other possibilities for FRP waste management (chemical recycling for example) and to various transport types while considering more complexity in FRP waste composition the multi-purpose nature of the recovered product. Economic impacts will be analysed thoroughly by considering investment, labour cost and other costs (dismantling, collection, stocks...). Environmental assessment will be carried out considering other environmental impacts other than those related to climate change. The recycling chain has indeed to be considered as a whole, and must be managed with respect to all the involved stakeholders. Multiobjective optimization has potential to examine the different compromise solutions to design a recycling system with respect to economic and environmental purposes.

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