TOWARDS A CIRCULAR ECONOMY FOR END-OF-LIFE CARBON FIBRE COMPOSITE MATERIALS VIA FLUIDISED BED PROCESS

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ABSTRACT

Carbon fibre reinforced plastic (CFRP) recycling shows reductions in environmental impacts compared to virgin carbon fibre (CF) production, but limited understanding of the financial viability of potential recycling technologies and reutilisation of recycled carbon fibre. In this study, we develop life cycle cost models to quantify cost impacts of recovering CF and using rCF products as substitutes for conventional materials (e.g., steel, aluminium) in automotive applications. Cost models including capital and operational costs are developed from process models of carbon fibre recycling and component manufacturing, and impacts on fuel consumption during vehicle lifetime. Mechanical properties of the resulting recycled CFRP are experimentally measured and accounted in the life cycle cost evaluation to ensure materials are compared on functional equivalence. A vehicle beam component, originally made of mild steel, is selected as a case study for lightweighting analysis via material substitution based on equivalent functional stiffness.

The minimum selling price of rCF set from net present value show sensitive to fluidised bed recycling plant capacity and feeding rate with up to \$5/kg. Financial analysis demonstrates that rCF composites induce significant cost reductions mainly due to the weight reductions under equivalent stiffness, indicating the market opportunities of rCF products. We use the financial results to set targets for the development of fibre alignment technologies that are currently under development and it could potentially improve financial performance provided technology development targets are met. These results show financial advantages of the CF recovery and reuse via material substitution for lightweighting, which supports the emerging commercialisation of CF recycling technologies.

1 INTRODUCTION

Carbon fibre (CF) demand for 2015 is estimated at approximately 68,000 tonnes, equating to a three-fold growth rate in 10 years [1]. From CF manufacturing to final carbon fibre reinforced plastic (CFRP) component production, approximately 18,000 tonnes of this CF will end up as manufacturing waste. The remaining 50,000 tonnes will go into finished parts that will have to be disposed of at end-of-life [2]. As CFRP materials are used in a wide range of products, from long-life aerospace applications to consumer sporting goods, time to end-of-life could vary from perhaps 2 to 40 years. Quantities of CFRP waste are expected to increase quickly into the future, including 6,000-8,000 commercial aircrafts expected to come to their end-of-life by the year of 2030 [3, 4].

The high energy intensity and cost of virgin CF (vCF) manufacture also indicates the possibility of recovering CF at lower cost than vCF. Direct energy consumption of vCF is 198-595 MJ/kg [4-7] from acrylonitrile and manufacture of vCF costs £20-40/kg (\$33-88/kg) [4]. The drivers for recycling are also from industries and legislations. In the automotive industry, legislations are on the disposal of composites waste including EU Directive on Landfill of Waste[8] restricting minimum wastes going to landfilling and End-of-life Vehicle Directive[9] requiring 85% of a vehicle to be recyclable from 2015.

Ideally, waste CFRP treatment should maximise value that can be extracted through CF recovery while achieving the lowest environmental impact. The current processes for the recovery of CF can be divided into mechanical processes, thermal processes including fluidised bed and pyrolysis technologies and chemical processes [10]. The fluidised bed process oxidising the epoxy matrix, allowing CF recovery with minimal degradation of mechanical properties have been developed at the University of Nottingham. The subsequent manufacture of lightweight components from recycled CF (rCF) by papermaking or fibre alignment conversion processes and final compression moulding or injection moulding manufacturing processes can potentially address cost barriers that currently restrict the uptake of CFRP in automotive applications. To date, however, there is limited understanding as to the potential financial and environmental viability of CFRP recycling processes and rCF reuse.

Therefore, for the full implications of any use of rCF to be considered, processes, performance, commercialisation and markets need to be combined to quantify environmental and cost benefits of CFRP recycling operations. In this paper, a techno-economic model analysis is undertaken to determine the financial viability of producing automotive components from rCF. The analysis considers: 1) the minimum rCF selling prices of a fluidised bed recycling process; 2) cost of manufacturing automotive components from rCF, competitor lightweight materials (vCF, aluminium) and conventional materials (steel); and 3) in-use fuel costs.

2 METHODS

Techno-economic models are developed to assess the feasibility of rCF use in automotive applications. The techno-economic analysis includes cost modelling of CFRP recycling in the full life cycle while assembly and end-of-life stages are excluded in this study. a) CF recycling by fluidised bed process, b) processing of rCF, c) manufacture of rCFRP into automotive component, d) in-use fuel cost. Life cycle cost of rCFRP parts are then compared to competitor lightweight materials (e.g. steel, aluminium, vCFRP) to assess potential financial viability in automotive component manufacture.

The techno-economic model is based on material functional requirements, manufacturing energy use from previous process models which account for manufacturing parameters, materials, and component dimensions. It includes capital cost (CAPEX) such as equipment and financing, and operational cost (OPEX) such as fixed operating and maintenance, utilities costs (energy), depreciation and overheads of CF recycling and reutilisation of rCF. Taxes, subsidies, and profit margins are not included in the analysis. Minimum rCF selling price of CF recycling by fluidised bed can determined based on characteristics and key parameters (plant capacity; CF feed rate) of a fluidised bed recycling process.

Overview of pathways and processes for manufacture of automotive components from rCF is as follows:

1) Random structure – Compression Moulding: rCF is processed by a wet papermaking process prior to impregnation with epoxy resin and compression moulding.
2) Aligned – Compression Moulding: rCF is processed by a fibre alignment process prior to compression moulding with epoxy resin.
3) Random structure – Injection Moulding: rCF is processed by wet papermaking and subsequently chopped prior to compounding with polypropylene (PP); rCF-PP pellets are subsequently injection moulded.

For comparison, similar composite materials produced from vCF are considered, specifically:

1) Woven – Autoclave: bi-directionally woven vCF is autoclaved moulded from prepreg with epoxy resin.
2) Chopped – Injection Moulding: chopped, unaligned fibres are compounded with PP; vCF-PP pellets are subsequently injection moulded.

The CF-based materials are also compared with mild steel, as a conventional automotive material, and potential lightweight materials (aluminium).

2.1 Capital and operational costs

The CAPEX estimation is undertaken by estimation for a hypothetical recycling plant and part production volume of 50,000 parts/yr to account for mass differences of different candidate materials. It is achieved by defining the recycling process, designing and costing of the plant and scaling up to the plant capacity required. CAPEX is estimated based on standard equipment, sized to required capacity and non-standard equipment from pilot plant using the factor method given by [11, 12]. All major equipment items are designed and costed based on the process information described below.

Costs are then extrapolated to year 2015 costs based on the Chemical Engineering Plant Cost Index [13]. An exponential relationship as shown in Eq. (1) is used to estimate equipment capital costs for different plant capacities. Normalised annual CAPEX is calculated assuming a 15% of return tax rate for a plant life of 10 years [14] where needed for part cost prediction.

$$C_v = C_u\left(\frac{v}{u}\right)^n \tag{1}$$

Where C_v is the equipment CAPEX with capacity v, C_u is the reference equipment cost at capacity u. A scaling factor (n) of 0.6 is assumed.

The annual operational cost is calculated as the sum of operating costs (labour, material, utility), plant overheads, maintenance cost, etc. This is mainly based on the factor method proposed by [11] but cost information is updated based on actual component of pilot plant or standard equipment where available. The labour cost is estimated based on an hourly pay rate of £18.2 ($27.7) in 2015 [15] for plant operation requirement of 3 shifts per day across 250 days per year. Other operational costs including materials, utilities, plant overheads and maintenance are obtained from literatures and adjusted to the plant capacities selected in this study.

2.2 Assumption and input data

The overall fluidised bed process consists of two main sub-processes, i.e. a shredding process and a fluidised bed process. Additional processes (e.g. post-curing) are not included. Process models of fluidised bed recycling plant have been developed in our previous study [16] and are used in this study to calculate energy requirements as utilities cost. Main components of the fluidised bed plant are shown in Figure 1, consists of shredder, fluidised bed reactor, cyclone, heat exchanger, electrical fans and pipework. The rCF minimum selling price is calculated for a set of operational parameters including plant capacity (50-6000 t/yr) and feed rate per fluidised bed area (3-12 kg/hr-m^2).

Recycled CF cannot be directly manufactured into CFRP, so it has to be converted by current wet papermaking process into random rCF mats or fibre alignment process into aligned rCF mats. Capital cost is estimated based on standard equipment using processing parameters from lab/pilot plant. Energy analysis of papermaking process has been performed based on the processing parameters previously [16] and used for energy cost estimation in this study. As the fibre alignment process is under development, no cost information is available for fibre alignment rig yet while there is a target cost that aligned rCF intermediate materials must achieve to compete with available random rCF materials.

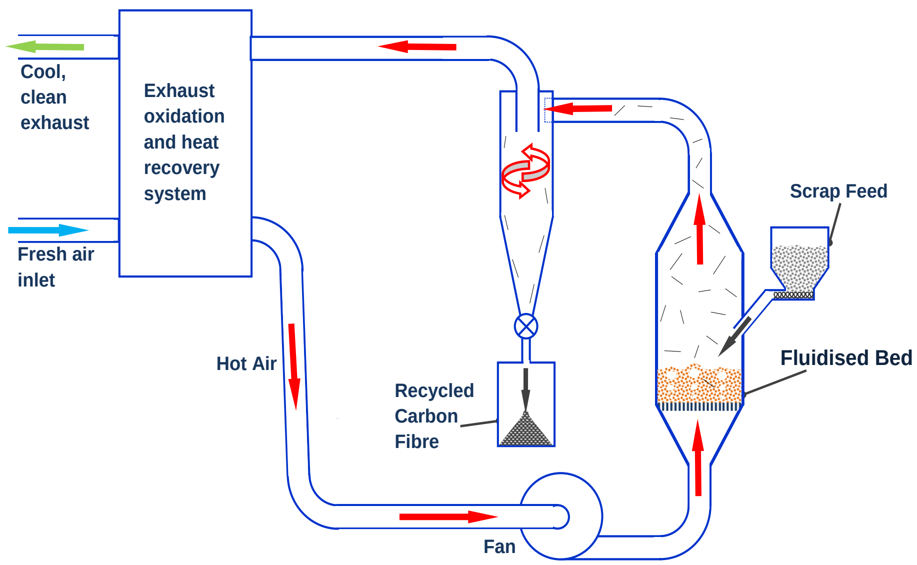

Figure 1: Main components and flow directions of the fluidised bed CFRP recycling process

After processing, rCF can be directly manufactured into the final CFRP products by either compression moulding or injection moulding from random/aligned rCF mats is estimated. The main equipment consists of a compression moulding press and a trimming machine of which fixed capital is $1,876k is estimated [17]. The injection moulding facility is made up of compounding, injection and trimming machines and the equipment capital cost ($24,822k) is obtained from literature [17] and scaled up to the required capacity and extrapolated to 2015. Operational cost is based on material requirements as in the discussion of material substitution under equivalent stiffness, manufacturing energy use (based on previously presented models of energy consumption), etc.

The reference automotive component is assumed to be made of hot rolled steel coil. The manufacturing devices are assumed to include a coil handling and a stamping equipment (CAPEX is $17,388k) and the manufacturing energy is 0.09 kWh/kg [17]. Aluminium is assumed to be manufactured by wrought methods including casting, punching and machining units (CAPEX is $5,960k) and the total energy requirement is 5.12 kWh/kg [18]. vCF is either manufactured by autoclave moulding (CAPEX is $137k [19]) into woven vCFRP or by injection moulding into chopped vCFRP similar as for rCFRP. Operational cost including materials, labour and utilities for these manufacturing processes are obtained from process models, literatures or online database [18-21].

In the use phase, the automotive part will influence vehicle fuel consumption due to its weight. Mass-induced fuel consumption and fuel reduction values are estimated for internal combustion engine vehicles [22, 23] to estimate the fuel use impacted by its weight [24]. A typical vehicle life of 200,000 km and the petrol price at £1.11/litre ($1.70/litre) in 2015 in UK [25] are assumed for the estimation of use phase fuel cost.

2.3 Functional unit

General automotive components, assumed to be made of mild steel and allocated a normalised thickness and mass of 1, are selected in this study When evaluating alternative materials, it is ensured functional equivalence is maintained by considering the design material index and varying component thicknesses to account for differences in each material's mechanical properties. Then a comparative financial analysis can be performed for rCF to achieve equivalent mechanical performance relative to virgin materials as explained below. For constant stiffness [26], mass ratio among components made of different materials is expressed below:

$$\frac{m_2}{m_1} = \frac{\rho_2}{\rho_1}\left(\frac{E_1}{E_2}\right)^{1/\lambda} \tag{2}$$

Where E_1, ρ_1 are the tensile modulus, thickness and density of reference materials (i.e. mild steel), E_2, ρ_2 are the tensile modulus, thickness and density of replacing material, (e.g. aluminium, CFRP), λ is the component-specific design material index. Depending on design purposes, the structural index λ value may vary between 1 and 3. λ=2 is for beam under bending and compression conditions in one plane as selected in this study

3 RESULTS AND DISCUSSION

3.1 CF recovery

Recovery of CF from CFRP wastes can be achieved at $5/kg and less across a wide range of process parameters. Figure 2 shows the minimum selling price of rCF with a breakdown costs at a range of capacities between 50 and 6,000 t/yr. The cost includes all variable and fixed costs plus the sale revenue from heat recovery associated with the construction and operation of the fluidised bed recycling plant. The relative contribution of fixed and operational costs is highly dependent upon the plant capacity for recycling. At capacities in excess of 500 t/yr, an rCF minimum selling price of less than $5/kg can be achieved. Operation at smaller capacities however is detrimental to financial viability: at relatively low capacity of 100 t/yr, rCF would have to achieve a market value of up to $15/kg to be financially feasible. This is primarily because of the higher relative share of fixed capital and labour costs. At all plant capacities, operational cost accounts for over 50% of the total cost of recycling. It is also noted that the sales from heat recovery make similar amount of contribution (-$0.17/kg) to the rCF minimum selling price under different capacities. However, as the recovery of heat depends on having a customer for heat, this could bring 1%-14% sensitivity of minimum selling price if excluding the sales revenue from heat recovery based on the plant capacities. Costs for sorting, dismantling and transport of waste CFRP to the facility are not included, but this can represent a significant cost, particularly if manual disassembly is required.

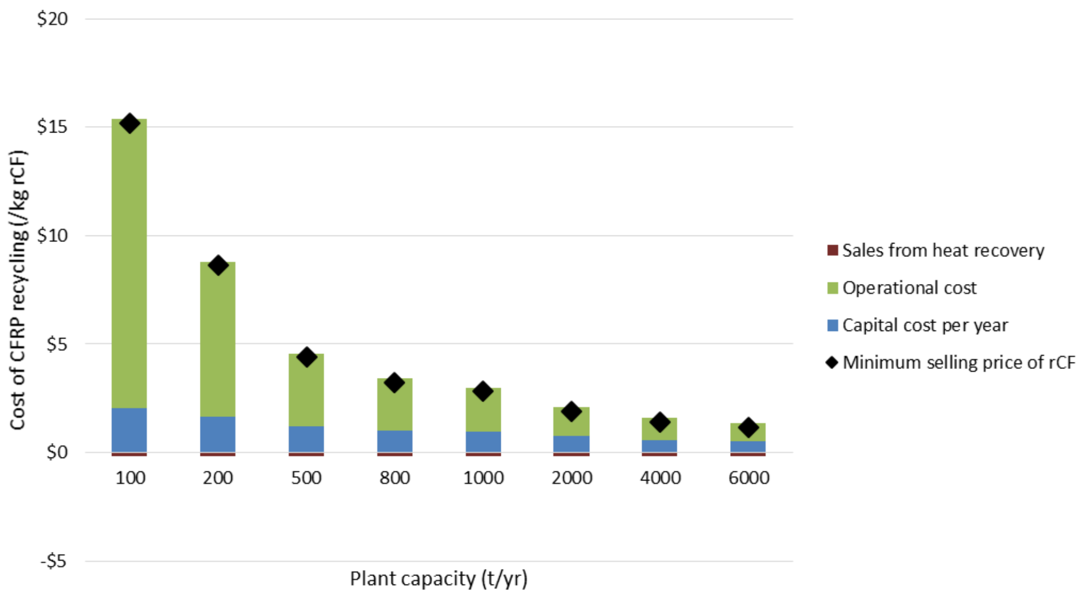

Figure 2: Minimum selling price of rCF and breakdown cost components for different plant capacities at feed rate of 9 kg/hr-m^2.

The minimum selling price per kg rCF varies from $3.9 to $2.0 with respect to feeding rate of 3 kg/hr-m^2 to 12 kg/hr-m^2. Prior analysis [16] also shows feeding rate is a key factor for environmental impacts which is correlated to the energy input. For a fixed plant capacity, with the increase of feed rate per unit bed area, the size of equipment can be reduced. Therefore, the annualised capital cost reduces relative to the increase of feed rate. Also, plant with higher feeding rate consumes less energy and thus has less operational cost due to less utilities cost while the other costs including labours remain unchanged.

3.2 Complete life cycle cost

Lightweighting materials including rCFRP materials tend to present the net financial benefits relative to steel as fuel savings in use phase due to weight reductions outweigh higher initial material costs. However, in some case, there is no cost advantage for lightweight materials including rCFRP over conventional materials. This is attributed to the impact of rCF content on material and manufacturing costs and different manufacturing methods of rCFRP materials (e.g. compression moulding, injection moulding).

With the increasing fibre content, rCFRP materials show better mechanical performance. Thus increasing the fibre volume fraction in CFRP materials is beneficial in reducing component mass for functional equivalence with steel. Significant weight reductions are seen in increasing the fibre content of random rCFRP components from 20% vf (54% reduction) to 30% vf (58% reduction); however, further increase to higher volume fractions of 40% vf compromises the weight reductions due to fibre damage during the manufacturing process while it achieves the same weight reduction as for 30% vf. Although achieving further high fibre volume fractions of 50% and 60% provides 65%-67% weight reductions, this requires new fibre alignment techniques, which are still under development.

Weight savings achieved during substitutions can lead in-use fuel saving and thus potential life cycle cost benefits. The normalised life cycle costs including vehicle use for material substitution in car beam are shown in Figure 3. The life cycle result of the reference steel part is presented and the life cycle cost of $266/part is normalised to 1. Life cycle cost of the parts made of rCFRP materials and other alternative lightweight materials are compared relative to steel. Composites manufactured from rCF can achieve significant reductions in life cycle cost and other lightweight substitution materials. However, the life cycle cost benefits from substitution are dependent on the automotive component design constraints as discussed in Section 2.7.

For car beam under bending and compression conditions in one plane, rCFRP components can significantly reduce cost relative to steel over the full life cycle. For random rCFRP parts with different fibre volume fractions, total normalised cost varies between $1.12/part for 20% vf, $0.98/part for 30% vf and $0.98/part for 40% vf. It is noted that for random rCFRP, from 30% vf to 40% vf, the life cycle cost is not expected to be reduced as from 20% to 30%. This is primarily because of unmatched weight reductions achieved between 20%-30% and 30% to 40% as discussed above. Raw material costs account for a large part of the life cycle cost (23%-29%) primarily due to the high cost of epoxy resin. On the contrary, although use phase cost of random rCFRP parts is 42%-46% that of steel part, these benefits do not compensate the material and manufacturing cost.

Compression moulding random rCFRP part costs only 61%-70% of that for injection moulded random rCFRP part in the full life cycle. Compression moulding random rCFRP part with higher fibre volume fraction (20% - 40%) shows better mechanical performance than injection moulded part, which results in different weight reductions (54%-58% vs 47%) in replacement of steel. Therefore, injection moulded random rCFRP part with 18% vf has less fuel savings and as such higher life cycle cost compared to compression moulded rCFRP part.

The life cycle cost results are used to set targets for the development of fibre alignment technologies that are currently under development. The diagonal column on Figure 3 shows the target cost that aligned rCF intermediate materials must achieve to compete with best available random rCFRP (i.e. rCFRP with 30% vf). If rCF can be produced at a cost of $3/kg at an annual throughput of 1000 t/yr, higher processing costs (i.e., fibre alignment cost) could be accommodated for high quality aligned rCFRP products to achieve the same cost level as the random rCFRP products or steel under different design constraints in the full life cycle. The target fibre alignment cost is $21.2/kg aligned rCF mat compared to $11.8/kg random rCF mat.

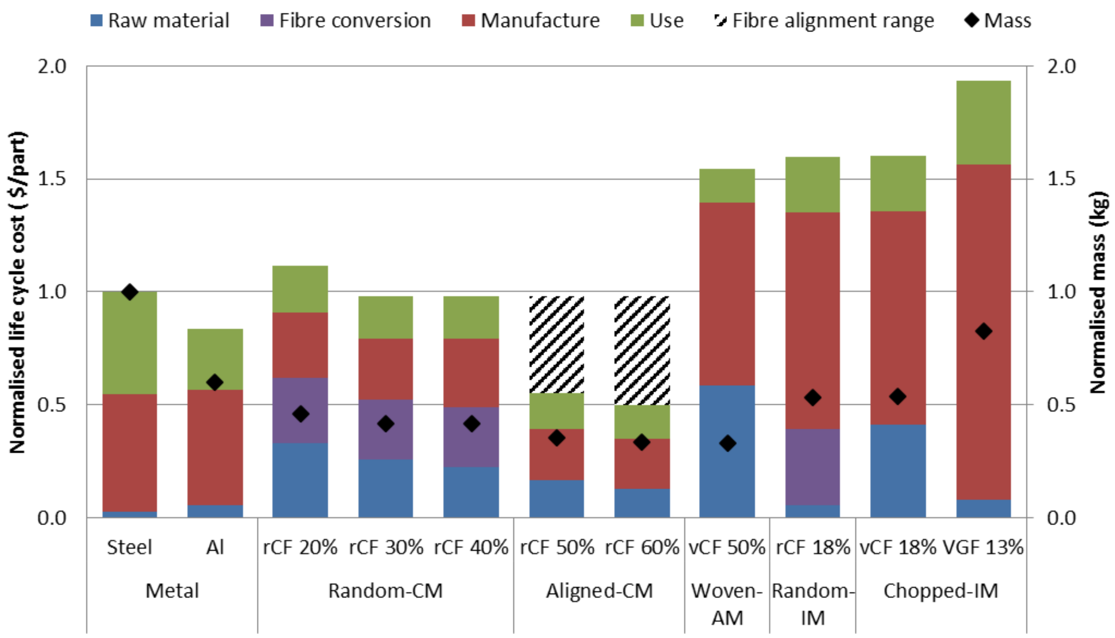

Figure 3: The normalised life cycle cost of the automotive beam made of steel and substitution materials. Diagonal columns represent fibre alignment cost range allowed to breakeven with other competitors.

It is also noted that due to extremely high cost of vCF, the total life cycle cost does not present significant benefits especially for low fibre volume fraction ($1.6/part for vCF 18%). But vCFRP parts with high fibre volume fraction (50%) show cost savings relative to steel due to the fuel savings from weight reductions outweigh vCF production cost. Conventional lightweight aluminium shows 16% cost savings.

3.3 Cost target for aligned rCFRP

In order to provide 60% weight saving or more over steel, high performance carbon fibre composites are required, such as woven vCF prepreg and aligned rCFRP. In Figure 5, the magnitude of life cycle cost of rCFRP against weight savings is compared to that of steel and other substitution alternative materials based on λ=2. Cost data for members of a particular group of material (e.g. vCFRP, rCFRP) cluster together and can be enclosed by an envelope. Results indicate large cost savings together with weight savings by using high-fibre-volume-fraction rCFRP for material substitution. Compared to vCFRP, providing the same weight reduction, aligned rCFRP materials potentially lead larger life cycle cost reductions in replacement of steel in automotive parts. This demonstrates fibre alignment could potentially improve financial performance provided technology development targets are met.

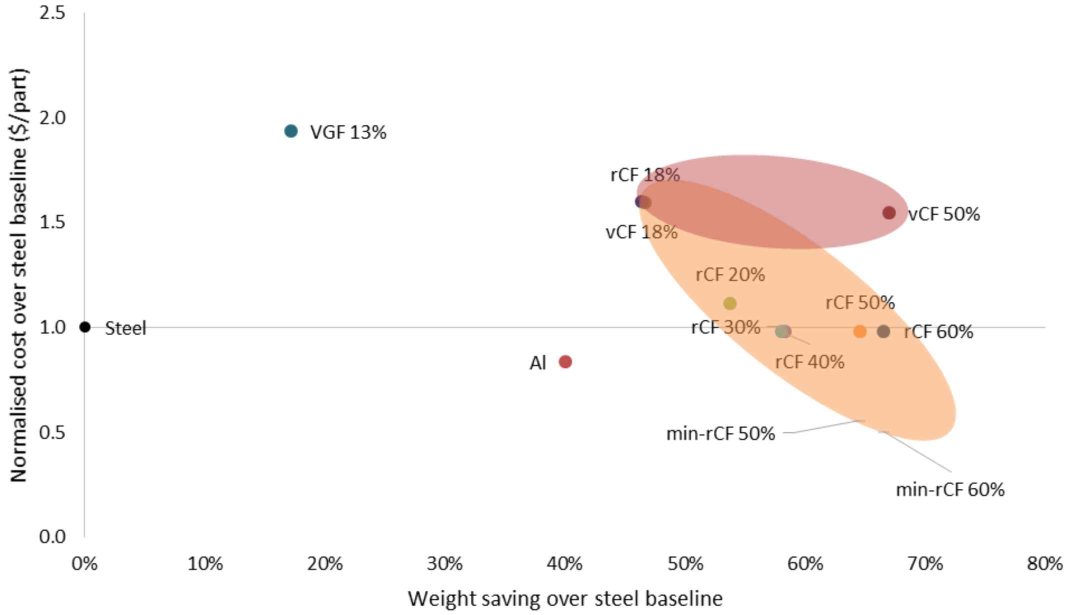

Figure 4: Weight saving for car beam under equivalent stiffness against cost target relative to steel baseline.

4 CONCLUSIONS

The need for a systematic identification of utilisation of rCF materials in order to reduce life cycle costs have been addressed. In the paper, techno-economic models have been developed for cost impact assessment of a hypothetical commercial-scale fluidised bed recycling plant and rCFRP manufacturing technologies to identify the market opportunities of rCF. Recovery of CF from CFRP wastes can be achieved at $5/kg or less across a wide range of key process parameters including plant capacity, feeding rate per unit bed area. The manufacture of rCFRP is selected for case studies in terms of material selection and substitution for steel under different design indices. Case studies are used to assess the life cycle cost performance of rCFRP which is required to be addressed before its wide applications in automotive industries.

The comparative assessment showed that rCFRP can be competitive material that can replace conventional metal materials and vCFRP materials in automotive applications. It is observed that significant weight savings achieved by rCFRP materials especially the aligned rCFRP in substituting steel materials while providing the same mechanical properties. Random rCFRP continues to show significant life cycle cost reduction including material cost reduction and manufacturing cost reduction. Financial credits are also from the vehicle in-use fuel cost savings due to mass-induced fuel consumption associated with mass reduction. This cost is already competitive with the conventional steel component, prior to monetising the environmental benefits of rCF materials (e.g. social cost of carbon). Aligned rCFRP as the lightest substitution alternative could potentially improve financial performance provided technology development targets are met.

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