Energy and environmental assessment and reuse of fluidised bed recycled carbon fibres

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ABSTRACT

Carbon fibre reinforced plastic (CFRP) recycling and the reutilisation of the recovered carbon fibre (rCF) can compensate for the high impacts of virgin carbon fibre (vCF) production. In this paper, we evaluate the energy and environmental impacts of CF recycling by a fluidised bed process and reuse to manufacture a CFRP material. A 'gate-to gate' life cycle model of the CFRP recycling route using papermaking and compression moulding methods is developed based on energy analysis of the fluidised bed recycling process and processing of rCF. Key recycling plant operating parameters, including plant capacity, feed rate, and air in-leakage are investigated. Life cycle impact assessments demonstrate the environmental benefits of recycled CFRP against end of life treatments-landfilling, incineration. The use of rCF to displace vCF based on material indices (equivalent stiffness and equivalent strength) therefore proves to be a competitive alternative for composite manufacture in terms of environmental impact.

KEY WORDS

Fluidised bed CFRP recycling, Compression moulding, Energy analysis, Life cycle assessment

1 INTRODUCTION

Growing demand for carbon fibre reinforced polymers (CFRP) for lightweighting in aerospace applications and, to a lesser extent, automotive applications contributes to fuel efficiency objectives in the transportation sector. In the past 10 years, the annual global demand for carbon fibre (CF) has increased from approximately 16,000 to 72,000 tonnes and is forecast to rise to 140,000 tonnes by 2020 [1]. The generation of CFRP-based wastes is correspondingly increasing, arising from manufacturing (up to 40% of the CFRP can be waste arising during manufacture [2-4]) and end of life products/components. CF recovery from wastes is a priority due to the energy intensity and high financial cost of virgin CF (vCF) production. Boeing aims to recycle at least 90% of retired airplane materials [5], which will increasingly require CF recovery in the future. Existing EU regulations aim to reduce the quantities of all wastes sent to landfill [6], while automotive sector-specific policy requires the recycling of at least 85% of end-of-life materials from 2015 [7]. In contrast to industry and policy goals, the vast majority of CFRP waste at present is not recovered: in the UK, for example, up to 98% of composite waste is disposed of in landfill or incinerated [8, 9]. Recovery of metals from end-of-life aircraft has proven to be beneficial in terms of cost and energy intensity relative to virgin material production [10], however, there is no detailed energy and cost information of the CFRP recycling processes. Thus, there is a need to identify an environmentally beneficial recycling technique to address these issues.

Recycling techniques take different approaches to recovering fibres from the cross-linked thermoset matrix material, including mechanical size reduction [11]and thermal processes to partially or fully decompose matrix [3]. Pyrolysis is a widely used thermal method, being established in commercial operations, e.g., ELG Carbon Fibre Ltd [12, 13]. A related thermal process is the fluidised bed process, being the subject of this paper, which has been developed for the recycling of glass fibre and CF at the University of Nottingham for over 15 years [3]. Although it has shown a strength reduction of up to 50% [3, 14, 15], this continuous process has been shown to be particularly robust in dealing with varied polymer types containing mixtures of different materials and other contaminants. Very low residual char remains on the fibre surface as organic material is oxidized and any metallic material, such as aluminium honeycomb, rivets etc. remains in the fluidised bed and can be removed by regrading the bed.

Prior studies have estimated energy requirements of various CFRP recycling technologies, finding substantially lower energy requirements compared to vCF manufacture. For instance, industry reports claim that recovered CF (rCF) achieves about 95% energy reduction to manufacture compared to vCF while the mechanical performance is comparable [5, 10]. To be specific, recycling energy consumption has been reported to be 0.17-1.93 MJ/kg for mechanical recycling of GFRP [16], 0.27-2.03 MJ/kg for mechanical recycling of CFRP [11], 3-30 MJ/kg for pyrolysis recycling of CFRP [16], 19.2 MJ/kg for solvolysis recycling of CFRP [17] and 60-90 MJ/kg for chemical recycling of CFRP in Japan [18] compared to 198-595 MJ/kg for vCF production. However, no recycling capacity or other processing details were specified in most literature, nor the modelling methodology for the energy intensity. Little work was focused on energy demand and environment burden particularly for fluidised bed recycling of CFRP, which needs to be addressed.

In addition, to comprehensively assess the environmental performance of CF recycling, however, evaluations should extend beyond the recycling process and account for the reutilisation of rCF in place of current materials. Life cycle assessment (LCA) is an internationally accepted environmental assessing method to quantify and evaluate the environmental impacts such as energy use and greenhouse gas emissions as described by [19]. A number LCA studies evaluating the use of CFRP in lightweighting applications have been conducted, generally finding that weight reductions owing to the use of CFRP to replace conventional materials such as steel and aluminium potentially leads to both energy and greenhouse gas (GHG) emission reduction in either aerospace or automotive industries [2, 20-25]. However, these studies have not considered the end-of- life of CFRP components and therefore do not completely assess environmental impacts. Very few studies have estimated the environmental impacts of a CFRP recycling technology [21, 26], however these have relied on hypothetical data regarding the energy intensity of the recycling process. The lack of data regarding CFRP recycling process inputs and impacts is a barrier to developing informative LCA models. While potential environmental benefits are claimed in technical studies of CFRP recycling processes and fibre reuse opportunities, these benefits have yet to be demonstrated in a comprehensive life cycle study.

Environmentally-beneficial recycling strategies are essential to support the role of CF-based materials in lightweighting applications to reduce transportation energy consumption. In this study, comprehensive life cycle models are developed to consider the fluidised bed CFRP recycling process and subsequent reuse of rCF in composite materials. Process models of the recycling process and composite manufacture with rCF are developed and validated against pilot plant data. Inventory data (material and energy inputs; direct emissions) are derived from the process models and input to the LCA models. Key environmental impacts (primary energy consumption, global warming potential) are assessed. Environmental impacts of composite production from rCF are estimated and compared with vCF-based composite material.

2 METHODS

This study evaluates the life cycle environmental impacts of CFRP recycling by the fluidised bed process and subsequent manufacturing of composite material from rCF. Results are compared with vCF materials to determine the environmental impacts of using rCF in place of vCF in composite materials and the following composites are considered:

1) Recycled CFRP (rCFRP): rCF recycled from fluidised bed process is processed by a wet papermaking process co-mingled with polyamide (PA) fibre to make a non-woven fabric, followed by compression moulding with a fibre volume fraction of 25%.
2) Virgin CFRP (vCFRP) 1: vCF co-mingled with PA fibre is manufactured into an intermediate non-woven mat via wet-papermaking to manufacture CFRP products by compression moulding with a fibre volume fraction of 25%.
3) vCFRP 2: a prepreg comprising bi-directionally woven vCF and epoxy resin is moulded in an autoclave to give a fibre volume fraction of 50%.

Key activities included in the study are shown in Fig. 1. Waste CFRP (including scrap and end-of-life CFRPs), comprised Toray T600SC CF in MTM28-2 epoxy resin, is first shredded and input to the fluidised bed process, which yields a fluffy fibre product. A co-mingled mixture of rCF and PA fibre is then manufactured into a non-woven mat via a wet-papermaking process before compression moulding into rCFRP products. For the vCF materials, we consider two separate manufacturing pathways (see Fig. 1). The first considers a similar process wherein chopped vCF (Tenax-A HTC124) co-mingled with PA fibre is manufactured into an intermediate non-woven mat via wet-papermaking to manufacture CFRP products by compression moulding (vCFRP1). As rCF recovered via fluidised bed exhibit no appreciable degradation of modulus but strength is reduced by 25-50%, the vCFRP1 material has better mechanical properties than rCFRP materials as experimentally measured[27]. A second, vCF material typical of high-performance applications is considered wherein woven vCF (Toray T600SC) is impregnated with epoxy resin and components are subsequently manufactured via autoclave moulding (vCFRP2).

Process models of the fluidised bed recycling and CFRP manufacturing processes are developed to estimate the energy and material requirements of commercially operating facilities and are validated using pilot plant operating data for the fluidised bed recycling process. Direct process inputs and emissions (derived from recycling and CFRP manufacturing process models) are input to the life cycle model and supplemented with

LCA databases to estimate the impacts of producing and using material and energy inputs (e.g., Gabi Database [28], Eco-invent [29]). The LCA evaluates CF recycling and CFRP manufacture on a “gate-to-gate” basis, corresponding to the activities shown in Fig. 1. Composite use and end-of-life activities are excluded from this study; potential implications of these activities are discussed in Section 3.3. Infrastructure and labour are not included within the study, as is common practice where impacts are expected to be small relative to the operation of the facilities (e.g., Zhang et al., 2010 [30]).

Two environmental impacts are quantified: primary energy demand (PED) in terms of MJ and global warming potential (GWP), based on the most recent IPCC 100-year global warming potential factors to quantify GWP in terms of CO_2 equivalents (CO_2 eq.) [31]. The functional unit for the analysis is one generic CFRP panel which could find use in a range of applications, including automotive and aircraft interior components. For this analysis, a panel size of 300mm x 190mm is selected to correspond to prior experimental analyses [27]. The component thickness is variable and is adjusted so that equivalent mechanical properties (equivalent bending stiffness and equivalent bending strength) can be met by CFRP produced from both rCF and vCF. Further details regarding the mechanical properties of the CFRP products are provided in Section 2.5.

2.1 Fluidised bed recycling process

A schematic diagram of the fluidised bed recycling process is shown in Fig. 2. CFRP wastes are shredded to typically between 6-20mm [32] before entering the fluidised bed reactor. The silica sand bed is used to volatilise the shredded scrap material and thus to decompose the epoxy resin and release the fibres. The fluidising air is able to elutriate the released fibres, while non-organic contaminants (e.g., metal) remain in the bed. The operating temperature of the fluidised bed is chosen to be sufficient to cause the polymer to decompose, leaving clean fibres, but not too high to degrade the fibre properties substantially. At the operating temperatures of 450°C to 550°C, resin decomposition products are oxidised to recover energy content. The fibres are then removed from the gas stream by a cyclone or other gas-solid separation device and collected. In the current pilot plant, the gas stream after fibre separation is directed to an oxidiser (combustion chamber) to fully oxidise the polymer decomposition products. Heat is recovered from the gas stream to pre-heat fresh air input before being exhausted through the stack.

Mass and energy models of the fluidised bed process are developed to evaluate the impact of operating parameters (CF feed rate per unit of fluidised bed area (kg/hr-m^2); annual plant capacity (t/yr)) on energy consumption and associated environmental impacts. Key details of the recycling process model are presented here subsequently; additional information can be found in the Supplementary Data (Section 1.1). Waste CFRP is assumed to be from manufacturing scrap or end-of-life prepreg, typically composed of high strength Toray T600SC CF (53% vf; 62% wt) and MTM28-2 epoxy resin. Parameters for the fluidised bed model are based on experience from operation of a 50 t/yr pilot scale facility but are selected to best represent expected conditions of a commercial operating facility. For all model variations, equipment and piping are sized assuming a representative fluidising velocity of 1m/s, pipework air velocity of 20 m/s, and minimal pipe length to accommodate equipment size for practical operation and maintenance. Thermal energy balances, including heat losses from equipment and pipework are calculated assuming a representative fluidised bed temperature of 550°C and oxidiser temperature of 750°C.

Inefficiencies arise in the process from heat loss to the surroundings and in-leakage of air due to the operation of the system slightly below atmospheric pressure. Energy inputs to the system are quantified by estimating process energy requirements and heat losses for each section within the fluidised bed system. Heat losses in the exhaust are mitigated by high efficiency heat recovery from the oxidiser outlet prior to exhausting. Pipework and equipment insulation are determined by economic optimisation of insulation costs and potential energy savings with minimum net present value. Fan power requirements are calculated to achieve airflow through the system and to maintain fluidised bed operating pressure at 500 Pa below atmospheric pressure to ensure that there is no leakage of gases from the system into the air [33]. The energy model is verified by comparing with experimental results from the pilot plant. The energy consumption predicted using the model agrees to within 1% of the pilot plant data, suggesting the model is reliable to develop life cycle inventory data.

Although the full chemical formulation of the epoxy resin is not available, for the purposes of stoichiometry calculations, it is assumed to be made of Diglycidyl ester of bisphenol A (DGEBA) in 87 % wt and Isophorone Dianmine (IPD) in 13 % wt. CO_2 emissions resulting from the oxidation of the epoxy matrix material are calculated on a stoichiometric basis assuming all carbon is fully oxidised to CO_2. Data on other potential GHG emissions (methane, nitrous oxide) are not available and are assumed to be negligible.

2.2 Wet papermaking process

The wet papermaking process has been successfully demonstrated to be an effective way to produce non-woven mats from rCF [27].The process can also use chopped vCF as a reinforcing fibre. CF with matrix polymer fibres (PA) is dispersed in a viscous aqueous solution, laid into a mat in random orientation, and dried via vacuum drying (with recovery of aqueous dispersion media for reuse) and a final thermal drying stage. The resulting mat consists of 25% CF (by volume) and an areal density of 100 gsm. Co-mingling of the CF and PA fibres during dispersion has the advantage of bringing reinforcement and polymer fibres close together, thereby reducing the melt flow distance in subsequent manufacturing stages and promoting more complete resin impregnation with minimal void formation.

Energy and material requirements of the papermaking process are estimated based on experimental data and, where possible, energy efficiency data of standard equipment. Process parameters are selected to achieve fibre dispersion and drying with minimised energy input, based on experimental evidence and model outputs. A critical parameter is the total fibre volume content (CF and PA fibres) of the dispersed slurry, which is assumed here to be 0.1% to avoid agglomeration of fibres during processing [34]. Increasing the fibre content could substantially reduce the energy requirements for papermaking and is the subject of ongoing research. Further details regarding the wet-papermaking process model can be found in the Supplementary Data, Section 1.3.

2.3 Manufacture of composite components via compression moulding

Components produced from co-mingled mats (rCFRP, vCFRP1) are manufactured via a compression moulding process. Mats are cut to size (300 mm x 190 mm) and stacked to achieve the required component thickness, typically requiring 15 layers of 100gsm mats to fill up the mould cavity. The moulding is subsequently compressed between two steel tools and heated to form the component. Energy analysis of each step (i.e., heating stage, curing stage, pressure build-up stage and finishing stage) based on heat transfer theory has been carried out based on the processing parameters for CF-PA composite (See Supplementary Data, Section 1.3). Differences between vCF and rCF component thickness to compensate for differences in material properties (see Section 2.5) are accounted for in our analysis of CFRP manufacturing energy use.

2.4 Virgin carbon fibre composite manufacture

The manufacture of vCF is modelled based on existing literature data. The life cycle inventory data input to our LCA models information is described in the Supplementary Data Table S2 and comprises data from literature and life cycle databases, with parameters selected based on literature consensus, expert opinion and results from a confidential industrial dataset. Publicly available data on vCF manufacture is limited and, in many cases, is lacking in key details that should be incorporated into LCA studies, in particular variations in CF mechanical properties (high strength vs high modulus) and corresponding production energy requirements.

Two vCF materials are considered: vCFRP1, which is produced via paper-making/ compression moulding as described above (Sections 2.2 and 2.3); and vCFRP2, a woven CF/ epoxy composite material manufactured via autoclave moulding of prepreg (Toray T600s and epoxy resin) with 50% fibre volume fraction. The composite has fibres oriented at 0° and 90˚ and exhibits a Young's modulus of 70 GPa in both the longitudinal and transverse directions [35]. Energy requirements of the autoclave process are obtained from literature, including prepreg production (4 MJ/kg) and autoclave moulding (average of reported values 29 MJ/kg) [21, 23, 36].

2.5 Mechanical properties of composite materials

To properly compare CFRP production routes from different CF sources (rCF, vCF), it is essential that the CFRP products exhibit identical mechanical properties. Two metrics are considered to determine functional equivalence of CFRP materials: bending stiffness and bending strength. To compensate for variations in material properties between the three materials (rCFRP, vCFRP1, and vCFRP2), thickness of the panel is varied in order to achieve the required bending stiffness or strength for a composite beam. The relative thickness of the components impacts both the life cycle inventory, as thicker components require greater quantities of fibre and matrix materials. Mechanical properties of the rCFRP and vCFRP1 materials are measured experimentally from samples prepared with 10 to 15 layers as required to fill the mould cavity [27]. Material properties for vCFRP2 are from the manufacturer's data [35] (see Table 1) while mechanical properties of rCF and vCF are measured experimentally as shown in Table S2.

The thickness ratio (R_t) comparing a CFRP components with a reference material (subscript *ref*) for constant bending stiffness and strength can be determined by:

$$R_{t-stiffness} = \frac{t}{t_{ref}} = (\frac{E_{ref}}{\mathrm{E}})^{\frac{1}{3}} \tag{1}$$

$$R_{t-strength} = \frac{t}{t_{ref}} = (\frac{\sigma_{ref}}{\sigma})^{\frac{1}{2}} \tag{2}$$

Where t is the material thickness (mm), E is the material tensile modulus, and σ is the tensile strength of the materials. Further details can be found in Supplementary Data, Section 1.5.

In assessing the relative thickness and corresponding relative mass of CFRP materials, the vCFRP1 material is selected as the reference. Relative to this material, rCFRP requires 5% and 7% greater thickness to achieve equivalent bending stiffness and strength, respectively (see Table 1). The woven vCFRP2 material exhibits superior mechanical properties and as such has low thickness ratios: 0.66 and 0.55 for equivalent stiffness and strength, respectively.

3 RESULTS AND DISCUSSION

3.1 Fluidised bed recycling process

CF can be recovered from CFRP with energy expenditure as little as 6 MJ/kg CF for the fluidised bed operating parameters considered. Fig. 3 shows the energy balance of the recycling process, including energy inputs (natural gas, electricity), energy release from resin oxidation, and heat losses, for a fluidised bed plant with 100 t/yr of annual throughput of rCF. The energy requirements of the fluidised bed recycling process are primarily dependent on two factors: the feed rate of CFRP processed per unit bed area (kg CF/hr-m^2), and the in-leakage of ambient air. At lower feed rates, relatively more air needs to be heated and transferred through the system per kg of CF recovered, leading to greater natural gas demand for thermal energy and electricity for the fans. At higher feed rates, thermal energy requirements are significantly reduced to the extent that most process heat can be provided by resin oxidation. Beyond a feed rate of 5 kg/hr-m^2, energy efficiency gains are minor as the resin energy input is fully exploited in heating the fluidised bed to 550 °C and there is minimum quantity required to raise the oxidiser temperature to 750 °C. Gas exhaust from the system following the oxidation and heat recovery stage is the primary mode of heat loss from the fluidised bed system. The heat recovery system is arranged to give the maximum practical heat recovery but that nevertheless the exhaust gases from the stack where exhaust temperatures range from 98°C to 208°C across parameters calculated in this study. Heat recovery from the stack for other process uses could therefore improve overall efficiency. Fluidised bed plants with annual throughputs of 50 to 1000 t/yr are analysed, finding that plant capacity has minor impacts on energy use, as shown in Supplementary Data, Fig. S4.

While energy efficiency gains are identified to be achievable by increasing feed rate, there are potential trade-offs in terms of resulting rCF properties. To avoid agglomeration in the recycling process at high feed rates, fibre length must be reduced [37]. However, fibre length may also affect the downstream CFRP manufacturing process and resulting CFRP product properties. It is expected that fibre lengths in the range of 1-10mm will be preferred for balancing fluidised bed performance and rCF properties for CFRP manufacture, however; this is a topic of ongoing research.

As described before, as the fluidised bed system operates below atmospheric pressure there is the potential for air in-leakage at pipework joints and in particular at shaft seals on the high temperature fans in the system. The air in-leakage rate impacts the thermal energy requirements as this introduces a mismatch in mass flow rate: additional air must be heated to 750 °C at the oxidiser, thereby resulting in greater exhaust heat losses. Air leakage also places an impact on fan power consumption by changing the mass flow rate. Air in-leakage rates up to 10% are evaluated, showing that natural gas and electricity requirements increase by up to 340% and 1% respectively (see Supplementary Data, Fig. S5). Air in-leakage could be minimised in a commercial plant design, but some would be unavoidable given the need to operate below atmospheric pressure to prevent emissions of untreated gases.

In comparison to rCF from composite recycling, vCF production is energy intensive, with reported energy requirement ranging from 198 to 595 MJ/kg [10, 20, 24, 38]. Across the range of operating parameters considered in the study, energy required to recover CF is generally less than 10% of that required to produce vCF, while operation of the fluidised bed process at higher feed rates with well controlled air in-leakage could reduce this figure to 3%.

Data is extracted from the fluidised bed recycling process model to input to the life cycle analysis, considering likely operating conditions: 500 t CF/yr annual capacity; 9 kg CF/hr-m^2 fluidised bed feed rate;

and 5% air in-leakage. These parameters correspond to an energy requirement of 7.7 MJ/kg rCF, comprised of 1.9 MJ/kg (natural gas) and 5.8 MJ/kg (electricity).

3.2 CFRP manufacturing

Direct energy requirements for the CFRP manufacturing processes (papermaking and compression moulding; prepreg and autoclave) are shown in Table 2. These results are presented on a mass basis and a part basis accounting for the relative stiffness/strength of the CFRP materials. Direct energy results presented in Table 2 assume a component thickness of 2 mm; implications of component thickness on manufacturing energy use are discussed below.

Papermaking – including fibre dispersion, vacuum drying and thermal drying steps – accounts for approximately 15% of the energy consumed during the manufacturing process for the rCFRP and vCFRP 1 materials. Based on expected process parameters, total energy requirement is estimated as 14 MJ/kg CF mat with approximately half from fibre dispersion and half from drying. Model parameters for fibre dispersion and drying affect energy requirements of the papermaking process; an assessment of the sensitivity of results to variations in these parameters and insights are presented in the Supplementary data (Section 2.2). As results are based on expected process parameters, it is noted that these could be varied in actual processes which could impact results presented here.

As shown in Table 2, final component manufacturing by compression moulding is much more energy intensive than the papermaking process. The heating and pressure build-up stages of compression moulding accounting for 60% and 16% of total manufacturing energy requirements, respectively. Energy requirements for compression moulding of a component are not strongly related to the component thickness for thicknesses in the range of the current study (1 to 10 mm). Heat losses and pressure build up energy consumption are largely dependent on the cross-sectional area of the panel and independent of component thickness. When considering components of different thickness, energy consumption in terms of MJ/kg can vary between materials as energy consumption is very similar despite differences in component mass (see Supplementary Data, Fig. S7). As a result, compression moulding energy requirements are similar for the rCFRP and vCFRP1 materials even when relative thicknesses required to achieve equivalent stiffness and strength are considered. Compression moulding energy consumption results presented here are high relative to literature sources (approximately 9 MJ/kg) [22] due to the higher processing temperature of PA fibre (270°C) in this study relative to unsaturated polyester resins used in the literature (30-80°C cure temperature).

For the autoclave component (vCFRP2), total manufacturing energy associated with prepreg production and autoclave moulding energy consumption (4 MJ/kg and 29 MJ/kg, respectively) is similar to values reported for the papermaking-compression moulding route on a mass basis. However, the vCFRP2 component can achieve equivalent strength and stiffness with a lower mass than with the rCFRP and vCFRP1 materials. Accounting for the relative mass of components results in lower manufacturing energy requirements for the vCFRP2, approximately 50% of energy consumption for rCFRP and vCFRP1.

3.3 Life cycle energy use and greenhouse gas emissions

The LCA results are presented by considering two environment metrics- primary energy demand (PED) in and global warming potential (GWP). All LCA results consider the relative thickness and mass of components required to achieve equivalent stiffness and strength. CFRP production from rCF results in substantially lower life cycle PED and greenhouse gas (GHG) emissions than vCF components of equivalent mechanical properties (see Fig. 4). The total PED for rCFRP component (51.1 MJ/part under equivalent stiffness; 51.8 MJ/part under equivalent strength) is 50%-51% of the vCFRP 1 component and 56%-68% of the vCFRP 2 component when considered under both equivalent stiffness and equivalent strength bases. This is primarily due to high PED associated with vCF manufacture, which represents 53% of total PED for the vCFRP1 component and 80% for the vCFRP2 component. In contrast, the energy consumption of the fluidised bed recycling process is relatively small, representing only 2% of the total energy use in rCFRP production. Manufacture of the matrix material (PA fibre) for the compression moulding pathways for either vCFRP1 manufacture or rCFRP is the next largest contributor to PED (21% of vCFRP1 manufacture; 44% of rCFRP manufacture). To achieve equivalent stiffness and strength, the rCFRP component requires greater relative thickness than the vCFRP materials (8% and 5% thicker than vCFRP1 and 96% and 60% thicker than vCFRP2 on equivalent strength and stiffness bases, respectively). Correspondingly rCFRP has larger requirements for fibre and matrix materials than the vCF alternatives. Production of the epoxy resin matrix material for the vCFRP2 material is associated with relatively small PED relative to matrix materials for the rCFRP and vCFRP1 components, due primarily to lower material requirements arising from the higher fibre volume fraction and lower relative mass of this material. Compression moulding and wet papermaking processes make up 20% and 7% of PED for the vCFRP1, respectively compared to 40% and 14% for the rCFRP under equivalent stiffness. The autoclave moulding and prepreg production are relatively less energy intensive, constituting 10% and 2% of the total CFRP manufacture, respectively.

The GWP results follow similar trends as the PED results. Total GWP is 5.8 kg CO_2 eq./part for vCFRP1 component, 5.1 kg CO_2 eq./part for vCFRP2 component and 2.8 kg CO_2 eq./part for rCFRP component, respectively under equivalent stiffness (Fig. 4b)) while total GWP is 5.8 kg CO_2 eq./part for vCFRP1 component, 4.3 kg CO_2 eq./part for vCFRP2 component and 2.9 kg CO_2 eq./part for rCFRP component, respectively under equivalent strength (Fig. 4d)). For the vCFRP1 and vCFRP2 components, the manufacture of vCF is the main GHG emissions source. Emissions associated with papermaking, compression moulding, and PA fibre manufacture are significant for both vCFRP1 and rCFRP, whereas component manufacture by autoclave, matrix materials represent relatively smaller contributions to life cycle GWP for vCFRP2. Avoided GWP associated with the rCFRP is dependent on the basis for comparison. Recycled CFRP can reduce GHG emissions by approximately 45% relative to vCFRP1 and vCFRP2 on an equivalent stiffness basis; however, as the autoclave produced vCFRP2 component exhibits a higher specific strength than the comparator materials, displacing this material with rCFRP can reduce GHG emissions by only 33%.

The life cycle PED and GWP results are robust across the range of fluidised bed operating parameters and air in-leakage rates considered in this study. At the least favourable operating conditions (low feed rate (3 kg/hr-m^2); high air in-leakage rate (10%)), the rCFRP component still exhibits substantial savings relative to the vCFRP component in terms of PED (45% reduction against vCFRP1 and 38% reduction against vCFRP2) and GWP (48% reduction against vCFRP1 and 40% reduction against vCFRP2) under equivalent stiffness. While vCF production dominates the energy intensity in manufacturing vCFRP, optimization of the fluidised bed process could further reduce the overall environmental impacts of rCFRP manufacture.

Results presented here consider a ‘gate-to-gate’ approach and as such do not consider the use phase of the manufactured components. If used in transport applications, lighter weight components would achieve energy savings by reducing mass induced fuel consumption. As such, the slightly greater mass of the rCFRP component relative to the vCFRP materials (see Section 3.2) could incur greater in-use energy consumption and associated GHG emissions relative to the vCFRP components. Disposal of rCFRP material is not considered as there is uncertainty as to whether rCFRP could be recycled for rCF recovery at end of life, or if a lower value recovery approach (e.g., incineration, mechanical recycling) would be required. Subsequent work will extend the current analysis to consider the full life cycle of rCFRP and vCFRP components to assess the net PED and GWP impacts.

It is found that CF recycling in the fluidised bed process can achieve substantially greater environmental performance than conventional waste treatments or mechanical recycling [39]. Fluidised bed recovery of CF and use of rCF to displace vCF-based composites provides substantial savings in PED (~ 65-330 MJ energy savings per kg of CFRP waste), offering an order of magnitude greater net PED savings compared to waste CFRP incineration. Further, avoided GHG emissions range from 3 to 19 kg CO_2 eq. per kg of CFRP waste processed by fluidised bed, depending on the vCF material displaced (vCFRP1, vCFRP2). In contrast, mechanical recycling of CFRP waste produces rCF suitable only for displacing glass fibres, achieving a far smaller GHG emissions reduction of 0.38 kg CO_2 eq. per kg CFRP waste [39].

Results of the current study are robust, despite potential implications of model assumptions and simplifications. The main contributors to PED and GWP of rCFRP materials are the production matrix material and the compression moulding process, for which well-established data are available. Operating parameters for the fluidised bed and papermaking processes are based on operating demonstration facilities and the best available experimental data, but are less certain. However, these stages represent only 2% and 14% of GWP, respectively, and so variations are not expected to appreciably impact the overall results.

4 CONCLUSION

A life cycle analysis of CF recycling process has been carried out in this study, based on a novel process model of the fluidised bed recycling process. Key recycling plant operating parameters, including plant capacity, feed rate, and air in-leakage are investigated. The feed rate per unit bed area is identified as the most important parameter for achieving energy-efficient CF recycling. The energy model shows that energy requirement of rCF production is very low relative to vCF and robust across likely operating conditions. Further optimisation of fluidised bed recycling process needs to balance to maximising feed rate per bed area to minimise process energy use and potential implications for rCF properties. Opportunities exist for recovering stack heat loss which could further improve the energy efficiency of the fluidised bed process.

The use of rCF to displace vCF in composite applications is found to achieve significant gate-to-gate life cycle energy and GHG emissions reductions. Resulting rCFRP components with identical mechanical properties to those produced from vCF can reduce PED by 32% to 50 % and GWP by 33% to 51%. Environmental performance far exceeds that of conventional waste treatment routes (i.e., landfilling, incineration).

A key question for future progress is the value of the rCF. The intrinsic value of CF is due to their high cost as virgin materials but excessive levels of touch labour associated with recovery and potentially high levels of energy use during recovery and rCF processing to a great extent weaken the business case for recycling activities. As the rCFs from fluidised bed process are in a fluffy form with random discontinuous length distribution as well as some strength reduction, it provides a number of challenges for cost-effective and high value re-use to manufacture CFRP composites. A series of studies [27, 40-43] at the University of Nottingham have proposed various routes to enable the use of rCF, including wet-papermaking process to manufacture non-woven mat analysed in this study. Furthermore, fibre alignment techniques and thermoplastic injection moulding methods have also demonstrated alternatives to process the rCF to manufacture high-value composite products. Progress in recycling process optimisation and manufacturing method development are key to achieving the significant environmental benefits that CF recycling can contribute to the aerospace and automotive industries.

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APPENDIX A. SUPPLEMENTARY DATA

Supplementary data related to this article is available.

REFERENCES

[1] Kraus T, Kühnel M. Composites Market Report 2014 Market developments, trends, challenges and opportunities-The Global CRP Market. 2014.

[2] Witik RA, Teuscher R, Michaud V, Ludwig C, Manson J-AE. Carbon fibre reinforced composite waste: An environmental assessment of recycling, energy recovery and landfilling. Composites Part a-Applied Science and Manufacturing. 2013;49:89-99.

[3] Pickering SJ. Recycling technologies for thermoset composite materials—current status. Composites Part A: Applied Science and Manufacturing. 2006;37(8):1206-15.

[4] Pimenta S, Pinho ST. Recycling carbon fibre reinforced polymers for structural applications: Technology review and market outlook. Waste Management. 2011;31(2):378-92.

[5] Boeing. The Boeing Company 2013 Environmental Report. 2014.

[6] European_Council. Directive 1999/31/EC on the landfill of waste. Off J Eur Union L. 1999;182:1-19.

[7] European_Council. Directive 2000/53/EC of the European Parliament and of the Council on end-of-life vehicles. Off J Eur Union L. 2000;L.269:34-269.

[8] Shuaib NA, Mativenga PT, Kazie J, Job S. Resource Efficiency and Composite Waste in UK Supply Chain. Procedia CIRP. 2015;29:662-7.

[9] Marsh G. Europe gets tough on end-of-life composites. Reinforced Plastics. 2003;47(8):34-6.

[10] Carberry W. Airplane Recycling Efforts benefit boeing operators. Boeing AERO Magazine QRT. 2008;4(08):6-13.

[11] Howarth J, Mareddy SSR, Mativenga PT. Energy intensity and environmental analysis of mechanical recycling of carbon fibre composite. Journal of Cleaner Production. 2014;81(0):46-50.

[12] ELG Carbon Fibre Ltd. <http://www.elgcf.com/>, (accessed September 2016).

[13] Carbon Conversions. <http://www.carbonconversions.com/>, (accessed June 2016).

[14] HLH Y, SJ P, Rudd C. Characterisation of carbon fibres recycled from scrap composites using fluidised bed process. Plastics, Rubber and Composites. 2002;31(6):278-82.

[15] Jiang G, Pickering SJ, Lester EH, Turner TA, Wong KH, Warrior NA. Characterisation of carbon fibres recycled from carbon fibre/epoxy resin composites using supercritical n-propanol. Composites Science and Technology. 2009;69(2):192-8.

[16] Shuaib NA, Mativenga PT. Energy demand in mechanical recycling of glass fibre reinforced thermoset plastic composites. Journal of Cleaner Production. 2016;120:198-206.

[17] Keith MJ, Oliveux G, Leeke GA. Optimisation of solvolysis for recycling carbon fibre reinforced composites, In European Conference on Composite Materials 17. Munich, Germany, 2016.

[18] Shibata K, Nakagawa M. Hitachi Chemical Technical Report: CFRP Recycling Technology Using Depolymerization under Ordinary Pressure. Hitachi Chemical. 2014.

[19] McKechnie J, Zhang Y, Ogino A, Saville B, Sleep S, Turner M, et al. Impacts of co-location, co-production, and process energy source on life cycle energy use and greenhouse gas emissions of lignocellulosic ethanol. Biofuels, Bioproducts and Biorefining. 2011;5(3):279-92.

[20] Duflou JR, De Moor J, Verpoest I, Dewulf W. Environmental impact analysis of composite use in car manufacturing. Cirp Annals-Manufacturing Technology. 2009;58(1):9-12.

[21] Song YS, Youn JR, Gutowski TG. Life cycle energy analysis of fiber-reinforced composites. Composites Part A: Applied Science and Manufacturing. 2009;40(8):1257-65.

[22] Das S. Life cycle assessment of carbon fiber-reinforced polymer composites. International Journal of Life Cycle Assessment2011. p. 268-82.

[23] Scelsi L, Bonner M, Hodzic A, Soutis C, Wilson C, Scaife R, et al. Potential emissions savings of lightweight composite aircraft components evaluated through life cycle assessment. Express Polymer Letters. 2011;5(3):209-17.

[24] Witik RA, Payet J, Michaud V, Ludwig C, Månson J-AE. Assessing the life cycle costs and environmental performance of lightweight materials in automobile applications. Composites Part A: Applied Science and Manufacturing. 2011;42(11):1694-709.

[25] Prinçaud M, Aymonier C, Loppinet-Serani A, Perry N, Sonnemann G. Environmental Feasibility of the Recycling of Carbon Fibers from CFRPs by Solvolysis Using Supercritical Water. ACS Sustainable Chemistry & Engineering. 2014.

[26] Duflou JR, Deng Y, Van Acker K, Dewulf W. Do fiber-reinforced polymer composites provide environmentally benign alternatives? A life-cycle-assessment-based study. Mrs Bulletin. 2012;37(04):374-82.

[27] Wong KH, Turner TA, Pickering SJ. Challenges in developing nylon composites commingled with discontinuous recycled carbon fibre., In 16th European conference on composite materials. Seville, Spain, 2014.

[28] Gabi. Gabi Extension Database VII Plastics. 2014.

[29] Weidema BP, Bauer C, Hischier R, Mutel C, Nemecek T, Reinhard J, et al. Overview and methodology: Data quality guideline for the ecoinvent database version 3. Swiss Centre for Life Cycle Inventories; 2013.

[30] Zhang Y, McKechnie J, Cormier D, Lyng R, Mabee W, Ogino A, et al. Life cycle emissions and cost of producing electricity from coal, natural gas, and wood pellets in Ontario, Canada. Environmental science & technology. 2010;44(1):538-44.

[31] The Japan Carbon Fiber Manufacturers Association. <http://www.carbonfiber.gr.jp/english/index.html>, (accessed July 2016).

[32] Turner TA, Pickering SJ, Warrior NA. Development of recycled carbon fibre moulding compounds – Preparation of waste composites. Composites Part B: Engineering. 2011;42(3):517-25.

[33] Jiamjiroch K. Developments of a fluidised bed process for the recycling of carbon fibre composites [Ph.D. dissertation]: University of Nottingham; 2012.

[34] Turner TA, Jiang G, Wong KH, Pickering SJ. Measurement of short fibre length using a rheological method, In 20th International Conference on Composite Materials. Copenhagen, 19-24th July 2015, 2015.

[35] GoodFellow. Technical Information - Carbon/Epoxy Composite. <http://www.goodfellow.com/>, (accessed August 2016).

[36] Witik RA, Gaille F, Teuscher R, Ringwald H, Michaud V, Månson J-AE. Economic and environmental assessment of alternative production methods for composite aircraft components. Journal of Cleaner Production. 2012;29–30(0):91-102.

[37] Jiang G, Wong W, Pickering S, Rudd C, Walker G. Study of a fluidised bed process for recycling carbon fibre from polymer composite, In 7th world congress for chemical engineering, Glasgow, UK. 2005.

[38] Meng F, Pickering SJ, Mckechnie J. Inventory analysis of fluidised bed recycling of carbon fibre reinforced polymers, In SAMPE Europe Conference & Exhibition. Amiens, France, September 2015, 2015.

[39] Li X, Bai R, McKechnie J. Environmental and financial performance of mechanical recycling of carbon fibre reinforced polymers and comparison with conventional disposal routes. Journal of Cleaner Production. 2016;127:451-60.

[40] Wong KH, Pickering SJ, Turner TA, Warrior NA. Compression moulding of a recycled carbon fibre reinforced epoxy composite, In SAMPE 2009 Conference. Baltimore, Maryland, 2009.

[41] Liu Z, Wong K, Thimsuvan T, Turner T, Pickering S. Effect of fibre length and suspension concentration on alignment quality of discontinuous recycled carbon fibre, In 20th International Conference on Composite Materials. Copenhagen, 2015.

[42] Wong KH, Turner TA, Pickering SJ, Warrior NA. The potential for fibre alignment in the manufacture of polymer composites from recycled carbon fibre. SAE International Journal of Aerospace. 2010;2(1):225-31.

[43] Wong KH, Syed Mohammed D, Pickering SJ, Brooks R. Effect of coupling agents on reinforcing potential of recycled carbon fibre for polypropylene composite. Composites Science and Technology. 2012;72(7):835-44.

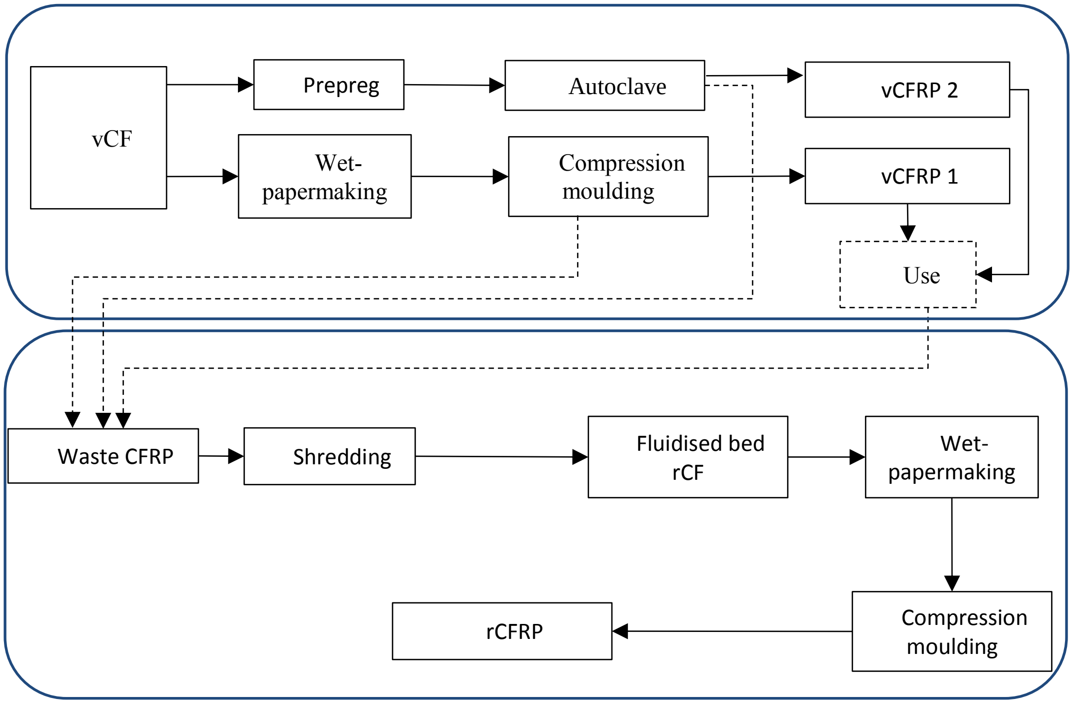


Fig. 1. Block flow diagram of CFRP manufacturing by waste CFRP recycling and compression moulding.

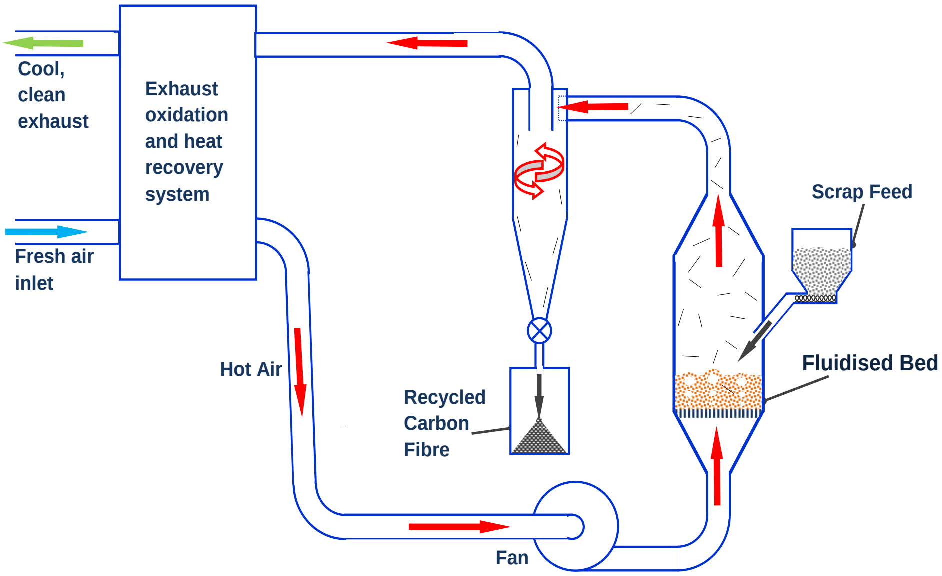


Fig. 2. Main components and flow directions of the fluidised bed CFRP recycling process

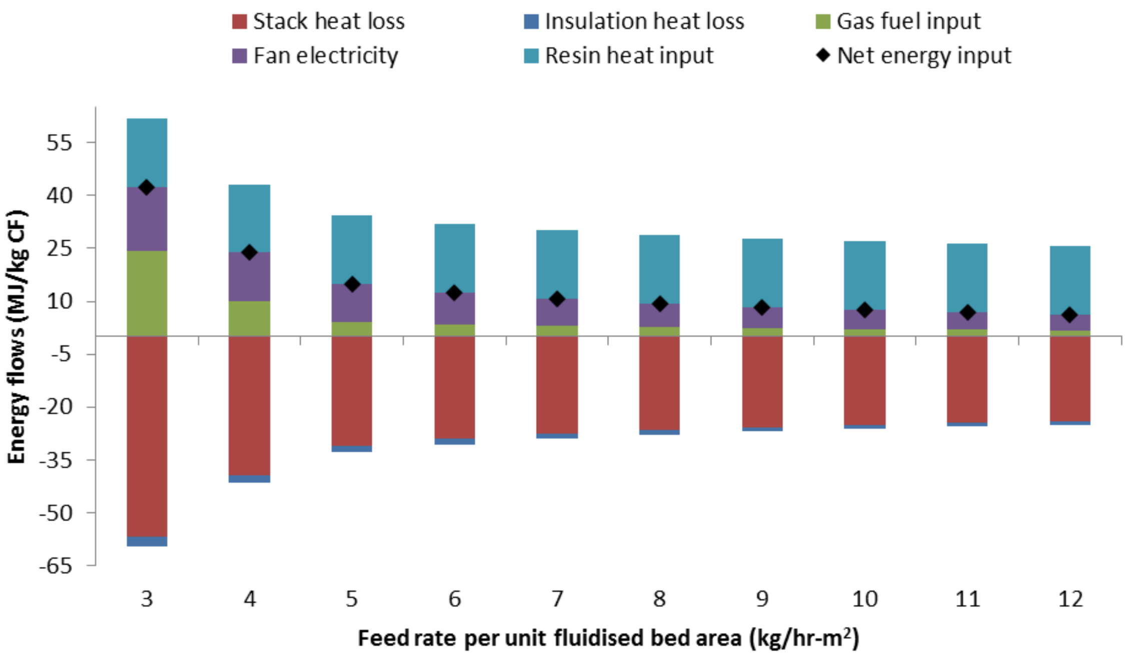
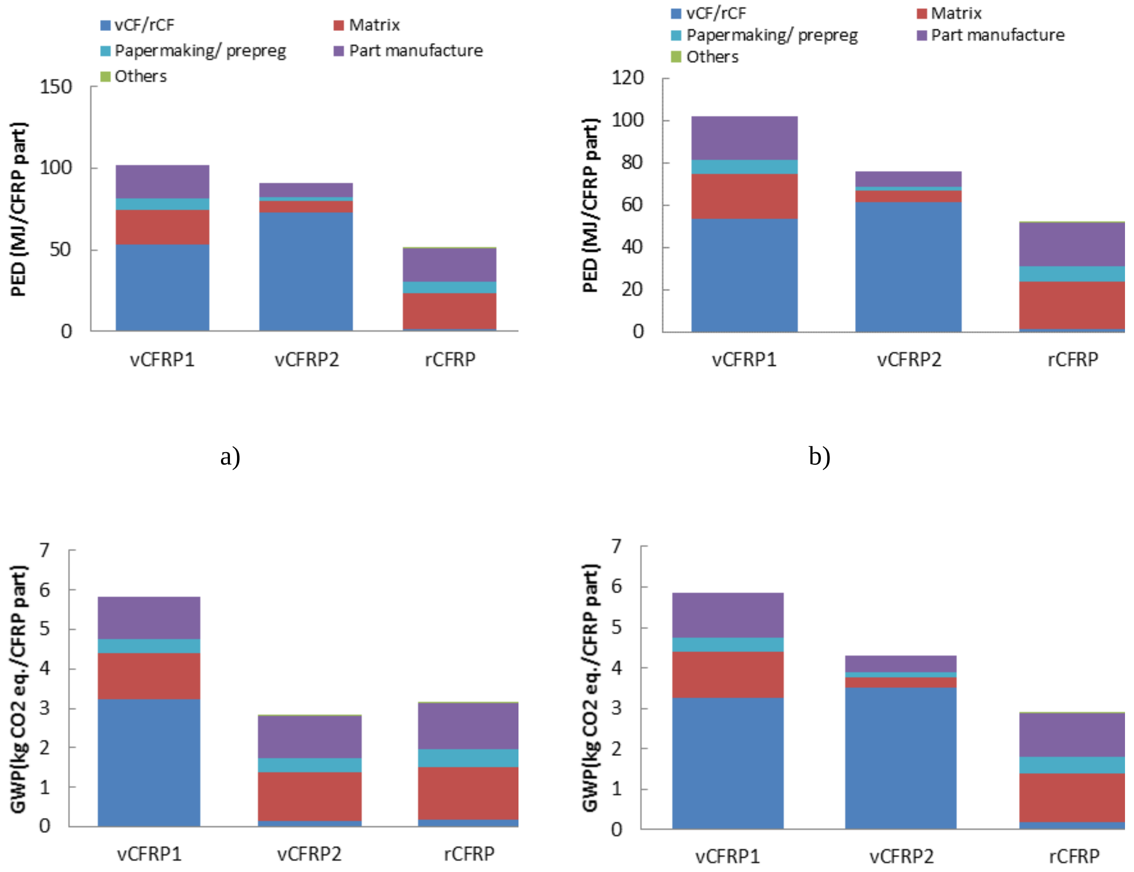


Fig. 3. Energy flows including heat losses from each component and energy value from resin and energy supply for plant corresponds to mass flow per unit area of bed



a) b)

c) d)

Fig. 4. a) Primary energy demand (PED) and b) Global warming potential (GWP) for composites produced from vCF and rCF under equivalent stiffness; c) PED and d) GWP for composites produced from vCF and rCF under equivalent strength

Table 1.

Mechanical properties of carbon fibre composite materials and corresponding thickness ratio and mass ratio required to achieve equivalent component stiffness and strength.

	Tensile strength (MPa)	Tensile modulus (GPa)	Equivalent stiffness		Equivalent strength		Fibre length (mm)
			Thickness ratio	Mass ratio	Thickness ratio	Mass ratio	
vCFRP1	171.59±6.64	19.74±1.19	1.00	1.00	1.00	1.00	12
vCFRP2	570	70	0.66	0.75	0.55	0.62	continuous
rCFRP	148.56±9.56	16.95±0.46	1.05	1.05	1.07	1.07	1.43

Table 2.

Direct energy consumption of CFRP manufacturing steps considering a nominal component thickness of 1mm.

Process steps			Energy consumption in MJ/kg (MJ/part)				
			vCFRP 1	vCFRP 2 Equiv. Bending Stiffness	vCFRP 2 Equiv. Bending Strength	rCFRP Equiv. Bending Stiffness	rCFRP Equiv. Bending Strength
CF processing	Papermaking	Fibre dispersion	3.45 (0.34)	-	-	3.45 (0.35)	3.45 (0.36)
		Vacuum drying	2.44 (0.24)	-	-	2.44 (0.25)	2.44 (0.26)
		Thermal drying	1.56 (0.15)	-	-	1.56 (0.16)	1.56 (0.16)
		Resetting (winding,washing, belt conveying)	0.41 (0.04)	-	-	0.41 (0.04)	0.41 (0.04)
	Prepreg for autoclave		-	4.00 (0.44)	4.00 (0.44)	-	-
	Cutting		0.37 (0.06)	0.37 (0.04)	0.37 (0.04)	0.37 (0.06)	0.37 (0.06)
Final part manufacture	Compression moulding	Heating stage	32.78 (4.84)	-	-	31.26 (4.85)	30.56 (4.85)
		Curing stage	2.10 (0.31)	-	-	2.01 (0.31)	1.96 (0.31)
		Pressure build-up	8.53 (1.26)	-	-	8.13 (1.26)	7.94 (1.26)
		Water cooling	0.90 (0.13)	-	-	0.90 (0.14)	0.90 (0.14)
	Autoclave moulding		-	29.00 (3.19)	29.00 (2.67)	-	-
	Deflashing and drilling		1.20 (0.18)	1.20 (0.13)	1.20 (0.11)	1.20 (0.19)	1.20 (0.19)
Total			53.75 (7.54)	34.57 (3.81)	34.57 (3.26)	51.73 (7.60)	50.79 (7.64)