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Environmental Aspects of Use of Recycled Carbon Fiber Composites in Automotive Applications

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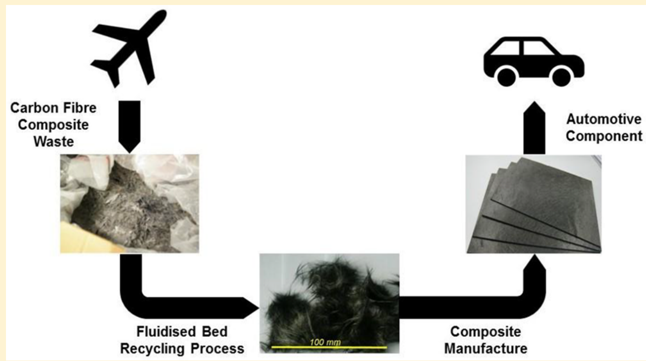
Supporting Information

ABSTRACT: The high cost and energy intensity of virgin carbon fiber manufacture provides an opportunity to recover substantial value from carbon fiber reinforced plastic wastes. In this study, we assess the life cycle environmental implications of recovering carbon fiber and producing composite materials as substitutes for conventional and proposed lightweight materials in automotive applications (e.g., steel, aluminum, virgin carbon fiber). Key parameters for the recycled carbon fiber materials, including fiber volume fraction and fiber alignment, are investigated to identify beneficial uses of recycled carbon fiber in the automotive sector. Recycled carbon fiber components can achieve the lowest life cycle environmental impacts of all materials considered, although the actual impact is highly dependent on the design criteria (λ value) of the specific component. Low production impacts associated with recycled carbon fiber components are observed relative to lightweight competitor materials (e.g., aluminum, virgin carbon fiber reinforced plastic). In addition, recycled carbon fiber components have low in-use energy use due to mass reductions and associated reduction in mass-induced fuel consumption. The results demonstrate environmental feasibility of the CFRP recycling materials, supporting the emerging commercialization of CF recycling technologies and identifying significant potential market opportunities in the automotive sector.



1. INTRODUCTION

As carbon fiber reinforced plastic (CFRP) is increasingly used in aerospace and finding emerging applications in the automotive sector,[1] systems need to be developed to deal with waste arising from associated manufacturing processes and end-of-life products. In 2015, carbon fiber (CF) demand was estimated at about 68 000 tonnes, of which 18 000 tonnes became manufacturing waste; the remaining 50 000 tonnes of CFs will end up as end-of-life products after expected lifetimes ranging from 2 to 40 years, depending on their application.[2] In the USA and Europe, 6000−8000 commercial aircraft are expected to come to their end-of-life by 2030, generating an estimated 3000 tonnes of CFRP scrap per annum.[3,4] More recent wide-body planes, Airbus A350 and Boeing 787 Dreamliner, have seen the expanded use of CFRP materials, more than 50% weight. The amount of CFRP to be recycled in the future will grow significantly when recent aircrafts will be taken out of service. Current waste policies are supportive of recycling initiatives, including general policies (e.g., the EU Directive on Landfill of Waste[5]) and application-specific legislation (e.g., the End-of-life Vehicle Directive[6]). They also align with aerospace industry targets to increase recovery rates for manufacturing and end-of-life wastes: Airbus targets for 95% of CFRP manufacturing process wastes to go through a recycling channel, with 5% of the waste products to be recycled back into the aerospace sector.[7] The high cost and energy intensity of virgin carbon fiber (vCF) manufacture also provide an opportunity to recover substantial value from CFRP wastes: recovered carbon fiber (rCF) could reduce environmental impacts relative to vCF production, while the potentially lower cost of rCF could enable new markets for lightweight materials. To support the development of rCF markets, technology demonstrators ((e.g., rCF seatback demonstrators− aircraft seatback (36% aligned rCF volume fraction with PPS matrix) and automobile seat base (42% aligned rCF volume fraction with PP resin)) have established the viability of CFRP recycling processes and composite manufacturing from rCF for aerospace and automotive applications.[8,9] However, there is still limited understanding as to the life cycle environmental impacts associated with CFRP recycling, reuse of rCF in composite manufacture, and potential uses of the resulting materials.

The current processes for the recovery of CF from end-of-life components and manufacturing scrap can be categorized into mechanical recycling, thermal recycling, and chemical recycling processes.[10] Maintaining the mechanical properties of CF

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through the recycling processes is a key challenge to overcome in developing a commercial recovery process and trade-offs clearly exist between the competing recycling technologies: the fluidized bed process, wherein the polymer matrix is oxidized to enable fiber recovery,[10] can accommodate contamination in end-of-life CFRP waste and shows almost no reduction in modulus and 18%−50% reduction in tensile strength relative to vCF,[10,11] this process has been developed to large lab scale. Several processes are now transitioning from lab scale to commercial facilities, e.g. Carbon Conversions in the USA with an annual capacity of 2000 t/yr[12] and ELG Carbon Fiber Ltd. in UK using a pyrolysis recycling process with an annual capacity of 2000 t/yr.[2] However, there is very little publicly available information regarding the performance of commercial scale facilities (e.g., energy efficiency or fiber recovery rate).

The handling of rCF and its processing to CFRP are difficult due to its discontinuous, 3D random filamentized form and low bulk density; these challenges risk limiting the penetration of rCF into vCF markets. A range of techniques have been explored for preparing composite materials from rCF, involving rCF-specific conversion processes (wet papermaking process[13,14] and fiber alignment[14−16]), and adaptations of composite manufacture techniques (sheet molding compound,[17] compression molding of nonwoven mats and aligned mats,[13,18] injection molding[19]). The wet papermaking process has been successfully demonstrated as an efficient way to produce planar nonwoven random mats from rCF manufactured into CFRP with fiber volume fraction (vf) of 20%−40%.[13,14] The fiber alignment process is under investigation to achieve higher fiber volume fractions and allow greater control of fiber orientation and resulting CFRP properties.[16,20] Impregnation of nonwoven rCF mats with polymer has been successfully employed in developing composite materials via compression molding and injection molding techniques.[13,19] Tensile properties (i.e., tensile modulus, strength, and impact strength) of composites reinforced with the rCF are comparable to those of similar materials produced with vCF and other general engineering materials such as glass fiber reinforced polymer.[14,19] As the processes of CFRP recycling, rCF processing, and CFRP manufacture are energy intensive, there is a need to assess the environmental impacts of the production routes.

Life cycle assessment (LCA) is a standardized method that can be used to quantify the environmental impacts of a product over its complete life cycle, including raw material production, product manufacture, use, and end-of-life waste management.[21,22] Previous studies have applied LCA methods to investigate vCF for lightweight vehicle applications but insights of these studies are not consistent. Whereas some have found lightweight CFRP components to reduce life cycle energy use and greenhouse gas (GHG) emissions,[23−25] contradicting studies have found that weight savings and associated improved fuel economy during the vehicle life are compromised by the energy intensity of vCF production, resulting in minimal net benefit[24] or even an increase in GHG emissions over the full life cycle.[26] This inconsistency arises primarily from data limitations for vCF production (as we have noted previously[27]), assumptions regarding vCF production process energy sources, and the ratio of vCF part mass to original part mass. All studies, however, clearly indicate that CF production is energy intensive and associated with significant GHG emissions relative to conventional materials. Using rCF in place of vCF can potentially reduce the environmental impacts of material production; however, maintaining similar material properties with vCF is crucial in order to realize benefits across the full life cycle (including production and use). The few studies that have assessed the cradle-to-gate environmental impacts of CFRP recycling have investigated different recycling technologies (fluidized bed, pyrolysis, mechanical recycling), generally concluding that CF recycling is far less impacting than vCF manufacture; however, these studies have not considered the use phase of rCF materials.[24,27−29] Overall, prior life cycle studies of CF recycling are limited by the availability of relevant data for recycling and rCFRP manufacturing processes and, to date, none has considered the use of rCFRP as lightweight materials in automotive applications.

Recycled CF has significant potential as a low cost and low environmental impact material for transportation applications. However, there is limited understanding as to the overall environmental impacts of the CFRP recycling, composite manufacture with rCF, and subsequent use of these materials. In this paper, life cycle models are developed to assess the performance of CF recycling, via fluidized bed process, and reuse in automotive applications. A set of rCFRP manufacturing approaches (compression molding, injection molding) are considered, and material production and its use are evaluated in a vehicle over its full lifetime. Case study automotive components are considered under different design constraints. The results are then compared with conventional automotive materials (steel) and competitor lightweight materials (aluminum, vCFRP) to identify opportunities where rCF can achieve a net environmental benefit.

2. METHOD

The goal of this study is to assess the life cycle environmental impacts of CFRP recycling and use of rCF for composite manufacture for automotive applications. Activities included within the life cycle model are shown in Supporting Information Figure S1, beginning with collected CFRP waste and including all subsequent activities related to CFRP recycling, rCF processing, rCFRP manufacture, and use phase. Recycled CF is assumed to be recovered from a fluidized bed recycling process, as analyzed previously.[27] Three rCFRP production pathways are considered:

(1) Random structure − Compression Molding: rCF is processed by a wet papermaking process prior to impregnation with epoxy resin and compression molding. Fiber volume fractions of 20, 30, and 40% are considered under molding pressure of 2−14 MPa.
(2) Aligned − Compression Molding: rCF is processed by a fiber alignment process prior to compression molding with epoxy resin. Fifty and sixty %vf are considered under molding pressure of 8 MPa.
(3) Random structure − Injection Molding: rCF is processed by wet papermaking and subsequently chopped prior to compounding with polypropylene (PP); rCF-PP pellets are subsequently injection molded. Fiber volume fraction is 18 %vf.

The rCFRP production routes are compared with similar composite materials produced from vCF, specifically:

(1) Woven − Autoclave: bidirectionally woven vCF preimpregnated (prepreg) is autoclave molded with epoxy resin; fiber volume fraction is 50%vf.[30]
(2) Chopped − Injection Molding: chopped, unaligned fibers are compounded with PP; vCF-PP pellets are

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subsequently injection molded. Fiber volume fraction is 18%vf.

CF-based materials are also compared with mild steel, as a conventional automotive material, and aluminum, a potential lightweight metal.

For recycling, a "cradle to gate" approach is taken which includes "initial resource extraction" (i.e., recovery of rCF for rCFRP products) and the manufacture of composite materials from rCF and the use. Upstream activities preceding the CFRP becoming a waste material are thus excluded from this analysis. For the vCF-based materials and metals (steel, aluminum), life cycle models include "cradle to gate" activities from initial resource extraction (e.g., CF feedstock production; ore mining), material production, component manufacture, and the use. We assume primary aluminum (no recycled content) is used in component manufacture to meet strict alloy composition limits.

Process models of the fluidized bed recycling, rCF conversion to an intermediate material (i.e., wet-papermaking/fiber alignment), and the subsequent CFRP manufacture (i.e., compression molding/injection molding) are developed to estimate the energy and material requirements of commercially operating facilities. This data is supplemented with databases to estimate impacts of producing and using material and energy inputs (e.g., Gabi[31] Ecoinvent[32]) assuming all activities to occur in the UK. Additional details related to waste CFRP recycling, rCF processing, and CFRP manufacture are included in the subsequent subsections.

Life cycle models are developed to assess the environmental implications of substituting steel with rCF materials and competing lightweight materials. Two environmental metrics are considered: primary energy demand (PED), 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_2eq).[33] A general approach is taken to ensure functional equivalence of producing automotive components from the set of materials based on the design material index (λ), a variable which is specific to the design criteria for any specific component. For further details see the references by Patton et al. and Ashby.[34,35] The component thickness is treated as a variable that is adjusted based on each material's properties and the specific applications design material index (see Section 2.5 for further details). Analysis results are presented on a normalized basis (relative to the mild steel reference material), and can thereby be easily applied to subsequent analyses that are undertaken for specific components where the material design index is known.

2.1. Carbon Fiber Recycling. A fluidized bed process is considered for the recycling of CFRP waste in this study. In the fluidized bed reactor, the epoxy resin is oxidized at a temperature in excess of 500 °C. The gas stream is able to elutriate the released fibers and transport out of the fluidized sand bed for subsequent separation by cyclone. After fiber separation, the gas stream is directed to a high-temperature combustion chamber to fully oxidize the polymer decomposition products. Energy is recovered to preheat inlet air to the bed. Mass and energy models of the fluidized bed process under varying conditions (e.g., annual throughput, CFRP feed rate) and insights regarding process energy efficiency and "gate-to-gate" environmental impacts have been presented previously.[27] For the current study, a plant capacity of 500 t rCF/yr and feed rate of 9 kg rCF/h m^2 are considered corresponding to energy requirements of 1.9 MJ natural gas/kg rCF and 1.6 kWh electricity/kg rCF.

2.2. Virgin Carbon Fiber Manufacture. The manufacture of vCF is modeled based on existing literature data. The life cycle inventory data input to our LCA models information was described previously[27] and comprises data from literature and life cycle databases, with parameters selected based on literature consensus, expert opinion, and results from a confidential industrial data set. 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 intermediate modulus) and corresponding energy requirements/environmental impacts. In this study, high strength vCF is assumed to be manufactured from a polyacrylonitrile (PAN) precursor followed by subsequent stabilization, carbonization, surface treatment and sizing processes. On the basis of a literature value for mass efficiency of 55%−62%,[36,37] a representative mass yield is assumed to be 58%. All inventory data have been recalculated relative to 1 kg CF and the total actual energy consumption is estimated to 149.4 MJ electricity, 177.8 MJ natural gas, and 31.4 kg steam. Direct process emissions are estimated based on available data[36] and adjusted to reflect the mass efficiency assumed in the current assessment.

2.3. Carbon Fiber Conversion Process. Two processes are considered to convert rCF to a form suitable for composite manufacture: wet papermaking to produce a random oriented mat,[13] and fiber alignment to produce a unidirectional fiber mat.[38] Mass and energy balances of these two rCF processing methods are established based on key processing parameters as described below.

To form a random mat via the wet-papermaking process, CF is first dispersed in a viscous aqueous solution to form a fiber suspension (assumed here to be a 0.1%vf to avoid agglomeration of fibers[39]) by stirring for 24 h at a certain rotational speed. The fibers are then deposited on a conveyor and washed, dewatered, and dried to produce a random mat. Energy requirements of each associated activity are estimated based on experimental data, parameter optimization to minimize energy consumption and, where available, energy efficiency data of standard equipment.[40,41] Further details of the papermaking process model development were reported previously.[27] A fiber alignment process is also considered wherein the fiber suspension is injected onto a mesh screen inside a rotating drum and the nozzle filters and aligns the fibers prior to dewatering/drying. This fiber alignment process is still under development, and so energy consumption is estimated based on a target for technology development (22 MJ/kg rCF mat) and summarized in the Supporting Information (Section S1.1). Because of confidentiality of the process in development, limited details of the fiber alignment process can be given. The implications of this assumption on results are discussed in Section 3.4.

2.4. Composite Manufacturing Processes. *2.4.1. Compression Molding.* Compression molding production of CFRP requires CF mats (random and aligned mats from rCF; prepreg from vCF) and epoxy resin film to be cut to size required to fit into the mold with cutting energy use of 0.37 MJ/kg.[42] Before applying compression pressure, a standard vacuum bagging procedure is implemented to reduce air entrapment during ply collation and thus to reduce the void content inside the composite. For random rCFRP, the mold is subsequently compressed under pressure of 2−14 MPa depending on fiber

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volume fraction required, with higher fiber fraction components requiring higher pressures.[13] For aligned rCFRP, the compression pressure is lower (8 MPa).[16] During compression molding, materials are heated to 120 °C for curing. A detailed description of our compression molding energy use models presented in our earlier work[27] and is summarized in the Supporting Information (Section S1.2.1).

2.4.2. Injection Molding. Injection molding has been successfully demonstrated to be an efficient way to process rCF into CFRP materials[19] and is capable of achieving mechanical properties similar to those of materials produced from injection molded vCF.[43] First, the CF is compounded with a thermoplastic matrix (polypropylene) to produce composite pellets for input to the injection molding. To produce rCF−PP pellets, randomly aligned rCF mat (100 g/m^2) is chopped to pellets 4 mm wide and 6 mm long in the current study. This may not be the efficient method to manufacture rCF−PP pellets but will be optimized where available in the future study. To ensure bonding between the rCF and PP matrix, PP is first compounded with a coupling agent (maleic anhydride grafted polypropylene coupling agent, 5% by weight) via a screw extrusion process at 210 °C with a screw rotational speed of 80 rpm and a residence time of 130 s. The rCF pellets are subsequently compounded with the PP pellet at 18%vf (30% weight fraction (wt)) by screw extrusion (210 °C, 50 rpm, and 150 s residence time). For vCF, a coupling agent is assumed to be not required and so vCF−PP pellets can be produced by a single compounding step with chopped vCF and PP granules (18%vf; 30 wt %) is required and is operated under the same conditions as the rCF-PP compounding step described above.

For injection molding of CF−PP pellets to form the automotive components, recommended parameters are presented in the SI. Although injection molding is normally used to manufacture relatively small parts and might not be the most appropriate manufacturing technique for larger parts such as automotive closure panels, it is still a comparable alternative manufacturing route for rCF and worthwhile for its investigation of environmental feasibility.

Compounding energy consumption is calculated accounting for polymer melting, screw driving, and cooling, and combined with output of the compounder obtained by the function of solid flow rate and simulation of factors in eq S3. Injection molding energy requirements are calculated to account for specific component geometry (mold cavity volume, projected area). Molding machine parameters, specifically the clamping force, injection pressure/temperature, ejection temperature, and screw drive rotational speed, are used to determine power requirements and combined with cycle time to estimate total energy requirements, based on relationships developed in prior studies.[44,45] Further details on the injection molding model development and parameters are given in SI Section S1.2.2.

2.4.3. Autoclave Molding. Autoclave molding is commonly utilized by the aerospace industry where heat and pressure are applied to prepreg laminates in a pressure vessel. It enables the manufacture of CFRP components with high fiber volume fractions and low void content but requiring intensive energy and high costs of both initial acquisition and use. In general, CF is preimpregnated with a thermoset resin before being put into a mold and curing under typical pressure of 0.6−0.8 MPa. Energy consumption for composite manufacture is substantially affected by processing parameters (e.g., curing temperature and time, degree of packing of the autoclave, etc.) which are associated with the geometry and size of the component. Because of the complexity of component design and autoclave process, industrial data and best available literature data are gathered to assess the environmental energy. Energy requirements of prepreg production 4 MJ/kg) and the subsequent autoclave molding (29 MJ/kg) are used in this study based on literature sources.[23,46,47]

2.5. Functional Unit. This study focuses on the development of flexible models capable of assessing a range of different automotive components, rather than focusing on a case study of a single component. The functional unit chosen for this study is a generic steel automotive component with requirements of bending and torsion stiffness and allocated a normalized thickness and mass of 1 to consider material substitutions. When evaluating alternative materials, functional equivalence measured by component stiffness is maintained by considering the design material index (λ) and varying component thickness to account for differences in each material's mechanical properties according to[34,35,48]

$$R_t = \frac{t}{t_{\text{ref}}} = \left(\frac{E_{\text{ref}}}{E}\right)^{1/\lambda} \tag{1}$$

where R_t is the ratio of component thicknesses between the proposed lightweight material (t) and the reference (mild steel, t_{ref}), E is the modulus of the two materials (GPa), and λ is the component-specific design material index. The normalized component mass is calculated based on the relative thickness and density of alternative materials.

Depending on design purposes, the parameter λ value may vary between 1 and 3: λ = 1 is appropriate for components under tension loading (e.g., window frame), λ = 2 is for columns and beams under bending and compression conditions in one plane (e.g., vertical pillar), and λ = 3 is suitable for plates and flat panels when loaded in bending and buckling conditions in two planes (e.g., car bonnet). Actual component designs require a finite element analysis to identify the material design index that would ensure design constraints are met. On the basis of finite element simulation, car joints, for example between the roof and vertical pillars, have been shown to have a λ value range of 1.2−2.0[34] while other car body structural members, such as floor supports, can have a λ value range of 1.21−2.4.[49] The present analysis considers λ values ranging from 1 to 3 to assess the environmental viability of rCF applications under different design constraints. Insights from this analysis can subsequently be applied to specific components where the exact design constraints are known.

Mechanical properties of vCFRP and random rCFRP were obtained from the previous experiments and manufacturers.[30,43,50] Properties of aligned rCFRP were calculated using a micromechanics model to estimate resulting CFRP properties.[51,52] Data for other materials (mild steel, aluminum, magnesium) are from online databases.[25,53,54] Material properties and corresponding relative thicknesses of component materials are summarized in Table S1.

2.6. Use Phase Analysis. During the use phase, the automotive components will impact vehicle fuel consumption due to their weight and corresponding mass-induced fuel consumption without powertrain resizing. In-use energy consumption is calculated with the Physical Emission Rate Estimator developed by the U.S. Environmental Protection Agency[55] and the mathematical model[56] for mass-induced fuel consumption. In brief, this method estimates vehicle power

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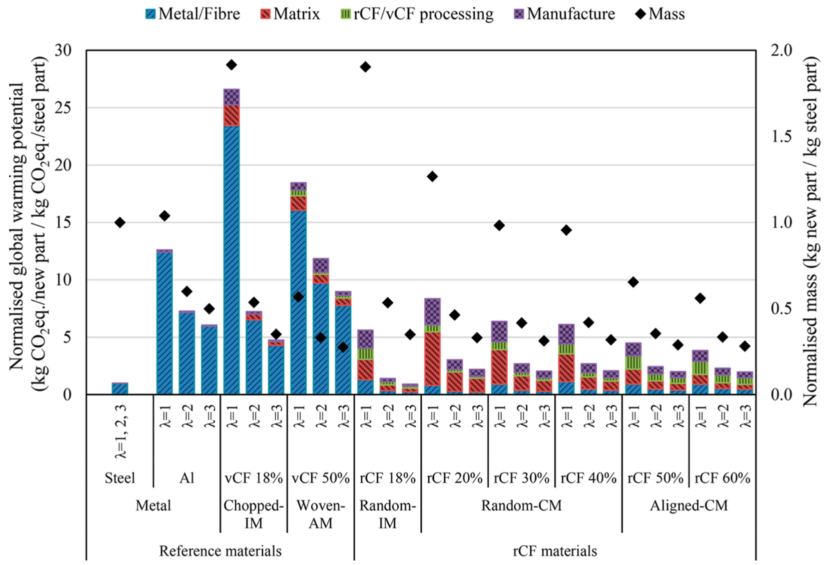

Figure 1. Normalized production GWP (kg CO_2eq/new part relative to kg CO_2eq/steel part) and mass (kg new part relative to kg steel part) of components to satisfy component design constraints for λ = 1, 2, 3. CM = compression molding, AM = autoclave molding, IM = injection molding.

demand, which is impacted by total vehicle weight, and integrates over a standard driving cycle as below[56]

$$W = \frac{1}{H_f \eta_i \eta_t} \int (mv(a + g^*\text{grade}) + Av + Bv^2 + Cv^3)\mathrm{d}t \tag{2}$$

where H_f is lower heating value of gasoline (32.20 MJ/L),[57] η_t is transmission efficiency, η_i is indicated (thermodynamic) engine efficiency, v is vehicle speed (m/s), m is vehicle mass (kg), a is vehicle acceleration (m/s^2), g is gravitational constant, grade is road grade (0 in the U.S. EPA test), A is target rolling coefficient, B is target rotating coefficient, C is target aerodynamic coefficient. The U.S. EPA combined fuel economy driving cycle is considered.

Model parameters for a set of production vehicles are available.[58] For this analysis a Ford Fusion is selected as a representative midsize light duty vehicle, which has a mass-induced fuel consumption factor of 0.38 L/(100 km·100 kg). Mass-induced fuel consumption is calculated based on the differences in vehicle mass from utilizing lightweight materials assuming no effect of material substitution on the vehicle aerodynamics. As a base case, a typical vehicle life of 200,000 km is used.[24,59] The sensitivity of results to these key parameters is evaluated.

3. RESULTS

3.1. Component Production. The normalized component mass and greenhouse gas (GHG) emissions associated with component production (excluding the vehicle use phase) for a component with material design index λ = 1, 2, and 3 are shown in Figure 1. As previous studies[25,34,48,60] have indicated, the weight reduction achieved with lightweight materials is strongly dependent on the material design index: at a higher λ value, lightweight substitution materials can provide more weight reduction, while at lower λ values, substitution materials present a lesser weight reduction or, in some cases, result in higher component weight. For material design indices of 2 and 3, substitution materials are capable of significantly reducing component weight relative to steel (normalized mass = 1). CFRP materials produced via compression molding and autoclave molding achieve the greatest weight reductions relative to steel. Increasing the fiber volume fraction in the rCF materials can be beneficial in achieving greater component mass reductions: significant weight reductions are seen in increasing the fiber content of random rCFRP from 20%vf to 30%vf. However, benefits of further increases in rCF content are minimal for the randomly oriented materials (e.g., 40%vf rCF) due to fiber damage during the manufacturing process and corresponding degradation of material properties.[13] Achieving high fiber content of 50%vf and 60%vf requires fiber alignment and can result in significant reductions in component weight; this demonstrates the importance of developing cost-effective techniques for aligning rCF. Similar to the aligned rCFRP, woven vCFRP achieves very low component weight. CFRP production via injection molding produces the heaviest CFRP components due to the low fiber volume fraction that is achievable (18%vf). However, injection molded CFRP components can still reduce component weight by 47% relative to steel (λ = 2). Aluminum can also achieve significant weight reductions benefits compared to steel (40% and 50% weight reduction for λ = 2 and 3, respectively). In contrast, for λ = 1 only aligned rCFRP and woven vCFRP can reduce weight relative to steel; aluminum and random rCFRP have similar weight, while injection molded rCFRP components have approximately double component weight relative to steel (see scatter plots in Figure 1).

GHG emissions and PED associated with component manufacture are proportional to component mass and, as such, follow trends similar to those of the relative mass results. For material design indices of λ = 2 and λ = 3, GHG emissions associated with the production of rCFRP components are generally less than those of other lightweight materials and, in some cases, represent only a minor increase relative to the reference steel component for components. Recovery of rCF from waste CFRP is very energy efficient and, correspondingly, is associated with very low GHG emissions. Production of matrix material, rCF processing, and final manufacture represent the largest shares of production emissions. Increasing the fiber volume fraction serves to reduce the production impacts of rCFRP components, as production of rCF is less

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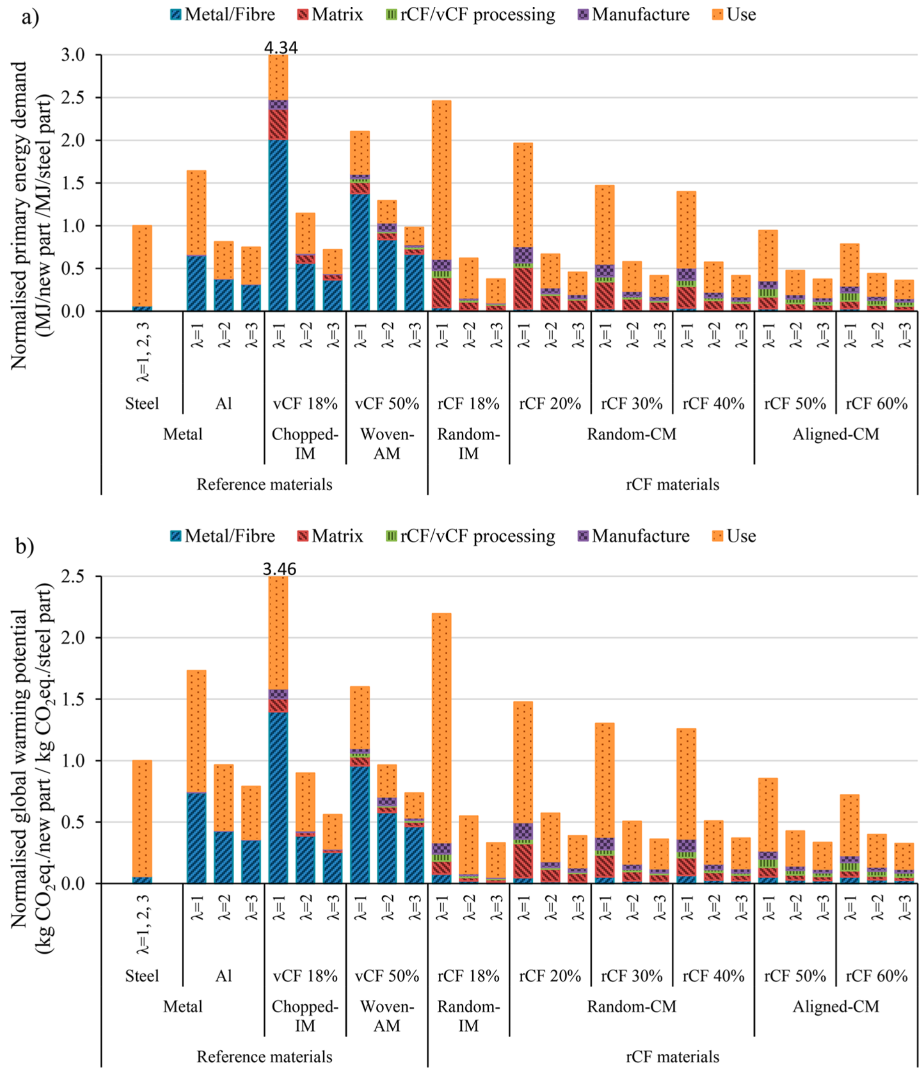

Figure 2. Normalized total life cycle (a) PED (MJ/new part relative to MJ/steel part) and (b) GWP (kg CO_2eq/new part relative to kg CO_2eq/steel part) of components made of different materials achieving equivalent stiffness in automotive steel components for different design constraints (λ = 1, 2, 3). CM = compression molding, AM = autoclave molding, IM = injection molding.

GHG-intensive than that of the epoxy or polypropylene matrix material. But rCFRP components cannot achieve weight reductions relative to the reference steel component (λ = 1), production emissions significantly exceed those of the steel component by factors of 4–8 (see Figure 1).

The very high GHG intensity of vCF manufacture results in relatively high vCFRP component production GWP, representing 82% and 90% of emissions for the manufacture of compression molded and injection molded vCF components, respectively. Manufacture of components from rCF is associated with GWP of 17–26% that of the woven vCFRP component produced via autoclave molding. Similarly, aluminum has embodied GHG emissions approximately an order of magnitude greater than the reference steel component, primarily due to the energy-intensive manufacture of the raw materials.

The primary energy demand (PED) results exhibit trends very similar to the GWP analysis. PED results are presented in SI Figure S4, alongside manufacturing model results detailing the energy and material requirements of individual processes for manufacturing rCFRP and vCFRP components.

3.2. Life Cycle Energy Use and Greenhouse Gas Emissions.

Components manufactured from rCF can, in some cases, achieve significant reductions in PED and GWP relative to steel and other lightweight materials over the full life cycle including vehicle use (Figure 2). However, the environmental benefits from substitution are dependent on the specific component design constraints and corresponding material design index (λ): at higher λ values, greater weight reductions are achieved, resulting in lower mass-induced fuel consumption during the vehicle use phase as well as lower material requirements during manufacture.

For design constraint λ = 2, which is typical for components under bending and compression conditions in one plane (vertical pillars, floor supports), rCFRP components can significantly reduce PED and GWP relative to steel over the full life cycle. Impacts associated with rCFRP components vary depending on the production route and fiber volume fraction. Random structure, compression molded rCFRP components can reduce PED relative to steel by 33% (20% rCF volume fraction) to 43% (40% volume fraction); similar trends are seen in GHG emissions. Injection molded rCFRP components have slightly lower energy use and GHG emissions compared to

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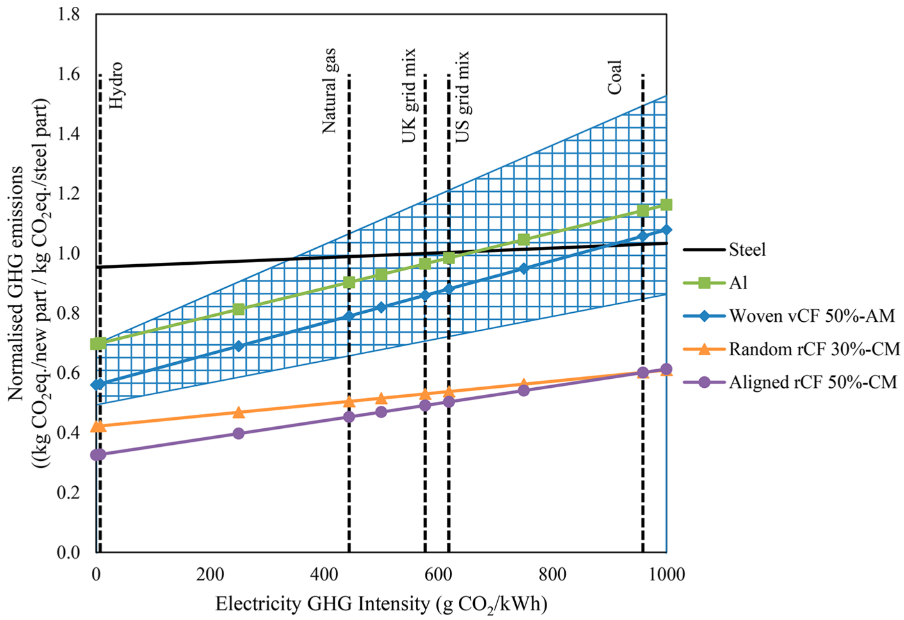

Figure 3. Sensitivity of life cycle GHG emissions (kg CO_2eq/new part relative to kg CO_2eq/steel part) of automotive component materials to the GHG intensity of grid electricity input to material production and uncertainty in energy requirements of vCF production (λ = 2). CM = compression molding. In the shaded areas, the bottom borderline represents that woven vCFRP production uses the low case of energy requirement of vCF production (198 MJ/kg), and the top borderline represents the high case (595 MJ/kg) relative to the base case (the blue line in the middle).

compression molded random rCFRP materials, primarily due to the low energy intensity of injection molding process (3 MJ/kg) and matrix material production (polypropylene for injection molding versus epoxy resin for compression molding). Achieving higher fiber fractions through alignment can deliver further PED reductions of up to 56% for the highest fiber content considered here (60%vf), demonstrating the potential advantages to be seen from developing alignment techniques. This finding, however, is dependent on alignment technologies meeting the development target energy consumption of 22 MJ/kg. As actual fiber alignment energy requirements may be more or less than this target, the break-even alignment energy consumption for aligned rCFRP materials are calculated to retain superior life cycle environmental performance over the best-case randomly aligned rCFRP material. This breakeven point is found to be 95 MJ/kg and 110 MJ/kg to achieve similar life cycle PED and GWP impacts, respectively. This result suggests that, should technology development objectives be achieved, then aligned rCFRP would be a promising low life cycle environmental impact material for automotive applications.

In contrast, the energy- and GHG-intensive manufacture of vCF precludes significant reductions in life cycle PED and GWP in all but the most promising substitution scenario (λ = 3). In agreement with previous analyses,[23,24] results indicate that although woven vCFRP components can achieve the lowest mass of all alternative materials considered in this study, in-use fuel savings can be counteracted by the impacts of vCF manufacture. In comparison, rCFRP components benefit from the low energy-intensity of rCF recovery (compared to vCF manufacture) and can thereby achieve significant reductions in life cycle energy use and GHG emissions. The lightweight aluminum components also present significant reductions in PED and GWP relative to steel mainly due to the moderate production impacts and large use phase fuel savings. They can achieve similar PED and GWP reductions with woven vCFRP components relative to steel, but still underperform the rCFRP components.

For λ = 1, for columns and beams under tension loadings (e.g., a window frame), there is limited scope for lightweighting with any of the materials considered in the present study. Only aligned rCFRP with high fiber volume fractions (i.e., 50% vf and 60% vf) can reduce life cycle PED and GWP relative to steel.

3.3. Sensitivity Analysis. The study results are sensitive to a number of key parameters, including material substitution assumptions, impacts of vCF manufacture, GHG-intensity of electricity inputs, impact of component weight on in-use energy consumption, and vehicle lifetime. Detailed sensitivity analysis results are presented in the Supporting Information (Section S2.2 and Figures S5–S7) and are summarized here.

Uncertainty associated with vCF production impacts arise from data quality issues as well as regional variability of electricity generation sources and associated impacts. The quality of life cycle inventory data for vCF manufacture is poor: publicly available data is limited; vCF production energy requirement and sources vary significantly (~200 to 600 MJ/kg from a mix of electricity, natural gas, and steam);[4,23,37,61] and studies have not linked production data to CF properties despite different processing conditions required to achieve high modulus and high strength CF. If the lower end of production energy estimates can be achieved, the life cycle GHG emissions of vCF-based materials correspondingly decrease by 17% (Figure 3 for λ = 2 and SI Figure S5), whereas the higher energy requirement estimate would increase emissions by 36%.

Life cycle GHG emissions are sensitive to the generation mix of input electricity; however, regardless of electricity source, components manufactured with rCF achieve the lowest emissions of all materials considered in this study (Figure 3). By utilizing hydroelectric power to produce the CF-based materials, life cycle GHG emissions can be reduced by 35% (woven vCF and aligned rCFRP) and 20% (random rCFRP) relative to the base case electricity source (UK grid mix). With

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increasing nonrenewable content of electricity, the ability of alternative materials to reduce GHG emissions relative to steel declines. As such, ongoing decarbonization of the electricity sector seen recently in many countries will serve to improve the relative performance of lightweight materials relative to conventional steel materials.

Uncertainty in vehicle life does not alter the finding that rCFRP components achieve the lowest life cycle PED and GWP impact (see SI Figure S5). As expected toward 300 000 km, the advantages of lightweight materials become more pronounced: aligned rCFRP components reduce GHG emissions relative to steel by up to 94%; vCF components become favorable to steel when vehicle life exceeds 250 000 km ($\lambda = 2$). Conversely, shorter vehicle life reduces in-use fuel savings and is therefore detrimental to the performance of lightweight materials. However, rCF components can reduce PED and GWP relative to conventional steel components even with very short distances traveled (<50 000 km). Uncertainty in estimates of mass-induced fuel consumption similarly impact the performance of lightweight materials (Figure S6). However, across the range of values considered in the study, rCFRP materials maintain the lowest life cycle environmental impact.

3.4. Discussion. Lightweight materials for automotive applications can reduce in-use environmental impacts and enable alternative transmissions (e.g., range extension for electric vehicles). However, weight saving is not always a reliable indicator of environmental performance as this single metric ignores the impacts associated with material production. Cost and embodied energy barriers associated with the production of lightweight metals and vCF materials can, in some cases, outweigh weight reduction and environmental benefits associated with reduced fuel use during the vehicle life. In the current study, the advantages of rCFRP materials for automotive applications are demonstrated and compared to competing lightweight materials (aluminum, vCF). Components produced from rCFRP can achieve weight reductions similar to or greater than competing lightweight materials while substantially reducing the impacts of production due to the low energy intensity of recycling and rCF processing activities.

For many components, while exhibiting low embodied energy/GHG emissions, the use of rCFRP results in significant reduction in GWP and PED relative to conventional steel components primarily due to the low energy intensity of recycling and large use phase fuel savings. The overall finding supports the emerging commercialization of CF recycling technologies and identifies significant potential market opportunities in the automotive sector. It has the potential to inform industry and policy-makers regarding environmental impacts related to CFRP recycling technologies and the development of relevant policies to encourage suitable utilization of rCF materials. By adjusting model values, the model can be used to evaluate environmental impacts of other jurisdictions, colocation scenarios, and coproduction scenarios; similarly, the model could be expanded to include additional environmental impact metrics, e.g.,those related to non-GHG air emissions from recycling, manufacturing, and use phases.

Recycled CF materials demonstrate significant environmental benefits for material selection processes and empower eco-friendly lightweighting strategies in the automotive sector. Identifying specific components where rCFRP materials can achieve substantial weight reductions is thus critical to maximizing their potential environmental benefits. In the current study, a range of design material constraints are considered. Further investigations must extend these methods that efficiently link component design criteria to life cycle environmental impact to integrate this approach with finite element analysis and whole-vehicle design considerations in order to identify the most promising applications.

Although the environmental performance of rCFRP materials is presently demonstrated, there is still less certainty as to the financial viability of their production and application in the automotive sector. Future work will be focused on the financial analysis of the recycling process and the subsequent manufacture of rCFRP and combined with LCA method to support material design and investigate applications of rCFRP for best trade-offs between environmental impacts and costs. Also of concern is the mismatch between rCF availability (estimated at about 50 000 t/yr in 2017[61]) and potential demands in the automotive sector, which produced in excess of 95 million vehicles globally in 2015,[62] and other potential applications of rCF materials. It will therefore be essential to identify optimal rCF utilization opportunities that maximize net environmental and financial benefits. Environmental assessment and further life cycle cost analysis will thus play a crucial role in identifying suitable waste management strategies to address the emerging waste burden of end-of-life and manufacturing scrap CFRP materials and to determine beneficial uses of rCF in automotive sector or in other applications.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.7b04069.

> Additional details on the overall method, description of process modeling of fiber alignment process, CFRP manufacture and environmental impact and sensitivity analysis results; equations S1−S9 explain how the energy requirements of recycling and remanufacturing process are related to the processing parameters; validations of process modeling are given; Figures S1−S6 show overview of recycling pathways, production PED of components, sensitivity of GHG emission to manufacture vCF, sensitivity of PED and GWP to traveling distance and mass induced fuel consumption; Table S1 shows mechanical properties used in the paper (PDF)

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Notes

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