

Comparing Life Cycle Energy and Global Warming Potential of Carbon Fibre Composite Recycling Technologies and Waste Management Options

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1 **Abstract**

2 Carbon fibre reinforced polymers (CFRP) are used in increasing quantities as they have some
3 of the best properties in terms of specific strength and stiffness of any widely available material.
4 By 2020, annual global CFRP production is expected to be over 140,000 tonnes. However, the
5 resulting increased quantity of CFRP waste has highlighted the need for sustainable treatment
6 options as carbon fibre manufacture has high-energy intensity. A life cycle methodology is
7 used to evaluate primary energy demand (PED) and global warming potential (GWP)
8 leveraging best available literature data, process models, and experimental work. Overall
9 results indicate that recycling scenarios are generally the environmentally preferable options
10 over landfill and incineration. However, the relative environmental benefits of advanced
11 recycling processes (i.e., pyrolysis, fluidised bed, and chemical recycling process) depend on
12 the method used to determine displacement of virgin carbon fibre by recycled carbon fibre.
13 Totally, recycling processes can achieve a representative GWP of -19 to -27 kg CO₂eq. and
14 PED of -395 to -520 MJ per kg CFRP, providing superior environmental performance to
15 conventional composite waste treatment technologies.

16 **Keywords: Carbon Fibre Recycling; Life Cycle Methodology; Primary Energy Demand,**
17 **Global Warming Potential; Waste Treatment Options**

18 **Introduction**

19 Recently, the steady increase in the use of carbon fibre reinforced polymers (CFRP) across
20 a wide range of aerospace (e.g., Boeing 787 airplane wing structures), automotive (e.g., BMW
21 i3 body panels), energy (e.g., wind turbine blades), and sporting applications (e.g., fishing rods,
22 bicycles) has been seen as CFRP contributes to significant weight reduction of the product

1 while providing excellent performance. In the past 10 years, the annual global demand for
2 carbon fibre (CF) has increased from approximately 16,000 to 72,000 tonnes and is forecast to
3 rise to 140,000 tonnes by 2020.¹ Global revenues of CFRP are estimated to be \$16.1 billion in
4 2011, and are expected to increase to \$28.2 billion in 2015 and \$48.7 billion by 2020.² However,
5 the resulting CFRP wastes from manufacturing (up to 40% of the CFRP can be waste arising
6 during manufacture)³ and end-of-life components are generated at an increasing speed in the
7 next decades. Quantities of CF in production and end-of-life waste are estimated to be 62,000
8 tonnes by 2020.⁴ Existing automotive sector-specific EU regulations requires the recycling of
9 at least 85% of end-of-life materials.⁵ Moreover, the high cost and energy intensity of virgin
10 CF (vCF) manufacture (198–595 MJ/kg) also provide an opportunity to recover substantial
11 value from CFRP wastes. Therefore, there is a clear and significant requirement to develop a
12 CFRP waste management system dealing with CF recovery to comply with this legislation.

13 Recycling has been recognised as a desirable end-of-life option to deal with CFRP wastes as
14 recycling has the potential to recover value from the waste materials rather than being disposed
15 in landfill or incineration, fulfilling legislative and sustainability targets. Current recycling
16 methods vary from conventional mechanical recycling to thermal recycling (e.g., pyrolysis and
17 fluidised bed process) and chemical recycling.^{6,7} Mechanical processes reduce the size of the
18 composites to micron level to be incorporated into the manufacture of new CFRP as fillers.
19 Secondly, pyrolysis is a widely used method, being established in commercial operations.
20 Pyrolysis thermally decomposes the resin into an oil phase of liquid hydrocarbons, a gas
21 fraction (primarily CO, H₂ and methane) and char covered fibres. Another thermal process is
22 the fluidised bed process, which has been developed for the recycling of glass and carbon fibres
23 at the University of Nottingham for over 15 years.⁶ In the fluidised bed process, the polymer
24 matrix is oxidised to enable fibre recovery⁶, which can accommodate contamination in end-

1 of-life CFRP waste. Recovered CF (rCF) shows almost no reduction in modulus and 18-50%
2 reduction in tensile strength relative to vCF.^{3,6} A chemical recycling process uses a solvent to
3 degrade the resin and recover the carbon fibres. Recycling processes are now transitioning from
4 lab scale to commercial facilities (e.g., ELG Carbon Fibre Ltd. in UK using a pyrolysis
5 recycling process with an annual capacity of 2,000 t/yr). Table 1 summarizes the details of
6 existing CFRP recycling plants. Recovered CF could reduce environmental and financial
7 impacts relative to vCF production, while the potentially lower cost of rCF can create new
8 markets for lightweight materials.^{8,9} However, to date there is no systematic study comparing
9 the environmental performance of different recycling technologies.

10 Table 1 CFRP recycling technologies: geographical location, key processing parameters
11 and capacity

12 Life Cycle Assessment (LCA)^{10, 11} has been widely recognized as a valuable tool to aid
13 decision making for waste management systems, or strategic decisions concerning resource use
14 priority. LCA can provide an overview of the environmental aspects of different waste
15 management strategies, and enable efficient comparison of the potential environmental impacts
16 of these options. Prior studies¹²⁻¹⁶ have estimated energy requirements of various CFRP
17 recycling technologies and found substantially lower energy requirements compared to vCF
18 manufacture. However, very few studies have been undertaken to quantify environmental
19 impacts of CFRP recycling processes. Li et al.¹⁷ found that mechanical recycling reduces GHG
20 emissions, primary energy demand, and landfill waste generation compared to landfilling,
21 however, it is not economically competitive. Meng et al.^{8, 9} evaluated the energy and
22 environmental impacts of CF recycling by a fluidised bed process and reuse of rCF to
23 manufacture a CFRP material for the first time. A few additional studies have conducted LCA

1 for some CFRP recycling technologies;^{4, 18} however, each study is based on the different system
2 boundaries and assumption and limited data estimates for recycling process energy and
3 material inputs. Thus, it is difficult to compare the environmental performance of different
4 recycling technologies and determine which one offers the most benefits. While potential
5 overall environmental benefits are claimed in technical studies of CFRP recycling processes
6 and fibre reuse opportunities to replace vCF, these benefits have yet to be demonstrated in a
7 comprehensive life cycle study that compares different recycling techniques.

8 Overall, prior analyses indicate reduced energy consumption for rCF compared to vCF. Due
9 to the lack of inventory data on recycling processes in any life cycle inventory (LCI) databases
10 and the markets for recycled materials, comparative LCA studies on CFRP recycling are not
11 well established. In this study, a detailed life cycle analysis of waste treatment options for
12 CFRP materials has been developed in order to quantify the environmental impacts (primary
13 energy consumption, global warming potential in 100 years) in a life cycle perspective.
14 Comparisons of conventional landfill, incineration and the most commercially/near-
15 commercially viable recovery technologies (mechanical recycling; fluidised bed recycling;
16 pyrolysis recycling; chemical recycling) are undertaken to identify relative environmental
17 performance of alternative waste treatment routes on the UK basis.

18 **Methodology**

19 The life cycle model built following the ISO standards^{10, 11} begins where the waste CFRP
20 has been collected. System expansion has been applied in the model that includes credits from
21 avoiding production of energy and virgin materials as potential outputs of waste treatments.
22 “Gate-to-grave” models are developed for CFRP waste treatment by landfilling and

1 incineration including waste processing (disassembly, shredding), transport (100 km) (between
2 recycling facilities only), and waste treatment (landfill, incineration) (see Figure 1). For
3 recycling, a “gate-to-gate” approach is taken to include the production of composite materials
4 from rCF. The production and use of CFRP prior to end-of-life is identical regardless of the
5 waste treatment route selected, thus is not included in the model; i.e., the boundary of our study
6 assumes availability of CFRP waste as a feedstock without any prior associated/allocated
7 environmental burdens. Maintenance and facility construction are also excluded as the
8 allocated emissions and energy use per functional unit from these long-lived assets are likely
9 to be small. The functional unit is one tonne of CFRP waste treated, primary from
10 manufacturing scrap or end of life waste from aerospace industry, which is assumed to consist
11 of 55wt% fibre content and 45wt% matrix (epoxy resin) content, to compare waste
12 management options (i.e., landfill, incineration, mechanical recycling, pyrolysis recycling,
13 fluidised bed recycling, and chemical recycling) for CFRP waste. In order to complete the full
14 life cycle model, data collected from process model based on the pilot plant, experimental data,
15 best available literature data and LCI databases (e.g., Eco-invent¹⁹) are the major sources to
16 provide process-specific data. Primary energy demand (PED) and global warming potential
17 (GWP) are the two main metrics examined from the life cycle models. Figure 1 shows a
18 schematic representation for waste treatment routes considered in this study and final products
19 of each process.

20 **Waste treatment routes on CFRP**

21 This study considers six potential waste treatment routes for CFRP: landfill, incineration and
22 mechanical, pyrolysis, fluidised bed, and chemical recycling processes. Each waste flow for
23 recycling processes can be seen in the following sections, and shown in Figure 2. For all

1 recycling processes, collected CFRP waste materials are transported to materials disposition
2 facilities by 32 tonne standard dump truck for shredding and separation before waste
3 treatment.³ Transport distances of 100 km to landfill and 200 km to incineration or recycling
4 facilities were assumed. Waste residues arising from the recycling process, which is either
5 landfilled or incinerated, is assumed to be transported an additional 100 km distance from the
6 recycling site to the landfill site or an additional 200 km to incineration site. Combustion ash
7 generated from incineration processes is assumed to be transported 100 km to landfill.
8 Recycling credits either from electricity production or CF replacement are allocated to the
9 waste treatment of CFRP waste as the methods specified in Section 2.3. The inventory data for
10 landfill and incineration is obtained from LCI databases – Gabi and EcoInvent database. The
11 inventory data for rCF is based on data collection of all the activities including recycling
12 processes and transport followed by documentation of the data obtained covering inputs and
13 outputs (see Table A1).

14  Figure 1 CFRP Waste treatment routes.

15 **Landfilling**

16 The disposition of waste CFRP in landfill is assumed to occur in a sanitary landfilling site
17 which is built for the final disposal of solid waste and isolates the waste from environment.
18 Before waste CFRP burying in landfill site, shredding pre-treatment is needed to reduce the
19 size of CFRP waste into scraps. No prior dismantling work is needed to isolate the CFRP waste
20 as it is disposed with other landfill fractions. Transportation distance is assumed as 100 km
21 from scrap yard to landfill. Impacts associated with CFRP landfilling are assessed based the
22 Ecoinvent sanitary landfill dataset.¹⁹ After burying waste CFRP scrap is assumed to emit no

1 further greenhouse gas (GHG) or consume any energy due to the largely inert property of CFRP
2 waste.¹⁷

3 **Incineration**

4 Incineration of CFRP provides an alternative way to treat the CFRP waste and recovers the
5 embodied energy. Prior results⁴ suggest that CFRP waste can be co-fired with municipal waste
6 and used as an energy source.

7 The potential for energy production from CFRP waste is dependent on its energy content and
8 the incinerator efficiency. Typically, CFRP energy contents is about 30 MJ/kg^{6, 20} but varies
9 depending on the specific CFRP composition. Based on the fibre/matrix ratio, an energy
10 content of 32 MJ/kg is used in this study.²¹ Compared to advanced power stations using
11 conventional fuels, waste incineration typically has a lower efficiency than conventional fuels;
12 a 13% electricity generation efficiency with a combined heat & electricity cogeneration
13 efficiency of 38% is assumed.¹⁹ We assume a “high-efficiency” incineration scenario with a
14 25% electricity generation efficiency with a combined heat & electricity cogeneration
15 efficiency of 80%. It is assumed that electricity generation displaces the average UK grid mix
16 and heat generation displaces heat produced from natural gas which is the major source for
17 heat production in the UK. Residue material after combustion is collected and transported to
18 disposal in landfill as described in Section 2.1.1. Emissions from waste incineration are
19 modelled based on stoichiometric balances, assuming all the carbon content of CFRP is
20 oxidised and emitted as CO₂. Net GHG emissions are dependent on the direct emissions from
21 combustion and avoided emissions from electricity and heat displacement.

1 **Mechanical recycling**

2 Among various recycling methods, the most mature technology is mechanical recycling. It
3 is currently used on a limited industrial scale to recycle waste composites, especially glass fibre
4 reinforced plastic.²² After initial size reduction, the material is ground in a hammer mill and
5 graded into different lengths through sieving. Using mechanical recycling, CFRP wastes can
6 be reduced to two useful fractions: fine powder and fine rCF fraction. Mechanical recycling
7 products are commonly used as fillers in lower value materials, such as bulk or sheet moulding
8 compounds to replace glass fibre (see Figure 2). The resulting materials have poor mechanical
9 properties compared to virgin CFRP (vCFRP) materials²³ and so are not suitable for
10 lightweighting or high modulus/strength applications. Coarse fraction waste residues are
11 assumed to be transported 100 km from the recycling site to landfill site or 200 km to
12 incineration site.^{4, 17}

13 Figure 2 System diagram showing material and energy flows for a) mechanical recycling
14 with landfilling and mechanical recycling with incineration, b) pyrolysis recycling, c)
15 fluidised bed recycling and d) chemical recycling processes. The arrow colour indicates a
16 type of each flow (red – energy flow, green – credits, and black – material flow).

17 **Pyrolysis recycling**

18 Pyrolysis is a thermal decomposition of polymers without oxygen or in a controlled flow of
19 oxygen at high temperatures between 300 °C and 800 °C, enabling the recovery of long fibres
20 with high modulus. An elevated temperature of 1000 °C can be applied but it will result in a
21 significant degradation of mechanical properties of the fibre products. Due to the significant

1 impact of temperature and residence time on the final quality of the rCF, the two factors must
2 be controlled strictly in the pyrolysis reactor.

3 As a thermal method, a shredding preparation of CFRP wastes before fed into the pyrolysis
4 recycling plant is required. The pyrolysis process uses external heat to allow for recovering
5 fibres with minimum properties reduction, which can then be used in the composite
6 manufacture industries as rCF. Studies have shown that rCF from pyrolysis could maintain 90%
7 or more of the original mechanical performances. In addition, the polymeric matrix can
8 potentially be recycled as an oil phase of liquid hydrocarbons.^{24, 25} Pyrolysis has now reached
9 early stages of commercialisation, e.g., ELG Recycled Carbon Fibre Ltd has 2,000 t of CFRP
10 waste/yr recycling capacity with an estimated process energy of 30 MJ/kg.²⁶ For this process,
11 we assume substitution for vCF for the recovered material. There is a data limitation in that we
12 are not able to include separation processes and so may be overestimating the environmental
13 benefit of recovering pyrolysis products to displace primary production of these materials.

14 An experiment of pyrolysis recycling of CFRP is conducted in laboratory-scale to obtain the
15 mass data. The process of the experiment setup is as follows. The CFRP waste used in this
16 experiment comprised of 55wt% CF and 45wt% epoxy resin same as specified in Nahil et al.²⁷
17 Five sheets of CFRP (total volume CFRP: 12''x12''x0.5'') with described composition were fed
18 into a large laboratory furnace with the size of chamber 16''x16''x16''. Pyrolysis recycling to
19 recover rCF from CFRP waste involves two stages of heating process. First, the pyrolysis
20 reaction was performed at 500°C which was chosen to achieve a reasonable yield of rCF while
21 retaining mechanical properties of CF. During the pyrolysis reaction, nitrogen gas was fed into
22 the furnace chamber with the flow rate of 2L/min to prevent significant property degradation
23 of the CF. After the pyrolysis reaction, CF was mostly covered with residual chars. The second

1 heating process was performed at 450°C to remove char and separate CF in an oxidizing
2 atmosphere for a short time period. During the char removal step, it is assumed that residual
3 char is completely oxidized into CO₂. Based on the specifications of the furnace, energy
4 consumption of two heating process is calculated as follow. The required heating power is
5 600W and 500W at steady state to maintain pyrolysis temperature and char-removing
6 temperature, respectively. The required power to achieve desired temperature with heating rate
7 5-10°C is 2 kW. Energy related inventory data are obtained from commercial operation from
8 ELG (2000t CFRP waste/yr).²⁸

9 **Fluidised bed recycling**

10 The fluidised bed (FB) recycling process requires a shredding process before feeding CFRP
11 wastes into the FB reactor. The silica sand bed is used to volatilise the shredded scrap material
12 and thus to decompose the epoxy resin and release the fibres. The fluidising air is able to
13 elutriate the released fibres for about 20 minutes, but degraded material remains in the bed. The
14 operating temperature of 450 °C to 550 °C of the FB reaction is chosen to be sufficient to cause
15 the polymer to decompose, leaving clean fibres, but not too high to degrade the fibre properties
16 substantially. The fibres can then be removed from the gas stream by a cyclone or other gas-
17 solid separation device and collected.³ However, organic materials from the gas stream will be
18 a mixture of different by-products and it may be more cost effective to oxidise them fully to
19 recover the energy value in a high temperature chamber. These out gases can be fed to power
20 a combined heat and power unit. Therefore, in the current pilot plant, the gas stream after fibre
21 separation is directed to a combustion chamber to fully oxidise the polymer by-products from
22 FB process. Heat is recovered from the gas stream to pre-heat fresh air input before being

1 exhausted through the stack. The mass and energy flow of fluidised bed recycling pathway can
2 be found in Figure 2.

3 Inventory data is extracted from the process model, considering likely operating conditions:
4 500 t rCF/yr annual capacity; 9 kg CF/hr-m² fluidised bed feed rate; and 5% air in-leakage.
5 These parameters correspond to an energy requirement of 7.7 MJ/kg rCF, comprised of 1.9
6 MJ/kg (natural gas) and 5.8 MJ/kg (electricity).⁹ Epoxy resin matrix is assumed to be made of
7 Diglycidyl ester of bisphenol A (DGEBA) in 87wt% and Isophorone Dianmine (IPD) in 13wt%.
8 CO₂ emissions resulting from the oxidation of the epoxy matrix material are calculated on a
9 stoichiometric basis assuming all carbon is fully oxidized to CO₂.

10 **Chemical recycling**

11 Chemical recycling process utilises a liquid solvent (such as water, acid, and alcohol) to
12 break down polymer resin and separate them from CF. The recycling process is able to recover
13 high quality CF with only about 1.1% tensile strength loss and recover polymeric matrix as an
14 organic compound with a solvent method in nitric acid solution as reported in²⁹ (it is assumed
15 to replace virgin epoxy resin). The rCF is normally semi-long or long rCF with low
16 contamination. However, the decomposition temperature and nitric acid concentration have an
17 impact on the mechanical properties.

18 Depending on the temperature and pressure process, the chemical process can be categorised
19 into supercritical, subcritical, and near-critical chemical. Schneller et al.³⁰ investigated the
20 fibre-matrix separation via chemical using sub- and supercritical fluids (pure water and a
21 water/ethanol-mixture). After chemical separation, the majority of resin content could be
22 removed at high temperature and at long processing time (see Figure 2). Due to this, there may

1 be no requirement for an additional oxidising surface treatment which is used to remove the
2 char resulted from oxidation of resin. Chemical recycling technique is feasible but processing
3 temperature, time, solvents and equipment have negative effects on the environment.

4 Primary data were obtained at laboratory scale for the chemical recycling process as in³¹.
5 However, process energy source types (electricity/gas), process efficiency and recovery of non-
6 energy inputs due to scales of plant operation can have impacts on the environmental impacts
7 and thus bring uncertainty of results, which has been addressed in Discussion section.

8 **Carbon fibre replacement**

9 The quality of life cycle inventory data for vCF manufacture is poor: publicly available data
10 is limited. vCF production energy requirement and sources vary significantly (198 to 595
11 MJ/kg from a mix of electricity, natural gas, and steam) and GHG emissions associated with
12 vCF production have been estimated at 30-80 kg CO₂eq.⁹ Further, studies have not linked
13 production data to CF properties despite different processing conditions required to achieve
14 high modulus and high strength CF (between 1000–1400°C for high modulus fibers, or 1800–
15 2000°C for high strength fibers). Therefore, there is inadequate information to match energy
16 intensity to fiber properties. In this study, the manufacture of vCF is modelled based on existing
17 data from literature and life cycle databases, with parameters (e.g., mass yield in acrylonitrile,
18 polyacrylonitrile and CF conversion steps) selected based on literature consensus, expert
19 opinion, and results from a confidential industrial dataset. All of these data have been
20 recalculated relative to 1 kg of CF, giving an energy consumption of 149.4 MJ electricity, 177.8
21 MJ natural gas, and 31.4 kg steam.⁹ Utilising CFRP recyclate to displace vCF in composite
22 production is desirable for maximising revenue from waste streams and minimising energy use
23 and GHG emissions.

1 In order to determine the quantity of rCF that replaces vCF, it is required to have an
2 equivalent material function. In this paper, two different CF replacement methods are
3 considered either based on variable fibre content or variable material thickness. These methods
4 will be described in detail in the next section

5 **Replacement - Variable fibre content**

6 The first method considers CF replacement under equivalent specific stiffness (E/ρ) can be
7 achieved by changing the fibre volume fraction of rCFRP to mitigate the mechanical properties
8 reduction of rCF relative to vCF. Generalised rule of mixtures for tensile modulus³² can be
9 described by:

$$E_c = \eta_\theta E_f V_f + E_m V_m \quad (1)$$

10 Where η_θ is composite efficiency factor (Krenchel), $\eta_\theta = 1$ for unidirectional, $\eta_\theta = 0.5$ for
11 biaxial, $\eta_\theta = 0.375$ for random (in-plane), E_f is the modulus of the fibres, E_m is the modulus of
12 the matrix, V_f is the volume fraction of the fibres and V_m is the volume fraction of the matrix,
13 $V_f + V_m = 1$. As shown in Figure 3, using generalised rule of mixture the tensile modulus can be
14 predicted based on the fibre volume fraction. Therefore, in this study, we use the rule of
15 mixtures to predict the modulus of vCF and rCF products for comparison.

16 Figure 3 Tensile properties of an epoxy recycled carbon fibre composite experimentally
17 measured. The solid and dotted lines represent the theoretical stiffness calculated using the
18 generalized rule for randomly distributed and perfectly aligned fibres.³³

19 Using the method based on eq (1), the fibre volume fractions of rCFRP using rCF recovered
20 using different recycling techniques are calculated as listed in Table 2. To meet the same
21 mechanical properties, a higher fibre fraction is required for rCF and thus more rCF to replace

1 vCF. Meanwhile, the difference of polymer matrix content due to varying fibre volume fraction
2 can be determined as well: higher fibre fraction giving corresponding less polymer matrix
3 content for the same total thickness.

4 Table 2 Recycled CFRP design properties for CF replacement method based on variable
5 fibre content.

6 Replacement - Variable material thickness

7 In comparison, the second method to determine the replacement of vCF is selected based on
8 variable material thickness but constant fibre fraction. When evaluating alternative materials,
9 functional equivalence can be maintained by considering the design material index (λ) and
10 varying component thickness to account for differences in each material's mechanical
11 properties:³⁴⁻³⁶

$$R_t = \frac{t_{rCF}}{t_{vCF}} = \left(\frac{E_{vCF}}{E_{rCF}} \right)^{\frac{1}{\lambda}} \quad (2)$$

$$R_m = \frac{m_{rCF}}{m_{vCF}} = \frac{\rho_{rCF}}{\rho_{vCF}} \left(\frac{E_{vCF}}{E_{rCF}} \right)^{\frac{1}{\lambda}} \quad (3)$$

12 Where R_t is the ratio of component thicknesses between rCF material (t_{rCF}) and the reference
13 vCF material (t_{vCF}), E is the modulus of the two materials (GPa), and λ is the component-
14 specific design material index. The expected CFRP component mass can be calculated based
15 on the relative thickness and density of alternative materials to calculate the equivalent CF
16 replacement (i.e., method 2). The relative thickness of the components affects both the life
17 cycle inventory, as thicker components require greater quantities of fibre and matrix materials.

1 Depending on design purposes, the parameter λ value may vary between 1 and 3. $\lambda=1$ is
2 appropriate for components under tension loading (e.g., window frame), $\lambda=2$ is for columns
3 and beams under bending and compression conditions in one plane (e.g., vertical pillar) and λ
4 $=3$ is suitable for plates and flat panels when loaded in bending and buckling conditions in two
5 planes (e.g., car bonnet) and is selected as base case. (Actual component designs require a finite
6 element analysis to identify the material design index that would ensure design constraints are
7 met.) The sensitivity of environmental impacts will be assessed for λ values ranging from 1 to
8 3. The mass ratios and corresponding fibre and resin mass calculated are shown in Table 2:
9 fibre fraction is constant, so larger components require more fibre and resin.

10 **Results and discussion**

11 Section 3.1 describes the environmental impacts of the various waste treatment options
12 covering gate-to-gate impacts of recycling processes while Section 3.2 shows the total life
13 cycle environmental impacts including the use of waste treatment products (recovered energy,
14 rCF, chemicals) to displace conventional products/production.

15 **Gate-to-gate life cycle primary energy demand and global warming potential**

16 The PED and GWP results, excluding recycling credits, are compared among selected CFRP
17 waste treatment methods as shown in Table 3. Landfill emits only minor GHG emissions of
18 0.13 kg CO₂eq./kg CFRP waste (0.03 kg CO₂eq. from shredding and 0.10 kg CO₂eq. from
19 sanitary landfill operation) plus 0.01 kg CO₂eq./kg from transport of the waste materials; GHG
20 generation in landfill is not of concern due to inert nature of CFRP waste. Incineration produces
21 larger amount of GHG emissions of 3.12 kg CO₂eq./kg CFRP waste. The large amount of GHG

1 emissions are mainly from the combustion process as the carbon content of CFRP is released
2 to the environment as CO₂.

3 Excluding the benefits of energy recovery or the use of rCF materials, recycling processes
4 require energy inputs to treat the CFRP wastes. Mechanical recycling with landfilling of the
5 remaining coarse fraction gives GHG emissions of 0.11 kg CO₂eq./kg CFRP waste and the
6 mechanical recycling process accounts for 0.03 kg CO₂eq. In comparison, mechanical
7 recycling with incineration produces larger GHG emissions of 1.80 kg CO₂eq./kg CFRP waste
8 due to combustion of coarse fraction but this option will have GHG deduction from energy
9 outputs to displace grid electricity and heat.

10 Thermal recycling processes - pyrolysis and chemical recycling - require greater energy
11 inputs and are associated with higher PED and GWP than the fluidised bed, primarily due to
12 the recovery of energy from oxidised matrix material in the fluidised bed process. Pyrolysis is
13 associated with 2.9 kg CO₂eq./kg CFRP waste, primarily from electricity and natural gas
14 consumption for recycling process. Transport accounts for only 1% of the total energy
15 consumption. Fluidised bed and chemical recycling processes have similar amount of GHG
16 emissions arising from recycling process, producing 1.56 kg CO₂eq. and 1.53 kg CO₂eq. per
17 kg CFRP waste, respectively.

18 Table 3 Primary energy demand and Global Warming Potential comparison of the carbon
19 fibre recovery and conventional landfill and incineration without credits from the use of
20 products of recycling processes.

1 **Total life cycle primary energy demand and global warming potential**

2 Including the recycling credits from CF replacement or electricity production, the PED and
3 GWP of different CFRP waste treatment methods based on method 1 and method 2 are shown
4 in Figure 4. Overall the LCA results indicate that recycling scenarios are generally the
5 environmentally preferable options for PED and GWP considered in this analysis, though the
6 exact net environmental impacts vary depending on the CF replacement method selected.

7 Conventional waste treatment processes (landfill, incineration) perform worst in terms of life
8 cycle PED and GWP. Even including energy credits, GHG emissions from incineration
9 exceeds the emission saving from electricity and heat power generation giving a net GHG
10 emission of 2.14 kg CO₂eq. while landfilling consumes more than 1.11 MJ energy due to no
11 environmental credit from displacement. High-efficiency incineration scenario has the
12 potential to further reduce the emission due to avoiding more raw energy production. Assuming
13 higher conversion efficiencies of 25% electricity generation with a combined heat & electricity
14 cogeneration efficiency of 80%, net GHG emissions can be reduced by half to 1.08 kg
15 CO₂eq./kg CFRP. However, even in this high efficiency scenario where useful energy outputs
16 are approximately doubled, avoided emissions associated with displacing UK grid electricity
17 and natural gas-fired heat generation are insufficient to compensate for CO₂ emissions arising
18 from CFRP combustion.

19 Mechanical recycling with landfilling of the coarse recyclate fraction exhibits a modest
20 global warming potential reduction relative to mechanical recycling with incineration. The
21 displacement of glass fibre production results in a GHG emissions credit of 0.48 kg CO₂eq./kg
22 CFRP, giving a net global warming potential reduction of 0.37 kg CO₂eq./kg CFRP. However,
23 if the coarse recyclate fraction is incinerated, mechanical recycling produces a net GHG

1 emission increase of 0.76 kg CO₂eq./kg CFRP. Compared to the advanced thermal recycling
2 process, mechanical recycling was not favourable primarily due to the low mechanical
3 performance obtained in the recovery.¹⁷

4 **Carbon fibre replacement - variable fibre content**

5 Due to different reductions of mechanical properties of recycling processes, rCF materials
6 must contain a higher fibre volume fraction than vCF materials of the same thickness in order
7 to achieve the same stiffness. Results show GHG emissions from fluidised bed recycling
8 process are mainly from the oxidation of the resin content in CFRP. However, rCF displacing
9 vCF provides environmental benefits by reducing raw material production, resulting in a net
10 reduction in GHG emissions.

11 As in Figure 4, fluidised bed recycling process shows the relative lower net primary energy
12 demand and GHG emissions and the main credits are from CF replacement. Considering
13 primary energy demand, the fluidised bed recycling method gives about -494.5 MJ net PED
14 per kg CFRP waste (Figure 4) by replacing the energy intensive vCF production (834.5 MJ
15 PED/kg⁹). Net primary energy demand equals to total energy input to recycling minus energy
16 reduction from displacement of vCF. In replacement method based on variable fibre content, 1
17 kg fluidised bed rCF can replace 0.95 kg vCF compared to 0.88 kg vCF per kg pyrolysis rCF
18 and 0.89 kg vCF per kg chemical rCF (see Table 2). Meanwhile, pyrolysis and chemical
19 recycling processes result in a 12% and 11% resin savings per kg rCF compared to 5% for
20 fluidised bed process. Primarily due to the difference from fibre replacement, pyrolysis and
21 chemical recycling processes show higher net PED (-452.9 MJ and -431.8 MJ, respectively),
22 in spite of additional benefits of by product, such as oil/wax from pyrolysis recycling process
23 and epoxy resin from chemical recycling process. Similarly, GWP of fluidised bed recycling

1 process is the lowest amongst the selected recycling options, -25.9 kg CO₂eq./kg CFRP
2 compared to 23.6 kg CO₂eq./kg CFRP for pyrolysis process and 23.7 kg CO₂eq./kg CFRP for
3 chemical recycling process.

4 Sensitivity analysis of CF replacement ratio has been performed to analyse its impact on PED
5 and GWP for CF replacement method based on variable fibre content. If fibre recovery can be
6 undertaken with no degradation of fibre properties, then 1 kg rCF could displace 1 kg vCF
7 (fibre volume fraction is 40% for both rCFRP and vCFRP). Compared to the base case,
8 pyrolysis, fluidised bed and chemical recycling process could achieve further reductions in life
9 cycle PED (12%, 5% and 10% further avoided energy use, respectively) and GWP (13%, 5%
10 and 11% further reductions in GWP, respectively). For 20% mechanical property reduction, 1
11 kg rCF can replace 0.8 kg vCF (fibre volume fraction is 50% for rCFRP compared to 40% for
12 vCFRP) and correspondingly there is 20% reduction in epoxy resin usage per kg rCF. As a
13 consequence, recycling processes have less PED and GWP benefits relative to base case: PED
14 is 92%, 86% and 92% of that of base case for pyrolysis, fluidised bed and chemical recycling
15 process, respectively and GWP has a similar trend.

16 Figure 4 a) Primary energy demand and b) Global warming Potential of different CFRP
17 waste treatment options including credits (CF replacement based on variable fibre content
18 and material thickness)

19 **Carbon fibre replacement - variable material thickness**

20 Similar with results based on variable fibre content, overall results based on variable material
21 thickness indicate the great environmental PED and GWP benefits obtained from recovery
22 process where benefits are primarily from replacing vCF with rCF.

1 Environmental benefits of recycling processes achieved by avoiding intensive energy
2 consumption associated with vCF production can be analysed by another replacement method
3 based on variable material thickness assuming a constant fibre volume fraction. Pyrolysis
4 recycling can achieve a net PED of -451.4 MJ/kg CFRP by accounting for the 490.26 MJ PED
5 reduction from avoiding 0.6 kg vCF production. Chemical recycling process can only achieve
6 a net PED of -431.8 MJ/kg CFRP while 90% benefits from vCF replacement and 10% from
7 avoiding of virgin epoxy resin production as epoxy resin content can be recovered using
8 chemical recycling technique. Fluidised bed recycling activities can achieve slightly larger net
9 PED reduction of 497.6 MJ/kg CFRP than any other thermal recycling processes. The main
10 difference is primarily due to the fibre replacement ratios of 0.94 kg vCF/kg pyrolysis rCF,
11 0.98 kg vCF/kg fluidised bed rCF and 0.95 kg vCF/kg chemical rCF, respectively. GWP results
12 show similar trend that fluidised bed rCF to replace vCF leads the best GHG emission
13 performance, -26.2 kg CO₂eq./kg CFRP.

14 Error bars shown in Figure 4 present PED and GWP of different thermal recycling processes
15 when λ value ranges in 1–3 relative to base case λ value of 2 for replacement method based on
16 variable material thickness. Results indicate that the relative performance remains similar
17 regardless of the rCF application. At higher λ values, greater weight reductions are achieved in
18 material substitution, resulting in less rCF and polymer matrix required and as such relatively
19 greater PED and GHG emission reduction. When $\lambda = 3$, recycling processes are able to provide
20 larger PED reductions relative to base case: 2.9%, 0.3%, and 2.6% reduction for pyrolysis,
21 fluidised bed, and chemical recycling processes, respectively. In contrast, when $\lambda = 1$, net PED
22 has 7.2%, 3.6% and 6.4% increase for pyrolysis, fluidised bed and chemical recycling
23 processes, respectively. GWP results show similar trends that different rCF applications based
24 on λ values result in up to 7% difference for these recycling processes.

1 Sensitivity analysis of variations of rCF mechanical property reductions of 20% and 0% are
2 performed similar with that for replacement method based on variable fibre content. If there is
3 no reduction in mechanical property of rCF relative to vCF, 100% vCF replacement can be
4 made and the largest PED and GWP reduction can thus be achieved. Minimum net PED is -
5 488.2 MJ, -513.6 MJ, and -461.0 MJ per kg CFRP waste for pyrolysis, fluidised bed and
6 chemical recycling process, respectively, corresponding to 8%, 3% and 7% less than the base
7 case assumed; similar trends for GWP results can be seen as well. These further reductions
8 demonstrate the need for technology improvements in minimising mechanical properties
9 reduction in the recovery process. Expected increase of PED and GWP can be seen when the
10 rCF mechanical property reductions go up to 20%. Especially for fluidised bed process, there
11 are 14% less PED and 15% less GWP reductions if rCF is 20% poorer than vCF in light of
12 mechanical property. Previously, potential trade-offs have been identified between increasing
13 feed rate and resulting rCF properties.⁹ In recycling process, in order to avoid agglomeration
14 at high feed rates as in fluidised bed process, fibre length must be reduced³⁷. However, fibre
15 length may also affect the downstream CFRP manufacturing process and resulting CFRP
16 product properties. Ongoing and future research has to balance recycling performance and rCF
17 properties for optimising environmental impacts as discussed above.

18 **Discussion**

19 Weight reduction achieved with CF composites can, in some applications such as aerospace,
20 achieve substantial reductions in life cycle energy use and GHG emissions; however, the large
21 energy requirement for vCF production can, in some uses, outweigh weight reduction and
22 associated environmental benefits due to reduced fuel use during the vehicle life.^{8,38} Delivering
23 more environmentally-beneficial CF materials to a wider range of opportunities depends on 1)

1 the development of energy efficient manufacturing processes for CF and CFRP (e.g., plasma
2 based processing or use of renewable energy feedstocks such as lignin),³⁹ and 2) the recovery
3 of high quality rCF so that rCF can meet partial demands for vCF materials. In the current
4 paper, environmental impacts of current advanced CF recycling technologies (i.e., pyrolysis,
5 fluidised bed and chemical recycling process) have been assessed and our results show that
6 they can achieve similar and significant environmental (PED, GWP) benefits. This is because
7 rCF from recovery processes only experiences minor degradation of mechanical properties and
8 can be reused in place of vCF. The environmental benefits via replacement are achieved
9 primarily by avoiding the production of energy-intensive CF and preserving primary material.

10 It should be noted that for pyrolysis process, we assume all pyrolysis products can be
11 recovered and displace primary production, but have not included any recovery activities nor
12 considered the financial viability of recovering these materials, especially if in small quantities.
13 Similarly, for chemical recycling, we assume 1 kg resin recovered can replace 1 kg new epoxy
14 resin without considering any additional processes nor cost aspects. Therefore, their potential
15 environmental benefits can only be true provided that assumptions made are met. In addition,
16 as we are not accounting for use phase, and how component weight would impact use fuel
17 consumption, future work is suggested to analyse the environmental performances among these
18 advanced recycling technologies in the full life cycle. A final point around the pyrolysis data
19 used in this study is that they were primarily based on laboratory experiments and at larger
20 scale they may have a lower energy footprint.

21 Maintaining the mechanical properties of CF through the recycling processes is a key
22 challenge to overcome in developing a commercial CF recovery process and trade-offs between
23 increasing the throughput and maintaining mechanical properties clearly exist between the

1 competing recycling technologies. Advanced recycling processes such as fluidised bed can
2 recover CF showing almost no reduction in modulus and 18-50% reduction in tensile strength
3 relative to vCF. Retention of tensile modulus and tensile strength is also achievable in the
4 studied recycling processes. In this paper, environmental performance of recovery processes
5 with varied rCF mechanical properties have been investigated and the most favourable 100%
6 retain of mechanical properties in rCF still depends on technical improvement. Current
7 commercial recycling processes (e.g., pyrolysis) cannot recover rCF without mechanical
8 properties reduction and will have to be selective in types of waste materials. Although
9 fluidised bed recycling process has high tolerance to contamination and varied polymer types,
10 it is still in transition to commercial scales.

11 As more CF is being produced, there are more opportunities for CF recovery from waste
12 from manufacturing and, in due course, more end-of-life CF waste will also be available for
13 recycling. Impacts of geographical location of waste could have an impact on environmental
14 and cost impacts of recovery processes. Therefore, an analysis can be done in what future
15 recycling systems would look like in terms of waste CFRP availability and location, which
16 would impact plant capacity, waste collection, transportation, location, and regional factors.

17 The advanced CF recycling technologies investigated in this study currently exist at varying
18 levels of technological maturity: pyrolysis is operated at commercial scale; fluidised bed
19 recycling has been proven at demonstration scale; and the chemical recycling process modelled
20 here is still on a laboratory scale. There is greater uncertainty in estimating the life cycle
21 impacts of emerging technologies; while data available for pyrolysis and fluidised bed systems
22 are comparatively robust, present estimates for chemical recycling do not consider how the
23 process could be developed for deployment at commercial scale (energy sources; minimisation

1 of heat losses; process yield and efficiency; recovery of non-consumed process inputs). As such,
2 the environmental impacts of the chemical recycling process could, in practice, differ
3 significantly from the results presented here and in previous publication¹⁶ and warrant further
4 investigation through process simulation/optimisation and, ultimately, validation by operating
5 commercial facilities. However, we note that the net energy and GHG impacts of rCF are
6 dominated by the displacement of vCF production, which provides a credit to the system
7 approximately 10 to 20 times greater than the estimated impacts of the recycling process.
8 Process efficiency improvements, therefore, would have a marginal impact on net life cycle
9 metrics evaluated in the present study, so long as the mechanical properties of rCF are
10 maintained to enable use in place of vCF.

11 While CFRP recycling has a range of potential advantages, challenges and opportunities co-
12 exist. Replacing vCF with rCF in CFRP manufacturing may be limited for applications
13 requiring the highest integrity materials (e.g., aircraft primary structure), but is viable for non-
14 structural lightweighting applications with less extreme strength requirement. Achieving the
15 high level of environmental benefits via recycling also depends on potential market. The
16 potential applications for replacing vCF with rCF are some transportation industries (e.g.,
17 automotive, or infrastructure (replace vCF in bridges), wind energy and sporting industries
18 (e.g., races boats using rCF reported by Land Rover)).^{8, 40} But there is of concern about the
19 mismatch between supply of rCF (estimated at about 50,000 t/yr in 2017) and potential
20 demands. The source of rCF is currently only industrial waste and end-of-life CFRP wastes are
21 not available in significant quantities yet. The automotive industry, for instance, needs high
22 volumes of material that are generally larger than industrial waste from aerospace and other
23 sectors currently using CF (in excess of 95 million vehicles globally in 2015⁴¹). It is therefore
24 significant to design the best recycling capacity, combination of advanced recycling technology,

1 and find the best target market to obtain the maximum potential environmental benefits.
2 Furthermore, full consideration of their environmental and financial impacts⁴⁰ would enable
3 inclusion of trade-off between CFRP waste management strategies and help to ensure
4 opportunities are pursued that provide the greatest overall net benefit.

5 **Appendix A**

6 Table A1 Inventory data of different CFRP recycling technologies

7 **Supporting information**

8 There is no SI file for publication.

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15 **Notes**

16 The authors declare no competing financial interest.

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Table 1 CFRP recycling technologies: geographical location, key processing parameters

3

and capacity

Recycling method	Recycling plant	Temperature, °C	Pressure	Processing capacity	Source
Mechanical recycling	University of Manchester, UK	Ordinary	Ordinary	~20 t/yr (scaled from lab plant)	¹⁴
	Toray Industries, Teijin, Mitsubishi Rayon	500-700	Ordinary	1000 t/yr	¹⁶
Pyrolysis	Takayasu, Japan	N/A	Ordinary	60 t/yr	¹⁶
	ELG, UK	350-800	N/A	2000 t/yr	⁴²
	CFK Valley Stade Recycling GmbH & Co KG, Germany	350-800	N/A	1000 t/yr	⁴³
	Carbon Conversions, USA	350-800	N/A	2000 t/yr	⁴⁴
	KARBOREK RCF, Italy	350-800	N/A	1000 t/yr	⁴⁵
Fluidised bed	Pilot plant, University of Nottingham	400-600	Below atmospheric	50 t/yr	⁹
	Shizuoka University, Japan	250-350	5-10 MPa	5 L	¹⁶
Supercritical fluid	Hitachi Chemical, Japan	200	Ordinary	12 t/yr	¹⁶
	University of Birmingham, UK	320	17 MPa	5 L (lab batch)	¹⁵
Subcritical fluid	Kumamoto University	300-400	1-4 MPa	0.5 L (lab batch)	¹⁶

4

Table 2 Recycled CFRP design properties for CF replacement method based on variable fibre content and variable material thickness.

	Fibre Tensile modulus, GPa	Epoxy resin Tensile modulus, GPa	Modulus Reduction	Density, kg/m ³	Variable fibre content				Variable material thickness			
					Fibre volume fraction, V _f	Fibre ratio, vCF/rCF	(Incremental) resin use, kg/kg rCF	Mass ratio, rCF/vCF	Fibre volume fraction, V _f	Fibre ratio, vCF/rCF	(Incremental) resin use, kg/kg rCF	Mass ratio, rCF/vCF
vCF	230.00 ⁴⁶	5.00	-	1.79	40%	-	-	-	40%	-	-	-
Pyrolysis rCF	202.40 ²³	5.00	12.0%	1.79	46%	0.88	-0.12	114%	40%	0.94	+0.09	106%
Fluidised bed rCF	218.04 ³³	5.00	5.2%	1.79	42%	0.95	-0.05	106%	40%	0.98	+0.04	102%
Chemical rCF	204.70 ²³	5.00	11.0%	1.79	45%	0.89	-0.11	113%	40%	0.95	+0.08	105%

Table 3 Primary energy demand and Global Warming Potential comparison of the carbon fibre recovery and conventional landfill and incineration without credits from the use of products of recycling processes.

	PED, MJ/kg CFRP					GWP, kg CO ₂ eq./kg CFRP				
	Landfill	Incineration	Recycling	Transport	Total	Landfill	Incineration	Recycling	Transport	Total
Landfill	0.97	-	-	0.14	1.11	0.13	-	-	0.01	0.14
Incineration	-	1.17	-	0.54	1.71	-	3.09	-	0.03	3.12
Mechanical+ landfill	0.16	-	0.69	0.35	1.20	0.05	-	0.03	0.02	0.11
Mechanical+ incineration	-	-	0.69	0.43	1.12	-	1.74	0.03	0.03	1.80
Pyrolysis	-	-	37.09	0.27	37.36	-	-	2.88	0.02	2.90
Fluidised bed	-	-	9.98	0.27	10.25	-	-	1.54	0.02	1.56
Chemical	-	-	38.12	0.27	38.39	-	-	1.51	0.02	1.53

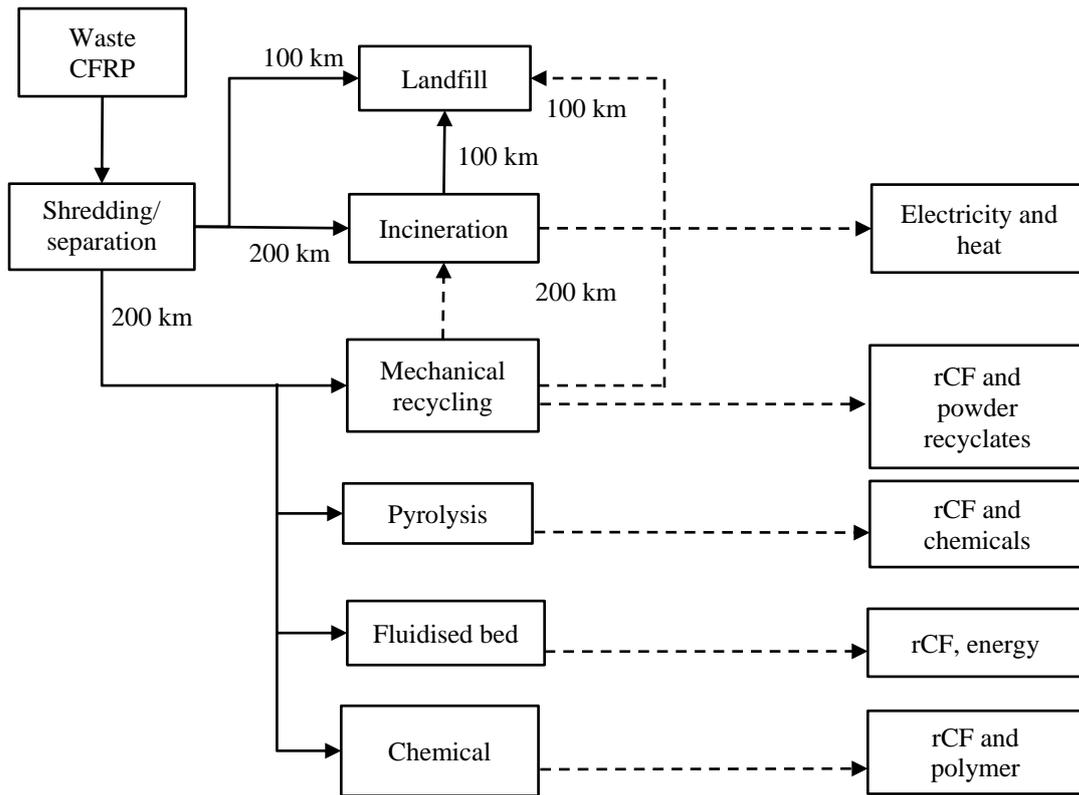


Figure 1 CFRP Waste treatment routes.

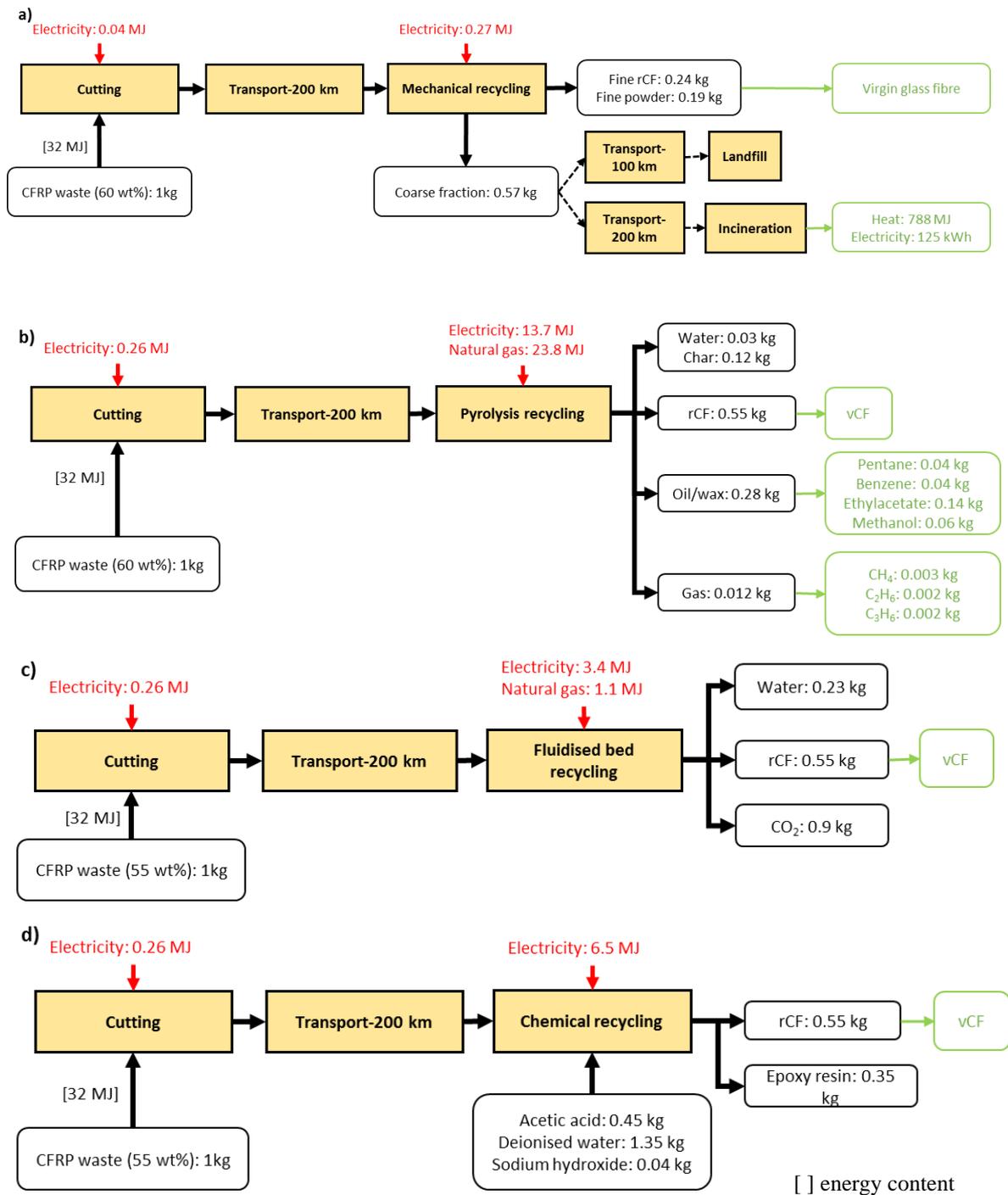


Figure 2 System diagram showing material and energy flows for a) mechanical recycling with landfilling and mechanical recycling with incineration, b) pyrolysis recycling, c) fluidised bed recycling and d) chemical recycling processes. The arrow colour indicates a type of each flow (red – energy flow, green – credits, and black – material flow).

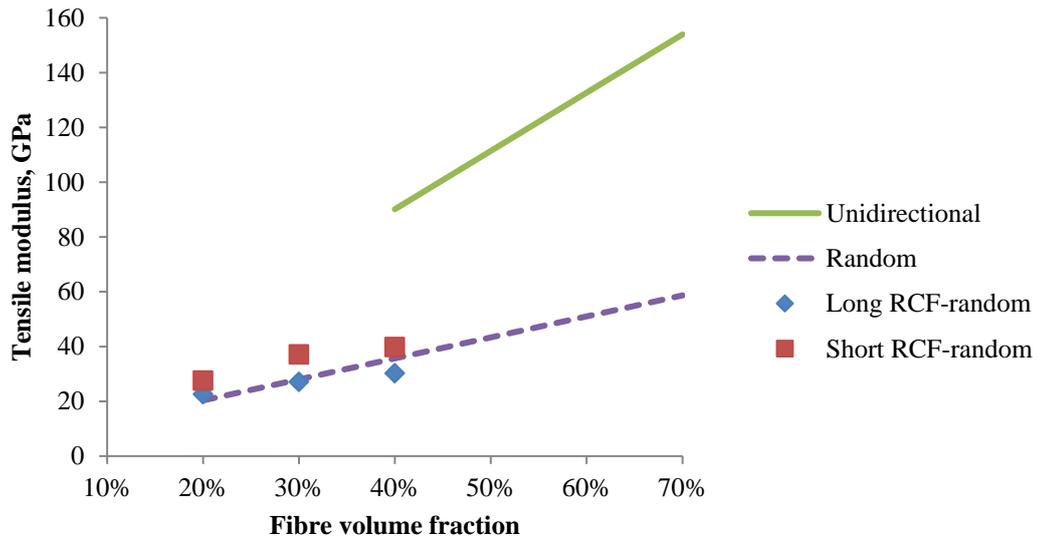
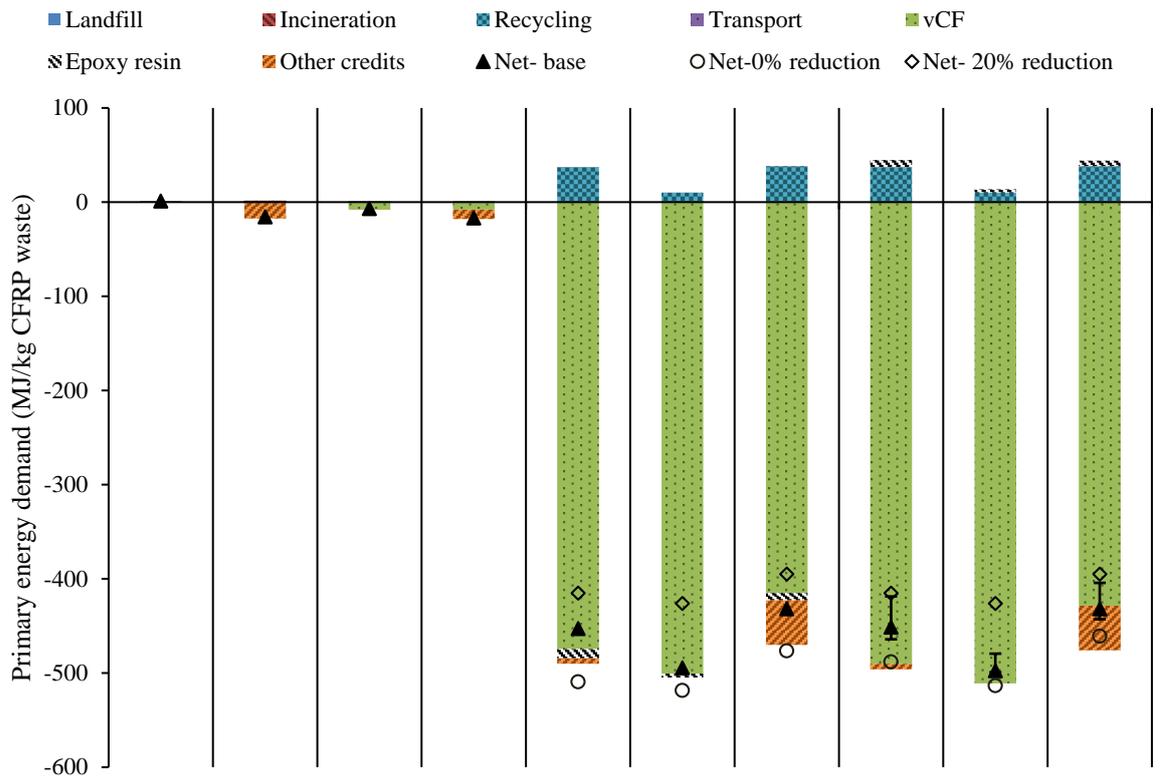


Figure 3 Tensile properties of an epoxy recycled carbon fibre composite experimentally measured. The solid and dotted lines represent the theoretical stiffness calculated using the generalized rule for randomly distributed and perfectly aligned fibres.³³

a)



b)

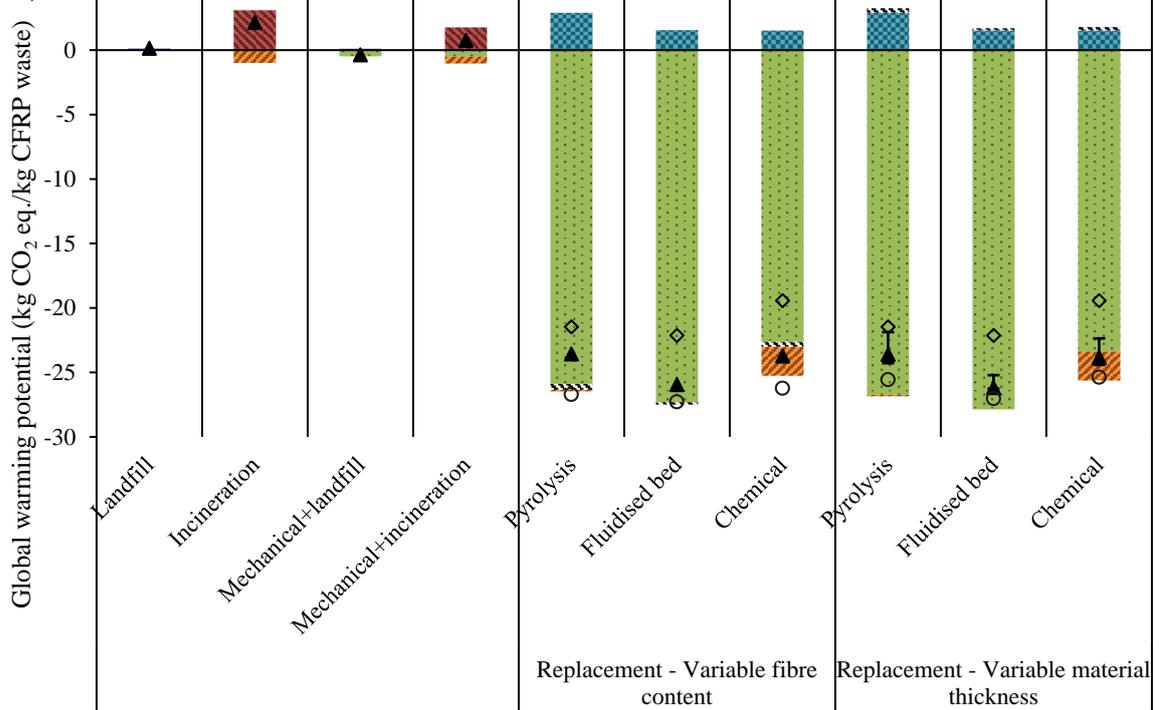


Figure 4 a) Primary energy demand and b) Global warming Potential of different CFRP waste treatment options including credits (CF replacement based on variable fibre content and material thickness)

Table A1 Inventory data of different CFRP recycling technologies

	Mechanical+ landfill	Mechanical+ Incineration	Pyrolysis	Fluidised bed	Chemical
Input					
CFRP waste, kg	1.00	1.00	1.00	1.00	1.00
Acetic acid, kg					0.83
Deionised water, kg					2.50
Sodium hydroxide, kg					0.07
Transport, km					
Cutting & shredding	Electricity, MJ				
Recycling	Electricity, MJ		7.6	3.4	6.5
	Natural gas, MJ		13.2	1.1	
Output					
rCF, kg	0.24	0.24	0.62	0.62	0.62
Fine powder, kg	0.19	0.19			
Coarse fraction, kg	0.57	0.57			
Epoxy resin, kg					0.67
Char, kg			0.14		
H ₂ O, kg				0.27	
CO ₂ , kg				1.02	
Incinerating CO ₂ from natural gas, kg				0.06	
NO ₂ , kg				0.03	
Liquid					
Water					
Oil/wax					
	Pentane, kg		0.03		
	Benzene, kg		0.03		
	Ethylacetate, kg		0.10		
	Methanol, kg		0.04		
Gas					
	CO, kg		0.001		
	CO ₂ , kg		0.003		
	H ₂ , kg		0.000		

	CH ₄ , kg	0.003
	C ₂ H ₆ , kg	0.002
	C ₃ H ₈ , kg	0.001
Propene/propylene	C ₃ H ₆ , kg	0.002

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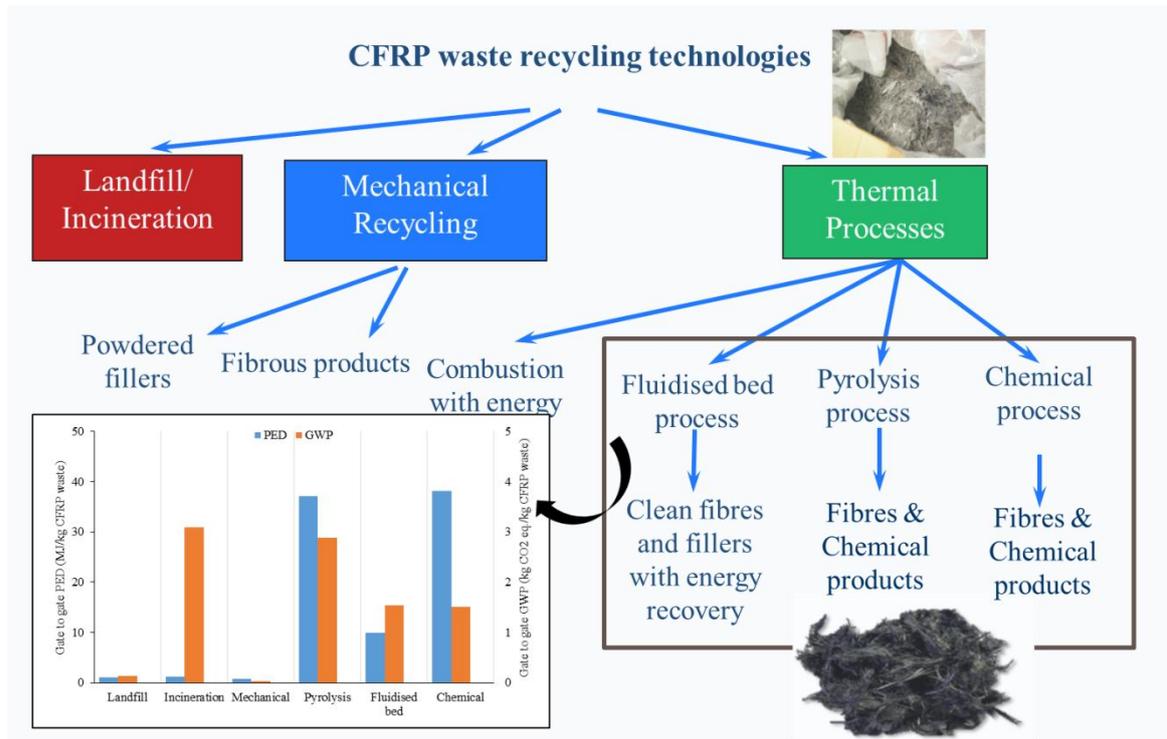


Figure shows gate-to-gate PED and GWP of waste management options for CFRP waste.

Sources from author Fanran Meng, Microsoft PowerPoint and author's publication³

The paper is of particular relevance for Sustainability given its focus on the life cycle environmental assessment of recovery of CFRP waste materials compared with landfill and incineration.