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ORIGINAL ARTICLE

Waste glass fibre composites valorization using the fluidised bed: a global warming potential and economic assessment

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Abstract
Glass fibre composites have become widely used in many applications, notably in wind turbine rotors. Fluidised bed valorization has demonstrated glass fibre recycling from waste composites, enabling reuse in traditional composite manufacturing technologies. This paper intends to inform long-term strategies for glass fibre composite waste by identify operating conditions that can optimise environmental and economic metrics for fluidised bed valorization. Experimentally derived operating parameters were integrated into energy models for a commercial-scale recycling process. An environmental assessment was conducted to compare the global warming potential of recycled glass fibres with that of virgin materials. In addition, a technoeconomic analysis was performed to assess the viability of the recycling technology at scale. The findings indicate that recycled glass fibre can achieve a global warming potential of less than 2 kg CO2e. per kg, contributing to a net reduction in greenhouse gas emissions when replacing virgin glass fibre. Furthermore, the economic analysis showed that a recycling facility with a capacity of just 10 kt per year could produce recycled glass fibre at a cost of $0.61/kg, significantly lower than the cost of virgin glass fibre. Overall, fluidised bed valorization presents an environmentally and economically sustainable solution for managing glass fibre composite waste.

Keywords Composites recycling · Fluidised bed · Circular economy · Life cycle assessment · Technoeconomic analysis

Introduction

The disposal of end-of-life composite products in an environmentally friendly and economically viable manner is one of the most important challenges currently facing the composites industry. The annual global production of fibre-reinforced plastics has surpassed 10 Mt/year [1], with thermoset-based polymers constituting about 60% of the market. Notably, glass fibre-reinforced polymer composites (GRP) make up over 90% of all fibre-reinforced composites currently manufactured [2]. This heightened demand for GRP results in substantial production waste and end-of-life (EoL) products. The annual global waste from EoL wind turbine blades (WTB), primarily composed of GRP, is projected to significantly rise in the coming decades, reaching around 0.5 Mt/year by 2030 and 1 Mt/year by 2040 [3]. Moreover, it is estimated that the current annual GRP EoL waste in the UK alone has reached 50–60 kt/year, with an additional 15 kt/year in GRP production waste [4]. Developing a recycling process capable of extracting glass fibres (GF) from GRP waste, to replace new fibres in GRP production, holds the potential to reduce the quantity of composite materials landfilled and conserve resources used in manufacturing virgin glass fibres (vGF).

Unlike thermoplastics which are readily recycled (for example through dissolution [5]), the inherent molecular crosslinking of thermoset-based GRP poses challenges for easy reuse and recycling. Recent research has focussed extensively on developing composite recycling techniques, leading to various strategies [6–10]. Among these, thermal recycling methods involve liberating reinforcing fibres by incinerating polymeric matrices, followed by their reuse in secondary composite components. Pyrolysis recycling has been widely studied as a method for recycling GRP, with applications such as the recycling of electronic circuit boards [11]. The fluidised bed process, as a form of thermally

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recycling GRP, demonstrates scalability, operational continuity, contaminant tolerance, the ability to process dissimilar polymers, and the production of char-free recycled glass fibre (rGF) [12–14]. Fluidised beds are widely used in various industrial technologies, leveraging good heat transfer, thorough mixing ability, and precise temperature control [15]. The GRP recycling process involves thermally degrading the polymer matrix within a fluidised bed reactor, freeing the reinforcement fibres for subsequent reuse. Oxygen in the fluidising medium (typically air) reduces char residue on the rGF. High operating temperatures, efficient gas–solid heat transfer, a constant oxygen supply, and attrition enable rapid decomposition of the polymer matrix in the fluidised bed process. The polymer volatiles can be fully combusted to recover their energy.

This study presents the first comprehensive investigation into the environmental and economic aspects of the fluidised bed process specifically for GRP recycling. While studies have highlighted the environmental benefits of carbon fibre composites recycling using the fluidised bed [16], no analogous studies for GRP recycling using this technology have been published. GRP recycling introduces unique environmental and financial considerations, including low fibre production costs and environmental impact, presenting additional commercial challenges that are explored in this study. The study uses life cycle assessment (LCA) and technoeconomic assessment to quantify key environmental and economic metrics. It is intended that these can be compared to other proposed GRP recycling solutions to inform long-term recycling strategies for GRP waste.

Methods

Life cycle assessment

Goal and scope

The objective of the environmental assessment was to qualify the global warming potential (GWP) associated with the fluidised bed process utilised in recycling GRP waste. In addition, the assessment aimed to examine how the GWP is influenced by the composition of the waste feedstock and the operating conditions during recycling. It was the overarching goal to identify optimal operating conditions and waste feedstocks to reduce the GWP of secondary materials produced using the fluidised bed recycling process.

Functional unit The functional unit for this assessment is 1 kg of recycled glass fibre (rGF) product produced with the fluidised bed recycling process, coming from waste GRP with any of the material compositions described in the study. The reference flow is 1 kg of rGF product.

System boundary Figure 1 shows the system boundary and the processes that are attributed to the GRP recycling/secondary materials production phase. All impacts associated with upstream manufacture, use, decommission of the GRP waste are out with the system boundary of the study, as shown in Fig. 1. As such, no burden is attributed to the GRP feedstock entering the system boundary and used in the production of secondary materials.

Scenarios

Table 1 describes the various scenario investigated relating to waste composition and plant operating conditions.

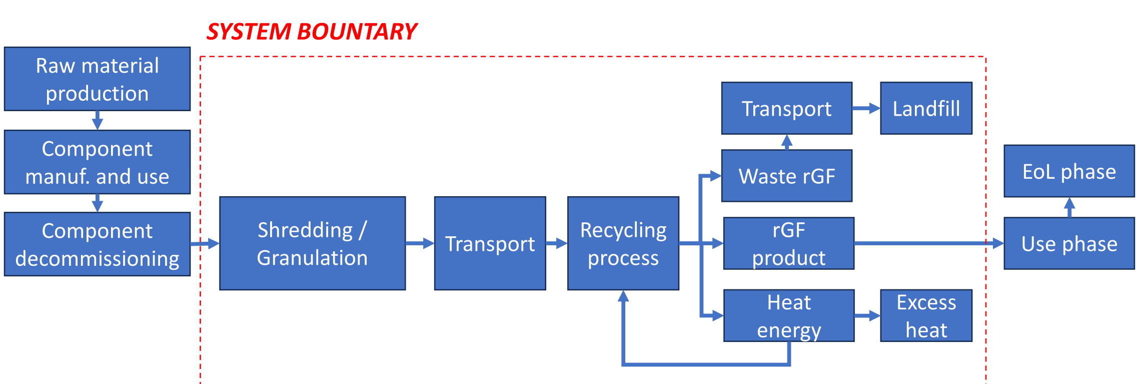

Fig. 1 System boundary of assessment

Table 1 Description of the various scenario investigated

Scenario	Description
Waste composition	
Polymer type	Four commonly used thermosetting polymer systems were investigated: epoxy, polyester, vinyl ester, and phenolic
Filler/fibre ratio	The polymer weight fraction in the GRP waste is held constant at 30% throughout this work, with a range of filler/fibre ratios (between 0 and 2.5) investigated to model a variety of GRP waste streams
Operating condition	
Plant capacity	The annual GRP throughput capacity of the fluidised bed plant was varied between 0.5 and 10 kt GRP/year
Reactor loading rate	The glass fibre mass feed rate into the fluidised bed as a function of reactor cross-sectional area was varied between 2 and 20 kg GF/h m^2

Assumptions in consequential methodology

In this research, a consequential methodology is employed to explore the outcomes of transitioning the manufacturing process of glass fibres (GF) from utilising raw materials (as typically done in the production of virgin GF products) to the process of producing them through recycling waste GRP feedstocks. Instead of allocating environmental impacts among different co-products, consequential LCA seeks to identify and quantify the overall changes in environmental impacts that result from a particular decision.

The GWP associated with recycling GRP using the fluidised bed was characterised in terms of (1) output GWP (GWP_{output}) and (2) Net GWP. Output GWP is defined as the sum of the direct and indirect greenhouse gas (GHG) emissions entailed by the operation of the fluidised bed recycling process. Direct GHG emissions include the combustion products of natural gas and the polymer fractions in the waste. Indirect emissions result from upstream transportation of waste and the generation of electricity used during downsizing and by the fluidised bed process itself.

The net GWP is defined as the GWP cost of recycling GRP to recover rGF and replace the production of new resources and is given in Eq. (1). This is calculated as the output GWP minus the reduction in GWP associated with (1) mitigating vGF production by replacing with and equal mass of rGF (GWP_{vGF}), (2) mitigating filler production by replacing with equal quantity of recovered filler (GWP_{filler}), and (3) utilising heat extracted from the system by the boiler to replace conversional heating source (GWP_{boiler}):

$$\text{Net GWP} = GWP_{output} - \left(GWP_{vGF} + GWP_{filler} + GWP_{boiler}\right) \quad (1)$$

GWP_{vGF} and GWP_{filler} were assumed to be 2.91 kg CO_2 eq./kg [17] and 0.27 kg CO_2 eq./kg [18]. GWP_{boiler} was calculated following the method and data given in UK government GHG conversion factors to convert energy to steam/heat using conventional natural gas heated boilers [19].

It is well established that GF experience performance loss during thermal recycling limiting applications for direct replacement of new materials [20]. Kennerley et al. have demonstrated that direct replacement of vGF with an equal mass of rGF in the production of bulk moulding compound (BMC) caused no adverse effect on subsequent mechanical performance of the composite material produced [15]. For such applications, where no impact on GRP performance is observed, it is reasonable to assume parity in the replacement rate of vGF using rGF.

Assumptions in inventory calculations

Waste pre-treatment, transportation, and disposal It is assumed that the GRP waste is first shredded (using a shredder with energy demand of 0.09 MJ/kg GRP [21]) and then granulated to a particle size < 25 mm, with energy demand calculated using data and methodology outline in Ref. [22].

In all scenarios, waste GRP is assumed to be transported using a 32-ton diesel heavy goods vehicle with a 20-ton GRP load capacity, meeting Euro VI standards with fuel consumption of 31 l per 100 km and emissions of 0.830 kg of CO_2 equivalent per km at a cruising speed of 70 km/h [23]. Transportation of GRP waste to the fluidised recycling facility is assumed to be 500 km. Waste produced at the fluidised recycling facility (e.g. waste GF) is assumed to be transported 100 km to landfill.

The disposal of waste GF byproduct from fluidised bed recycling is presumed to take place in a sanitary landfill designed for the ultimate disposal of solid waste. Given the inert characteristics of GF, it is presumed that landfilling does not lead to substantial direct emissions. The energy requirement for typical landfilling activities is assumed to be 0.167 MJ/kg GRP, with the energy distribution divided between the UK electricity supply and fossil fuels [24].

Fluidised bed recycling A laboratory-scale fluidised bed reactor, located at the University of Strathclyde, has effectively demonstrated the recycling of waste WTB and the utilisation of recycled glass fibres in crafting a 3 kW WTB demonstrator blade, as depicted in Fig. 2. For an in-depth description of this laboratory-scale fluidised bed, refer to

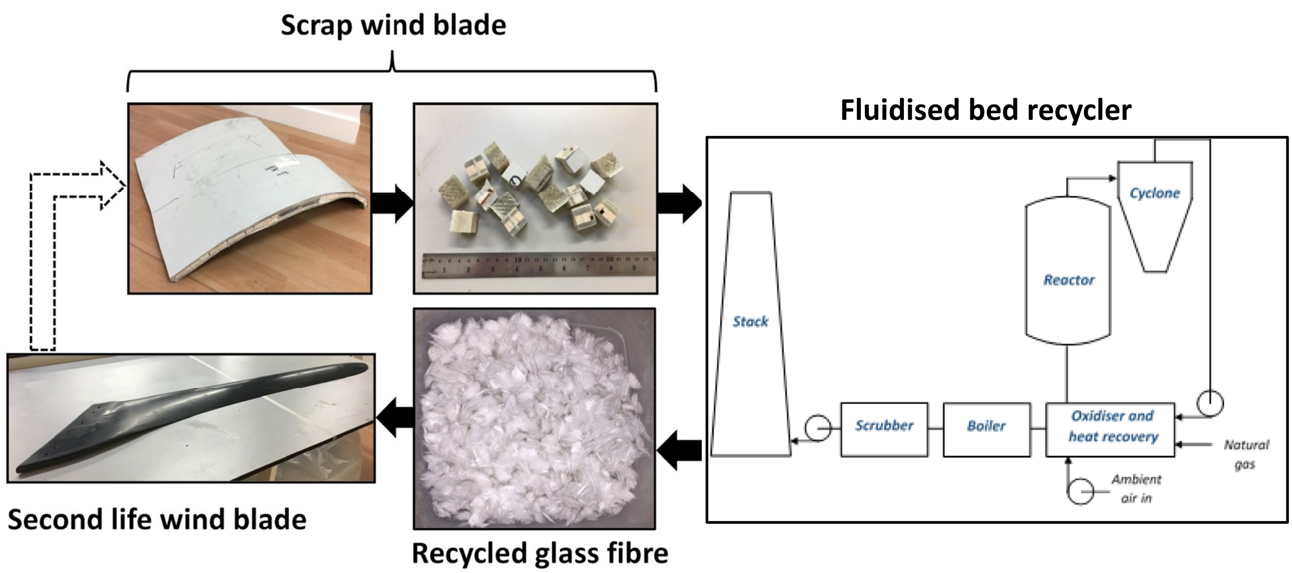

Fig. 2 Wind turbine blade recycling at the University of Strathclyde

the author's prior publication [25]. Currently, the University of Strathclyde is in the process of scaling up this technology as part of a UK wind turbine blade recycling pilot plant [26].

The operational parameters determined through experimentation for the fluidised bed have been integrated into energy models tailored for a commercial-scale process. The proposed plant's schematic is outlined in Fig. 2. The reactor is consistently maintained at a temperature of 550 °C to accelerate the decomposition of the polymer matrix, liberating the clean fibre and filler components. These components are carried out of the reactor by the gas stream, then separated and collected. Combustion gases undergo complete oxidation using natural gas in an oxidising chamber to eliminate volatiles. Subsequently, they pass through a sequence of high and low-temperature heat exchangers to recover heat for reuse within the process. Positioned upstream of the stack is a boiler to generate a process stream for internal use or local sale. Fans are employed to ensure adequate flow throughout the system and overcome pressure losses in various components.

To determine the necessary heat and electricity input into the system, an energy model was devised. This model was informed by the operation of an in-house developed fluidised bed recycling process. Heat is introduced into the system through the oxidation of the waste GRP polymer matrix within the reactor, as well as through the oxidation of natural gas in the oxidiser. The flow rate of natural gas required to sustain the reactor's temperature for polymer decomposition was established by balancing heat inputs and outputs. The electricity demand from the process fans was predicted based on the required gas flow and pressure increases throughout the system.

The variable operating parameters are used to determine the required reactor cross-sectional area of the fluidised bed reactor, as described in Eq. (2):

$$\text{Reactor area}\,[\mathrm{m^2}] = \frac{\text{Installed Capacity}\left[\frac{\text{kg GRP}}{\text{yr}}\right] \times \text{GF weight fraction}\left[\frac{\text{kg GF}}{\text{kg GRP}}\right]}{\text{Operating time}\left[\frac{\text{hr}}{\text{yr}}\right] \times \text{Reactor loading rate}\left[\frac{\text{kg GF}}{\text{hrm}^2}\right]}. \tag{2}$$

The superficial air velocity passing through the fluidised bed and flow through the pipes is set to 1 and 20 m/s, respectively. From this, gas flow rate through the system can be defined and the other plant components are scaled accordingly.

Installed capacity—the annual GRP throughput capacity of the fluidised bed plant (kt GRP/year).

Reactor loading rate—the glass fibre mass feed rate into the fluidised bed as a function of reactor cross-sectional area (kg GF/(h·m^2)).

A more exhaustive description of the assumptions made in the fluidised bed energy model and the life-cycle inventory are given in the Supplementary Materials.

The source of direct emissions from the fluidised plant is oxidation of GRP polymeric fraction in the reactor and oxidation of natural gas in the oxidiser. The emissions produced because of oxidation of the polymer matrix material are calculated on a stoichiometric basis assuming all carbon and nitrogen are fully oxidised to CO_2 and NO_2, respectively. Direct emission from recycling GRP with epoxy, polyester, vinyl ester and phenolic polymer matrices is considered and is given in Table 2. Emissions from natural gas oxidation were calculated using a conversion factor of 0.186 kg CO_2/kWh, as prescribed by UK national energy statistics [27].

Technoeconomic assessment

Technoeconomic analysis was carried out for a representative recycling facility to assess the economic feasibility of the technology at scale. This involved evaluating crucial operational factors such as plant capacity and the composition of composite waste (described in Table 1). The cost of recycling was estimated through multi-variable analysis, considering profitability metrics such as plant profit and capacity at breakeven. It was the overarching goal to identify optimal operating conditions and waste feedstocks to increase economic performance of the fluidised bed recycling process.

The financial model for a commercial fluidised bed plant considered capital costs (CAPEX) and operational expenses (OPEX), alongside revenue streams such as products derived from recycled filler and rGF, gate fees charged for scrap GRP waste, and the recovery of heat energy from the process. The net cost of recycling GRP was calculated using Eq. (3) and presented as a function of the mass of rGF, effectively representing the minimum re-sale price of rGF required for the plant to reach breakeven. Determining plant profit involved estimating the re-sale price of rGF and identifying breakeven conditions by setting annual plant profit equal to zero:

$$\text{Min. rGFprice}\left[\$/\text{kg rGF}\right] = \frac{\text{OPEX}\left[\$/\text{yr}\right] + \text{CAPEX}\left[\$/\text{yr}\right] - \text{Revenue}\left[\$/\text{yr}\right]}{\text{rGFmass}\left[\text{kg rGF}/\text{yr}\right]} \tag{3}$$

An exponential relationship, as depicted in Eq. (4), was employed to project the capital cost across different scales of the plant. Traditionally, capital cost would be adjusted in proportion to plant capacity, defining the size and subsequent cost estimation of the plant equipment. However, as outlined in Eq. (2), the reactor's cross-sectional area, a parameter influenced by plant capacity, reactor loading rate, and waste composition, defines the scale of the plant. Hence, in this investigation, capital cost is scaled with the reactor's cross-sectional area. To derive data input for Eq. (4), reference data from a comparable 1 kt/year carbon fibre fluidised bed recycling process were utilised, with the exponent α set to 0.6 in alignment with the described approach for the analogous process in Ref. [31]:

$$PlantCAPEX = Ref.plantCAPEX\left(\frac{Reactorarea}{Ref.plantreactorarea}\right)^{\alpha} \tag{4}$$

All input data for the plant financial model can be found in Supplementary Materials, following the methodology outlined in Ref. [32]. It is assumed that 3 staff members are present during plant operation, regardless of capacity, and are paid according to average UK labour wages [33]. A plant life span of 15 years was assumed.

Table 2 Summary of energy and GWP inputs used to model the various processes and in the environmental assessment

	GWP
Virgin glass fibre [17, 28]	2.91 kg CO_2 eq./kg
$CaCO_3$ (GRP filler) [18]	0.27 kg CO_2 eq./kg
UK grid electricity [29]	0.21 kg CO_2 eq./kWh[a]
Natural gas (combusted) [27, 29]	0.19 kg CO_2 eq./kWh
Diesel (combusted) [30]	0.25 kg CO_2 eq./kWh
Epoxy (combusted)[b]	3.30 CO_2 eq./kg
Polyester (combusted)[b]	2.60 CO_2 eq./kg
Vinyl ester (combusted)[b]	2.95 CO_2 eq./kg
Phenolic (combusted)[b]	3.18 CO_2 eq./kg

[a]Incl. transmission and distribution losses

[b]See Supplementary Materials for assumptions in estimating GHG emissions from polymer combustion

Results and discussion

Life cycle assessment

Influence of reactor loading rate

Figure 3 gives the sources of GWP in a fluidised bed process recycling polyester-based GRP with filler/fibre ratio of 1. For all reactor loading rates analysed, the main source of GWP is GHG emissions from the polymer matrix oxidation, accounting for more than 75% of GWP contributions for loading ≥ 6 kg rGF/h m^2. Figure 3 shows that reducing the energy input by improving system efficiency could be beneficial in reducing output GWP; however, the overall degree of this reduction is restricted by the significantly larger emissions from the resin oxidation in the reactor. Without carbon capture, this is an inevitability for thermo-oxidative GRP recycling/disposal techniques such as the fluidised bed and energy from waste plants. For reactor loading rate ≥ 6 kg rGF/h m^2, net GWP is below zero, which is indicative of positive environmental impact provided by the recycling process. The ability to recycle at negative net GWP for reactor loading rate ≥ 6 kg rGF/h m^2 is a result of reduced energy input to the system and surplus heat that can be extracted and offset against conventional heat production. Figure 3 shows that even without heat recovery, which

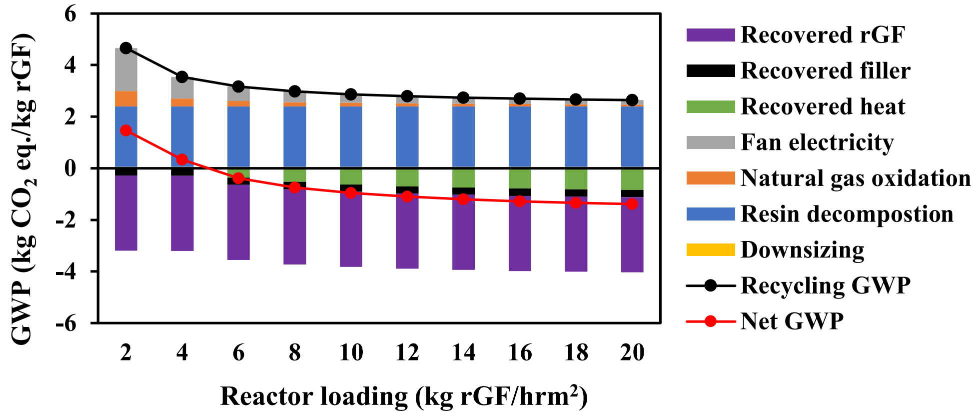

Fig. 3 Breakdown of sources of GWP in the fluidised bed process recycling polyester-based GRP at 5 kt GRP/year with filler/fibre ratio of 1

is dependent on local demand to truly offset new energy production, the net GWP is below zero for reactors loading ≥ 6 kg rGF/h m^2, which is well within the operating parameters of the fluidised bed for GRP recycling [15].

Influence of plant capacity

Figure 4 shows the influence of plant capacity on GWP for polyester-based GRP waste. Given that the main contribution to GWP is GHG produced during polymer oxidation (Fig. 3), the net GWP is largely unaffected by the plant capacity. A slight reduction in GWP is observed with plant capacity due to the increase in natural gas requirements to compensate for higher relative heat loss in smaller plants. This means that fluidised bed recycling plants could be developed to a variety of scales to meet local demand without significantly compromising on the net GWP.

Influence of waste composition

Figure 5 gives the sources of GWP for a fluidised bed process recycling polyester-based GRP with a range of different filler/fibre contents. The net GWP is highly dependent on filler/fibre ratio. The additional resin mass combusted (relative to rGF mass) is responsible for greatly increased GHG production in the fluidised bed reactor, and, therefore, higher GWP for waste with higher filler contents. Even when accounting for GWP mitigation by replacing conventional heating sources with heat recovering via the boiler (enabled by the relatively greater amount of resin combusted), the net GWP increases with filler/fibre ratio, however, remains less than zero for all conditions analysed in Fig. 5.

Figure 6 gives a breakdown of the sources of GWP for recycling GRP with the various resin types containing equal amounts of filler and fibre. The GWP of the oxidative decomposition of polymer matrices is dependent on carbon and nitrogen content in the resin systems. The oxidation of nitrogen containing systems (epoxy and phenolic resins) has a higher GWP than those comprising solely carbon, oxygen and hydrogen, as is shown in Fig. 6. A greater GWP offset through additional heat recovery is observed for

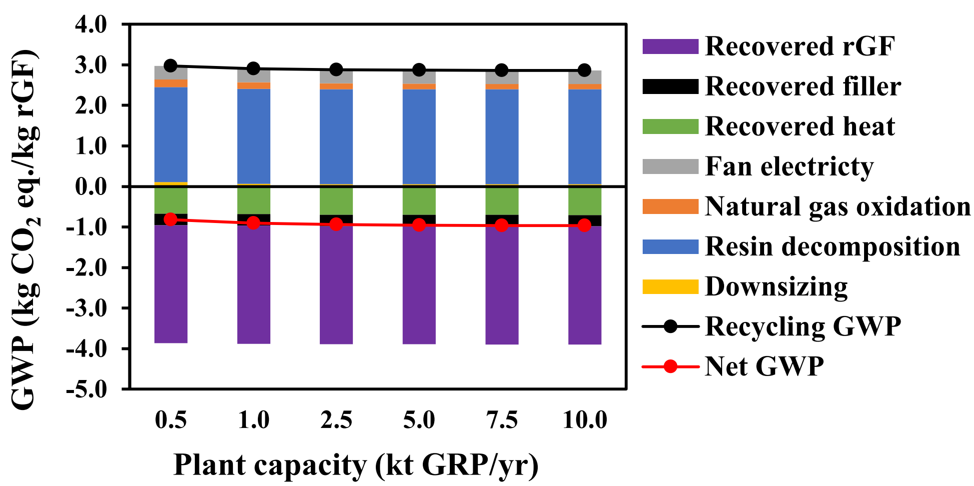

Fig. 4 Breakdown of sources of GWP in the fluidised bed process recycling polyester-based GRP with filler/fibre ratio of 1 and reactor loading rate of 10 kg rGF/h m^2 at a range of plant capacities

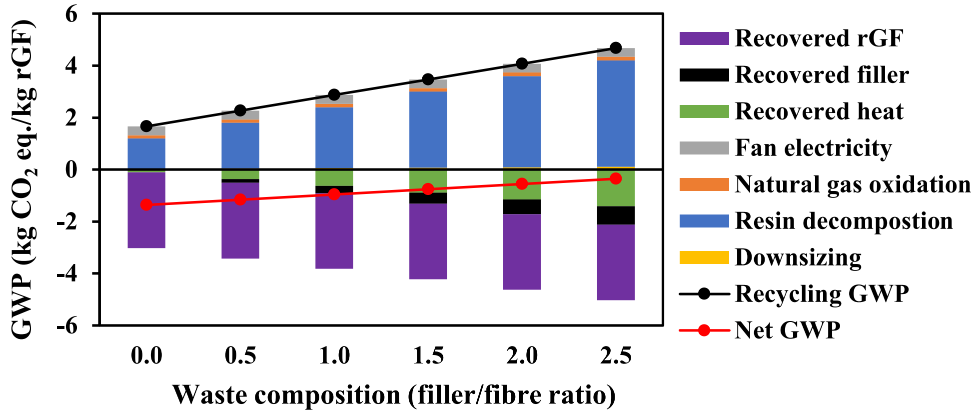

Fig. 5 Breakdown of sources of GWP in the fluidised bed process recycling polyester-based GRP at 5 kt GRP/year with reactor loading rate of 10 kg rGF/h m^2

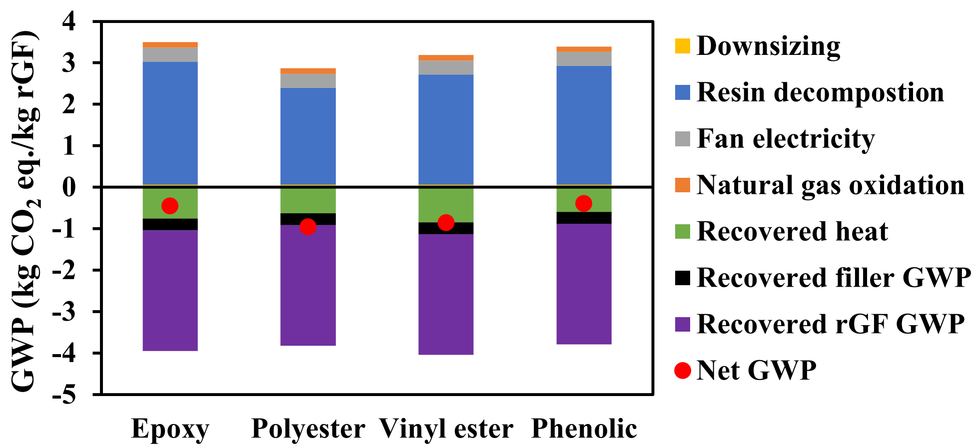

Fig. 6 Breakdown of sources of GWP recycling GRP with the various resin types with filler/fibre ratio of 1 and reactor loading rate of 10 kg rGF/h m^2 at a plant capacity of 5 kt GRP/year

higher calorie dense resins, such as vinyl ester. However, this offset is low relative to the GWP of resin decomposition, which remains the greatest predictor of net GWP for GRP recycling.

In this study, the resin fraction within the waste GRP has been held constant at 30%wt. Given that most of the output GWP is a result of resin oxidation, it is understood that the resin content within the waste GRP influences the net GWP of GRP recycling. Increasing resin content of waste GRP requires additional resin mass to be oxidised to recover clean rGF, resulting in greater GHG emissions and consequently increased net GWP.

In Fig. 7, the resin weight fraction in waste GRP where net GWP is equal to zero is given as a function of waste composition for each of the resin types. This represents a boundary where, for all resin weight fractions below this boundary, GRP can be recycled using the fluidised bed under negative net GWP conditions. Several GRP types have also been included in Fig. 7: WTB [36], BMC [34], sheet moulding compound (SMC) [34], in order to give context to where conventional GRP compositions lie within this plot. There is a wide range of BMC and SMC compositions depending on the product/application, therefore, an average and upper/lower bound for resin fraction and filler/fibre ratio for these materials are given in Fig. 7 [34]. Since the composition of WTB and SMC fall below the epoxy and polyester resin boundaries, respectively, Fig. 7 shows that the fluidised bed process can recycle these GRP types at negative net GWP. Since BMC fibre fraction tends to be relatively low (10–25%wt.), the average BMC composition falls above the

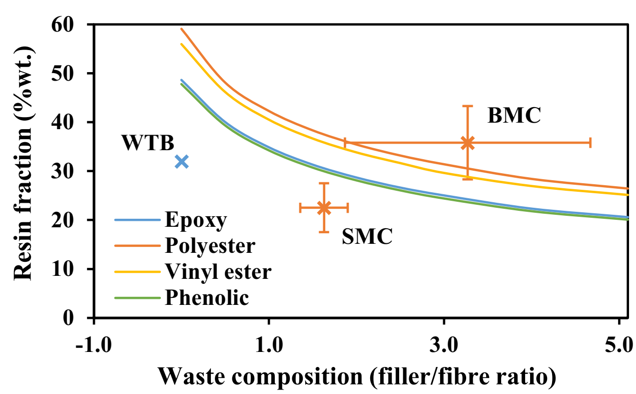

Fig. 7 The resin fraction within waste GRP where net GWP equals zero as a function of waste composition, given for the range of resin types. Reactor loading rate of 10 kg rGF/h m^2 and plant capacity of 5 kt GRP/year used for analysis

resin fraction boundary for polyester resulting in net GWP greater than zero. There is a broad range in BMC composition, however, with higher fibre fraction BMC materials able to be recycled at negative net GWP.

Establishing a GRP recycling facility focussed on a singular waste stream offers the advantage of consistent feedstock in the process, enhancing predictability in plant operations and the resulting materials. Managing waste GRP from WTB stream simplifies the process by circumventing challenges linked to sorting, separating, and handling mixed GRP waste streams. Moreover, the composition of GRP from WTB remains relatively uniform compared to the broader spectrum of GRP waste, which could alleviate many practical challenges associated with GRP recycling. The anticipated annual global waste from EoL WTB is projected to increase to approximately 0.5 Mt/year over the next decade [3]. According to data from Zero Waste Scotland [3], the UK's annual WTB waste is expected to reach 10 kt/year by 2025. Figure 7 illustrates that a fluidised bed could be an environmentally sustainable choice for this specific waste stream.

However, a facility exclusively processing GRP from WTB may achieve a negative net GWP but could be constrained in capacity, leading to economic implications discussed below. To operate at larger scales, a recycling plant would likely process waste GRP from various streams, each with different compositions. GRP waste streams with diverse compositions could be selectively chosen for fluidised bed recycling, ensuring that the combined feedstock composition maintains a negative net GWP.

Technoeconomic analysis

Influence of reactor loading rate

Figure 8 gives the various costs and revenues for a 5 kt GRP/year fluidised bed process recycling GRP containing equal amounts of fibre and filler material. The cost of recycling GRP can be significantly lowered by increasing reactor loading rate, largely due to the reduction in effective capital investment, electricity and scrubber operational costs (within "other direct costs" in Fig. 8). As reactor loading rate is increased, the required reactor size for a given plant capacity is reduced which facilities a lower capital investment. Similarly, the operational cost of both the fans and scrubber are proportional to gas flow rate through the system, which is also a function of reactor size and is, therefore, lowered with an increase in reactor loading rate. It is clear from Fig. 8 that to minimise cost of GRP recycling using the fluidised bed, the plant should be operated at the highest reactor loading rate possible without incurring fibre entanglement issues. The cost of new E-glass fibre is approximately 1–2 \$/kg which closely aligns with the net cost data in Fig. 8 for reactor loading rate ≥ 4 kg rGF/h m^2 [35]. It is well understood, however, that GF experience a reduction in mechanical performance during thermal recycling; therefore, it may be expected that rGF must be sold at a lower cost than vGF to remain competitive [14].

Influence of plant capacity

Figure 9 gives the various costs and revenue for fluidised bed process recycling GRP at a range of plant capacities. The indirect costs are operational costs which include plant overheads, insurance, administration, distribution, and R&D. As described in the Supplementary Materials, these are estimated as a fraction of labour or capital costs.

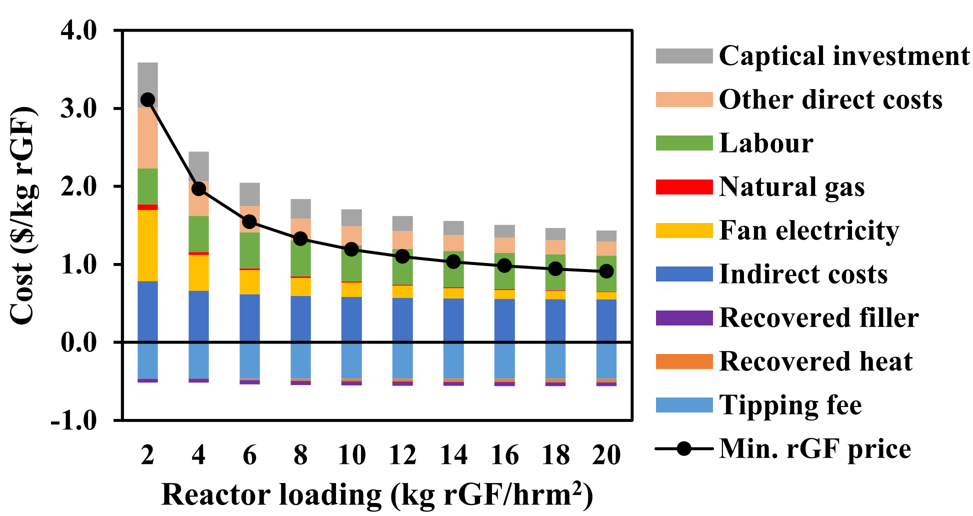

Fig. 8 Summary of various costs and revenues as a function of reactor loading rate for a 5 kt GRP/year fluidised bed process recycling GRP with filler/fibre ratio of 1

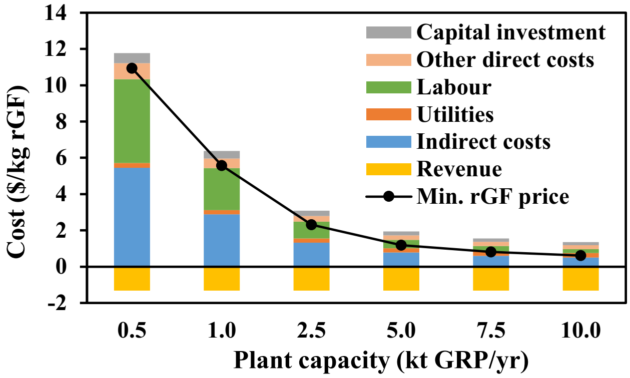

Fig. 9 Summary of various costs and revenues as a function of plant capacity for fluidised bed process recycling GRP with filler/fibre ratio of 1 at 10 kg rGF/h m^2

The net cost of GRP recycling can be significantly lowered by increasing the operating plant capacity because of lowering labour and indirect costs associated with plant operation. The number of plant workers, therefore, total labour costs are held constant under all operating conditions analysed. Many of the primary indirect costs, such as plant over heads and administration, are estimated as a fraction of the total labour cost, resulting in a reduction in these costs at higher plant capacities. The relative capital investment is also reduced significantly at higher plant capacities due to the non-linear scaling of plant capital cost in Eq. (4). It should also be noted that the cost analysis in Fig. 9 is performed using a conservative reactor loading rate of 10 kg rGF/h m^2, which is shown in Fig. 8 to significantly influence the recycling cost. The min. rGF price for a 10 kt GRP/year plant in Fig. 9 drops from 0.61 to 0.35 $/kg rGF by increasing the reactor loading rate from 10 to 20 kg rGF/h m^2.

Given the data presented in Fig. 9, a recycling plant should be developed at a scale to maximise annual GRP throughput to reduce the cost of recycling. The potential plant capacity is informed by the quantity of GRP waste available to be processed and is likely to vary between regions. The current total annual GRP waste in UK alone is estimated to be 65–81 kt/year [4, 36], which far exceeds pant capacities analysed in this work. Practical challenges associated with extracting GRP waste from mixed/contaminated waste streams may limit the total supply of material and/or add additional costs to a GRP recycling plant. Relatively consistent GRP waste streams such as composite production waste and EoL WTB are available but do not account for the bulk of current GRP waste. During commercialisation of the process, the location of the plant should be well considered to ensure proximity to suitable GRP waste streams that allow for maximising plant capacity as a means of reducing the recycling costs.

Influence of waste composition

Figure 10 shows the influence of waste composition on various costs and revenues of GRP recycling using the fluidised bed. The differences in waste composition means that as filler content in GRP waste, the mass of rGF recovered decreases, effectively increasing the labour cost per kg of rGF product. Despite generating a higher income from tipping fee (per kg of rGF product), this is insufficient to overcome the additional labour costs, therefore, rGF from GRP waste with high filler content (such as BMC) will require a higher min. rGF re-sale price.

Figure 11 gives the required plant capacity for breakeven at a range of waste compositions and rGF re-sale prices. At the time of writing, the author could not source any rGF on the market, therefore, a range of re-sale prices of rGF were analysed, given as a percentage of the price of new E-glass fibre – conservatively assumed to be 1 $/kg [35]. As would be expected, reducing re-sale price of rGF requires a larger plant capacity to breakeven, regardless of waste composition. Figure 11 shows that the breakeven plant capacity for low filler/fibre ratio GRP is far more sensitive to variation in re-sale cost compared to higher ratios investigated.

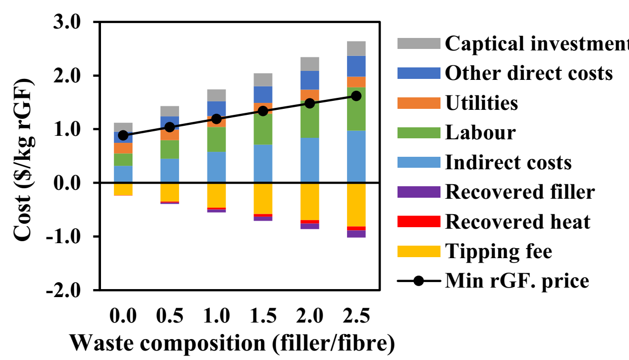

Fig. 10 Influence of waste composition on various costs and revenue of GRP recycling using fluidised bed with plant capacity of 5 kt GRP/year and reactor loading rate of 10 kg rGF/h m^2

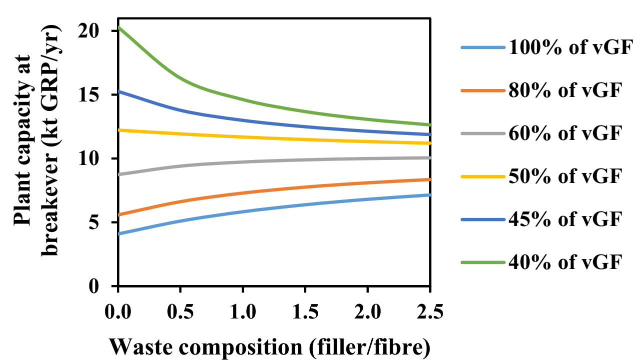

Fig. 11 Required plant capacity for breakeven at a range of waste compositions and re-sale prices for a fluidised bed recycling process with reactor loading rate of 10 kg rGF/h m^2

The specific composition of waste processed by a fluidised bed plant will be dictated by the source(s) of the GRP waste and is likely to vary across regions and industries. This study highlights that the composition of GRP waste plays a significant role in influencing both the GWP and the cost of fluidised bed GRP recycling. Therefore, it is essential to establish and characterise available GRP streams before developing a recycling plant. This preliminary step informs the design criteria of the plant, ensuring that optimal operating conditions can be met.

There is a possibility of developing a recycling plant to process homogeneous sources of GRP waste, such as EoL WTB, which is expected to become a growing concern in the coming decades [3]. Figure 11 indicates that the required plant capacity at breakeven is relatively low for materials with high fibre content, especially when the re-sale price is greater than 50% of vGF. Fluidised bed recycling plants processing mixed GRP waste will have some amount of filler entering the system, meaning larger capacity plants will be needed to breakeven. However, these capacities remain considerably lower than the annual GRP waste in regions such as the UK.

Figure 12 presents the estimated annual profit of a fluidised bed GRP recycling plant across various capacities and waste compositions, assuming a fixed re-sale price of $0.80/kg rGF. The figure suggests that the fluidised bed process could be a profitable technology for GRP recycling under certain conditions. This study emphasises the importance of establishing the potential re-sale price of rGF to better inform future plant development and financial analyses of GRP recycling.

The re-sale price of rGF as reinforcements will ultimately be determined by several factors, including reinforcement potential, re-processability, and the inherent commercial value as a recycled product. While the loss in tensile strength may limit the market for rGF as reinforcement materials, recent advancements in rGF property regeneration show promising improvements in strength and surface functionality [20]. These treatments, though incurring additional costs not considered in this model, could diversify the applications for rGF and increase their market value.

This work assumes that rGF is sold with no additional reprocessing. It is acknowledged that the modulus of GF is not negatively impacted following exposure to recycling temperatures used in this study [37]. Therefore, a potential route to market for rGF as a reinforcement medium may be in lower-strength GRP applications requiring additional stiffness. Promising applications include reinforcement in bulk and injection moulding compounds, where fibre strength and length are less critical. It has been demonstrated that rGF from the fluidised bed can replace up to 50% of the glass fibre content of BMC with no measured change in GRP tensile strength [13]. For such applications, with no impact on GRP performance or production costs, it is reasonable to assume that rGF could be sold at the same price, if not higher, than that used in Fig. 12.

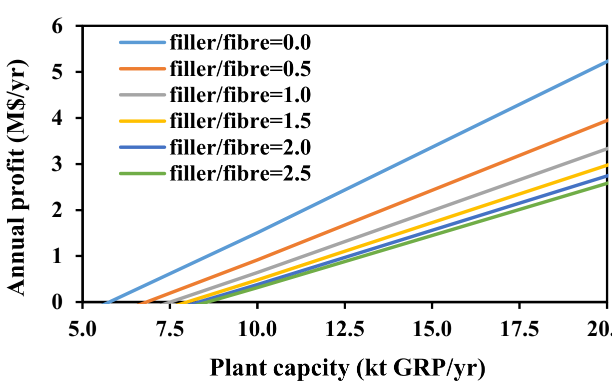

Fig. 12 Estimated annual profit of a fluidised bed GRP recycling plant with reactor loading rate of 10 kg rGF/h m^2, at a range of plant capacities and waste compositions with a rGF re-sale price of $0.80/kg rGF

Conclusions

This work has investigated a range of operating parameters on the environmental impact and economic viability of a fluidised bed process for recycling GRP waste. It was found that the fluidised bed could recycle a broad range of GRP waste composition while maintaining negative net GWP. Direct GHG emissions resulting from resin decomposition in the fluidised bed accounts for the greatest source of output GWP, however, this can be offset through material and heat recovery. Given the high GWP offset potential through glass fibre recovery, high fibre GRP such as WTB make optimal feedstock for the fluidised bed process in terms of minimising net GWP. A cost analysis of fluidised bed GRP recycling was carried out, concluding that rGF could be cost competitive against vGF; with plant capacity and reactor loading rate being the key determinants of the net cost for recovering rGF. At a plant capacity of 10 kt GRP/year, it was found that rGF could be recovered for as low as 0.61 $/kg, significantly lower than the cost of vGF. Moreover, high fibre fraction waste streams could be processed at breakeven with a rGF re-sale price just 60% of vGF and operating at a plant capacity of approximately 9 kt GRP/year. From both an environmental and economic perspective, the fluidised bed process appears to be an ideal candidate to address a range of GRP waste compositions, in particular the growing supply of WTB.

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Author contributions All the authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Kyle Pender. The first draft of the manuscript was written by Kyle Pender, and all the authors commented on previous versions of the manuscript. All the authors read and approved the final manuscript.

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