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Research article

Glass fibre composites recycling using the fluidised bed: A study into the economic viability in the UK

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Abstract: As it stands, the UK has no commercialised process capable of recycling waste glass fibre reinforced thermosets, resulting in disposal via landfill or energy from waste facilities. Thermal recycling within a fluidised bed process has been demonstrated to successfully recover clean glass fibre from composite waste materials, such as wind turbine blades, and successfully reuse it as a reinforcement phase in second life composites. If brought to a commercial scale, this technology has the potential to divert up to 1200 kt of mixed glass fibre reinforced plastics (GRP) waste and an additional 240 kt of wind blade waste away from UK landfill sites over the next fifteen years, while offsetting the environmental impact and raw material consumption of virgin glass fibre production. Despite this, commercialisation and long-term success depend on economic viability and resilience of the recycling technology, ensuring that sufficient value is added to offset costs required to bring recyclate products to market. In this study, techno-economic analysis was used to analyse the economic outlook for at scale fluidised bed recycling plants within the context of the current and future UK glass fibre reinforced plastic waste landscape. It was found that fluidised bed recycling plants operating well within current UK waste volumes can maintain gate fees that are competitive with landfill while producing recycled glass fibre (rGF) at less than 50% of the prices of virgin counterparts. Plants processing single waste streams, such as wind blades, can maintain long term profitability despite irregular flow of waste feedstock availability. Despite higher transportation cost, total recycling costs are lower for national level plants. Therefore, it is recommended to accept composites from multiple waste streams to maximise operating capacity, profits and return on investment.

Keywords: composites recycling; fluidised bed recycling; techno-economic analysis; wind turbine blades; end-of-life strategy; composites sustainability

1. Introduction

The disposal of end-of-life composite products in an environmentally friendly manner is one of the most important challenges currently facing the composites industry. The annual global production of fibre reinforced plastics is exceeding 10 Mt/yr [1]. Thermoset based polymers account for approximately 60% of the market, whereas glass fibre reinforced composites account for more than 90% of all the fibre-reinforced composites currently produced [2]. A consequence of this high demand for glass fibre reinforced plastics (GRP) is a large amount of composite production waste and end-of-life (EoL) products. Annual global waste from EoL wind turbine blades (EoL-WTB), made predominantly from GRP, is expected to greatly increase over the coming decades, approaching 0.5 Mt/yr and 1 Mt/yr by 2030 and 2040, respectively [3]. By 2037, the UK will decommission 240 kt of EoL-WTB, adding to existing annual GRP waste volumes of 65–80 kt/yr [4,5]. A recycling process capable of extracting glass fibres from GRP waste, which can replace new fibres in the production of GRP, could have the benefits of both reducing the quantity of composite materials landfilled and saving resources required to manufacture virgin glass fibres (vGF).

It has been demonstrated that the fluidised bed recycling (FBR) process, as a means of thermally recycling glass fibre reinforced thermosets, has many advantages, such as scalability, operation continuity, contaminant tolerance, processing dissimilar polymers and yielding char-free fibres [6–8]. The process for GRP recycling involves thermally degrading the polymer matrix within a fluidised bed (FB) reactor and liberating the reinforcement fibres, which are subsequently collected for reuse. Oxygen is present in the fluidising medium (typically air) to diminish char residue on the recycled fibres. High operating temperatures, excellent gas–solid heat transfer, a constant supply of oxygen and attrition allow for rapid decomposition of the polymer matrix in the FB process. The polymer volatiles can subsequently be fully combusted for recovering their energy.

A major barrier to commercial FBR for GRP is uncertainty in the financial viability of at scale operations. vGF has low market value, meaning any recycling process aiming to replace this material with recycled glass fibre (rGF) must do so economically to remain cost competitive. Few studies have investigated the economics of FBR of composite materials. Studies have reported the financial viability of carbon fibre reinforced polymer composites (CRP) recycling using the fluidised bed [9–12], which is made possible by the anticipated high market value of recycled carbon fibres. Despite this, these investigations have shown that scale of operation (e.g., plant capacity) is critical to the profitability of CRP recycling using the FBR plant.

Pickering et al. conducted an economic analysis of a model commercial FBR process for GRP [13], concluding that a FBR plant would break even with a plant capacity of 9 kt GRP/yr. The study was limited to one GRP feedstock composition (analogous to sheet moulding compound) and does not consider how the variation in EoL GRP product composition would affect the economics of the FBR plant. Moreover, this analysis was (at the time of writing) conducted over 20 years ago and therefore does not account for inevitable changes in cost inventory data.

More recently, Liu et al. conducted an economic comparison of different recycling technologies (including the fluidised bed) for GRP sections of EoL wind blade structures [9]. Liu et al. reported that the fluidised bed was not a financially viable solution for GRP blade sections, concluding that only mechanical and chemical recycling technologies were profitable. Liu et al. considered the cost of upstream waste processing steps such as blade cutting and transportation within the cost of the analysis and attributed this to the cost of GRP recycling [9]. The economics of wind blade decommissioning are not widely published; however, it is more likely that the cost associated with upstream blade preparation (e.g., initial cutting, removal from wind farm, secondary/tertiary cutting, transportation to recycler) is paid for by the waste owner, opposed to the GRP recycler. As a result, it is anticipated that the operational costs associated with GRP recycling for a FRP plant have been overestimated and should be refined.

This study is the first to comprehensively investigate the present economic outlook of the fluidised bed recycling process for a variety of GRP waste streams. Through techno-economic analysis, this work examined the economic outlook of the FBR process as a means of recycling GRP waste within the context of the current and future UK composite waste landscape. Key parameters such as waste type, number of UK recycling facilities and transportation distance were analysed to better inform future development of recycling technologies for UK composite waste streams. This paper is intended to inform long term recycling strategies for GRP waste by quantifying key economic metrics which can be used to compare against other proposed technologies.

2. Methods

2.1. Fluidised bed recycling process

A laboratory scale fluidised bed reactor located at the University of Strathclyde, which has successfully demonstrated waste WTB recycling and reuse of recycled glass fibres in the manufacture of a 3 kW WTB demonstrator component, was used and is shown in Figure 1. A description of the laboratory scale fluidised bed is given by Pender in [14]. The University of Strathclyde is in the process of scaling up the technology as part of the UK's first wind turbine blade recycling pilot plant [15].

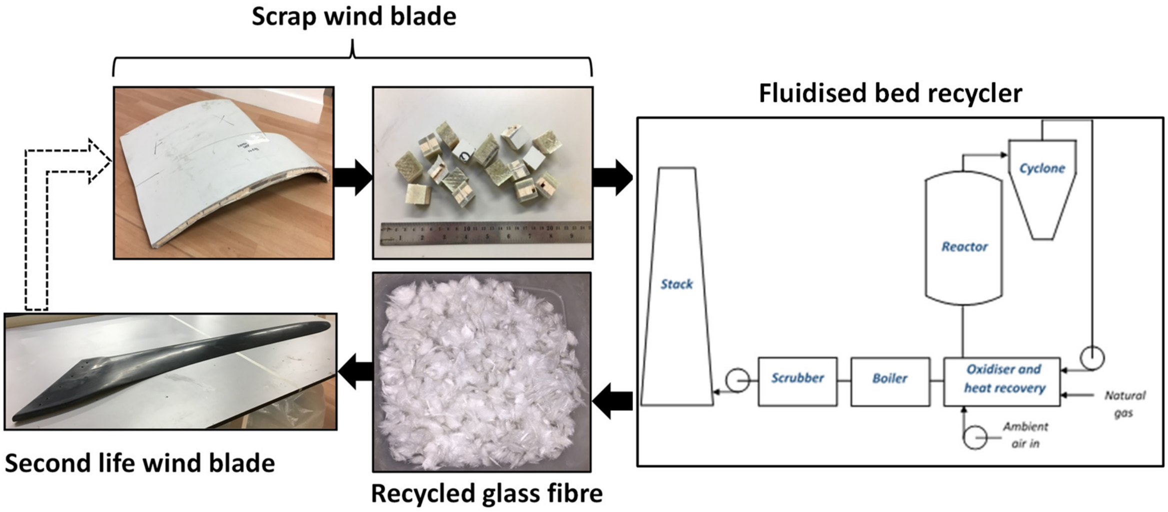

Figure 1. Wind turbine blade recycling at the University of Strathclyde, described in [14].

A schematic of a proposed commercial fluidised bed recycling (FBR) plant is given in Figure 1. GRP (such as WTB) waste is downsized to 5–25 mm and fed into the reactor, which consists of a bed of silica sand particles fluidised by a stream of preheated air. The reactor is set to 550 °C to facilitate rapid thermal oxidation of the polymer matrix (determined using thermogravimetric analysis and fluidised bed process optimisation), liberating the clean fibre and filler fractions, which are transported by the gas stream out of the reactor and subsequently separated from the gas stream and collected. The combustion gases are fully oxidised using natural gas in an oxidising chamber to remove volatiles and then passed through a series of high and low temperature heat exchangers to recover heat to be fed back into the process. A boiler is located upstream of the stack to produce process steam to be used internally or sold locally. Please note that while boilers are used in other fluidised bed combustion processes (e.g., in the burning of solid fuels), this has not yet been demonstrated for FBR plant in practice. Primary data for steam generation are not available, and principles of thermodynamics (as described in Section 1.1 in Supplementary Materials) have been used to estimate the amount of steam that can theoretically be produced from waste heat. Fans are used to maintain adequate flow through the system and overcome the pressure losses through the various components.

An energy model was developed to determine the required heat and electricity input into the system. This was informed by operation of the in-house developed FBR process and used to estimate the utility costs for operating the plant [16]. Heat was supplied into the system through oxidation of the waste GRP polymer matrix in the reactor as well as natural gas oxidation in the oxidiser. The flow rate of natural gas required to maintain adequate reactor temperature for polymer decomposition was found by balancing heat inputs and output. Electricity demand from process fans was modelled based on required gas flow and pressure increases through the system. The energy model is expanded upon in Section 1.2 in the Supplementary Material.

In practice, GRP will be present in a range of waste streams, many of which will require additional sorting steps to separate them from other materials such as metals, fabrics and neat plastics. Modelling such processes is outside the scope of this study; however, it should be noted that this will demand additional resources. Decommissioning and dismantling of large GRP structures such as EoL-WTB will incur additional costs; however, this is assumed to be done off-site and not at the expense of the recycler.

Equation 1 was used to scale the FB reactor. Reactor loading rate in Eq 1 is defined as the glass fibre mass feed rate into the FB as a function of reactor cross sectional area and was fixed at 10 kg GF/(hr·m^2) throughout the study. GF weight fraction was determined by the composition of waste processed. Importantly, from Eq 1, it should be noted that while the rate of GF mass processed is fixed at 10 kg (GF/hr·m^2), variation in fibre content means that composite feed rate is not fixed. GRP with lower GF weight fraction can have more rapid GRP mass throughput when compared to other, higher fibre, waste types. In this study the installed plant capacity is defined as the maximum annual throughput of a given FBR plant, which is assumed to operate at 8000 hr/yr. The installed capacity alone dictates the scale of the plant installed and consequently the initial capital investment. Operating capacity is defined as the actual annual throughput of a given FBR plant and is expressed in absolute terms (mass GRP/yr) or as a percentage of the installed capacity of the plant (%). The operating capacity dictates the number of hours the plant operates annually to achieve the required mass of GRP processed, where 100% operating capacity is equal to 8000 hr of operation.

$$Reactor\ area\ [m^2] = \frac{Installed\ \ Capacity\ \left[\frac{kg\ GRP}{yr}\right] \times GF\ weight\ fraction\ \left[\frac{kg\ GF}{kg\ GRP}\right]}{Operating\ time\ \left[\frac{hr}{yr}\right] \times Reactor\ loading\ rate\ \left[\frac{kg\ GF}{hrm^2}\right]} \tag{1}$$

2.2. Fluidised bed plant financial model

The financial model for a commercial FBR plant considered capital expenditure (CAPEX) and operational costs (OPEX) as well as revenue sources such as recycled filler and glass fibre products, gate fee charged to scrap GRP waste and heat energy recovered from the process.

Two economic models were developed to carry out (1) a "steady-state" analysis and (2) a "temporal" analysis. The steady-state model considers a single operating year in isolation, whereas the temporal analysis can extend the time of analysis over a selected duration to understand how changes in supply and demand can affect the long-term prospects of the recycling plant.

For the steady-state model, the net cost of recycling GRP was found using Eq 2 and expressed as a function of rGF mass, making it equivalent to the minimum rGF re-sale price required for the plant to break-even. Plant profit could be found by estimating rGF re-sale price and break-even conditions determined by setting plant profit = 0 \$/yr.

$$Min.rGF\ price\ \left[{}^{\$}/_{kg\ rGF}\right] = \frac{OPEX\ \left[{}^{\$}/_{yr}\right] + CAPEX\left[{}^{\$}/_{yr}\right] - Revenue\ (excl.rGF\ resale)\left[{}^{\$}/_{yr}\right]}{rGF\ mass\left[{}^{kg\ rGF}/_{yr}\right]} \tag{2}$$

The temporal analysis investigates a fifteen-year period, considers factors such as currency devaluation and cash flow over time and outputs data such as investment payback time, return on investment and internal rate of return. The temporal analysis assumes capital investment prior to operation and assesses the annual cash flows with break-even conditions corresponding to scenario(s) where net present value = 0. The temporal analysis was used to compare investment in FBR plant against other potential investments. When calculating present value in the temporal analysis, the discount rate is assumed to be a baseline alternative low risk stock investment with 6% interest rate. Inflation rate is assumed to be 1.4%.

An exponential relation shown in Eq 3 was used to estimate the capital cost at a variety of plant scales. Typically, capital cost would be scaled with plant installed capacity, as this would define the size and subsequent cost estimate of the plant equipment. As defined in Eq 1, however, reactor cross sectional area (which ultimately dictates the scale of the plant) is influenced by plant installed capacity, reactor loading rate and waste composition. In this study, capital cost is therefore scaled with reactor cross sectional area, which is calculated using Eq 1. Reference data for an analogous 1 kt/yr carbon fibre FBR process was used as data input into Eq 3, where the exponent $\alpha = 0.6$ is used as described for analogue process in [11].

$$FBR\ plant\ capital = Ref.FBR\ plant\ capital\left(\frac{Reactor\ area}{Ref.plant\ reactor\ area}\right)^{\alpha} \tag{3}$$

Input data for FBR plant financial model can be found in Table S2, which was modelled following the methodology outlined in [13]. It is assumed that 3 staff members are present during plant operation, regardless of installed capacity, and are paid according to average UK labour wages [17]. The annual capital investment used in Eq 2 was established by assuming a plant life span of fifteen years.

In addition to utilities and labour, there are many other direct and indirect operational costs associated with plant operation such as plant overheads, maintenance, operating supplies, administration, distribution costs and more. These are estimated as a function of the labour and/or capital investment (presented in Table S3). In addition to the equipment capital cost required for plant operation, other direct and indirect costs are incurred during development including infrastructure, such as building and service facilitates, electrical systems and other costs. In this analysis, it is assumed that the FBR plant is installed within a pre-existing and operational site, most likely parasitically on an established waste management facility. This reduces developments costs and is logistically advantageous during operation.

2.3. GRP transport

In all cases, waste GRP transportation is assumed to be carried out using a 32 t diesel rigid heavy goods vehicle, with load capacity of 20 t GRP. Transportation distances for waste GRP prior to recycling was considered, which is dependent on the number of recycling plants located in the UK. For this study only GRP waste from the mainland UK was considered given the practical challenges of transporting waste between Northern Ireland and the rest of the UK. Transportation distances were found as a function of number of plants, assuming even distribution across the mainland UK.

2.4. GRP waste streams

The outlook for GRP waste processing in the UK was assessed by considering the waste stream in terms of quantity and type/composition of GRP. Three waste streams were considered:

- Current UK mixed GRP waste (Mixed GRP)
- GRP from projected UK end of life WTB waste (EoL-WTB)
- GRP from combined UK end of life WTB waste and UK GRP manufacturing waste (EoL-WTB + Manf.)

2.4.1. Mixed GRP

The quantity and composition of various types of composites currently comprising the UK GRP waste stream were estimated in [5] and reproduced in Figure 2. Four commonly used resin types, unsaturated polyester resin (UPR), epoxy, vinyl ester and phenolic resins, are given in [5] and are therefore considered in this study. Despite a range of filler types being used in GRP production, quantities for discrete filler types are not presented in [5]. For the purposes of this study, it is assumed that “filler” material comprises only $CaCO_3$ which exhibits mass continuity during processing and, when reused, can be directly used in place of new $CaCO_3$. Table 1 gives the combined mass of materials within the UK GRP waste stream in addition to the relative contributions of each. “Mixed GRP” is defined as GRP waste which contains all types of GRP in the proportions given in Figure 2, which has the composition given in Table 1.

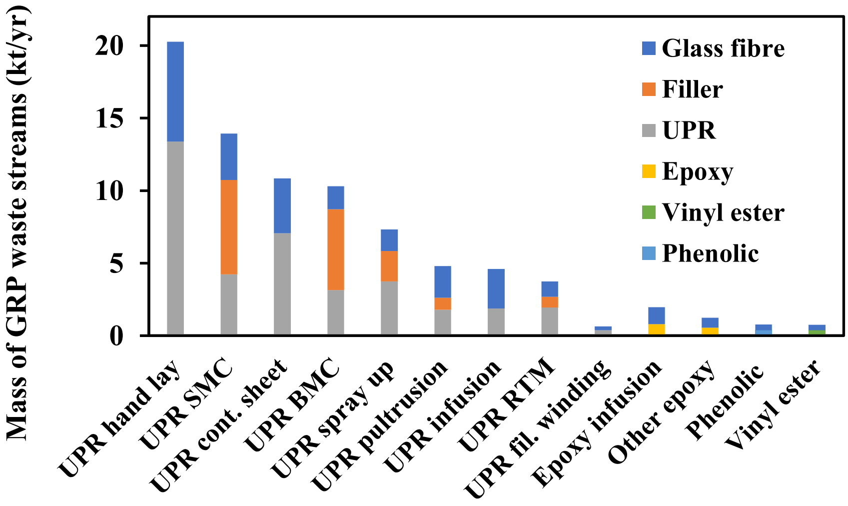

Figure 2. Estimated mass of GRP types and constituent materials in UK waste stream, produced using data from [5].

Table 1. Compiled mass and composition of total UK mixed GRP waste stream, produced using data from [5].

Material	Mass in UK GRP waste (kt/yr)	Fraction of GRP waste (%)
Glass fibre	25.8	31.9
Filler	15.8	19.2
UPR	37.6	46.3
Epoxy	1.36	1.67
Vinyl ester	0.38	0.47
Phenolic	0.38	0.46
Resin total	39.7	48.9
GRP total	81.2	100

2.4.2. EoL-WTB

Developing a GRP recycling plant around a single waste stream has the advantage of consistency in the process’s feedstock, giving more predictability in the plant’s operation and output materials. Waste GRP from EoL-WTB can be easily managed, avoiding the challenges associated with separating, sorting and managing mixed GRP waste streams. GRP from EoL-WTB is also relatively consistent in composition when compared to GRP waste as a whole. Given the relative uniformity of this waste stream, developing a recycling plant with EoL-WTB as the sole feedstock may mitigate many of the practical challenges associated with GRP recycling. Figure 3 projects the mass of GRP from EoL-WTB, showing that this is a rapidly growing source of waste GRP in the UK. EoL-WTB are assumed to be 60 and 32 wt% glass fibre and epoxy, respectively, with the remaining 8 wt% composed of paint, adhesive, foam and balsa [18].

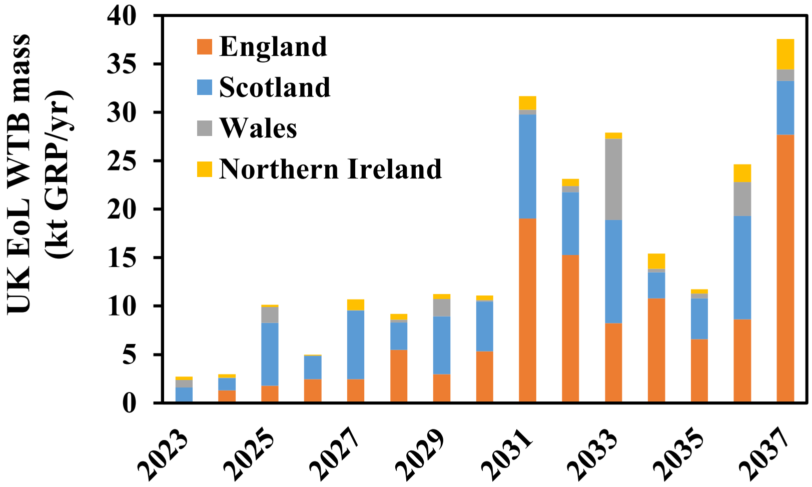

Figure 3. Projected GRP mass in UK EoL-WTB by country.

2.4.3. EoL-WTB + Manf.

UK GRP production waste is approximately 15 kt/yr, accounting for around 20% of annual waste GRP volumes [4]. Without prior integration into mixed material supply chains, GRP manufacturing waste and EoL-WTB will likely require less sorting than other GRP waste, making them an attractive feedstock for a recycling plant. In this work "EoL-WTB + Manf." is the UK EoL-WTB and GRP manufacturing waste streams combined. GRP manufacture waste is assumed to have the same composition as UK mixed GRP waste given in Table 1 and a fixed mass of 15 kt/yr. The mass and composition of EoL-WTB + Manf. changes annually due to the changes in projected volumes of EoL-WTB shown in Figure 3.

3. Results and discussion

3.1. Influence of waste type

Figure 4 presents the associated recycling costs, revenue (excluding rGF sales) and minimum rGF resale price to break even for the range of GRP types in the current UK mixed waste stream. Plant installed capacity is fixed at 20 kt GRP/yr (approximately 25% of current UK mixed GRP waste volumes). Figure 4 shows that the composition of the waste has a significant influence on the overall cost to recycle GRP. This is demonstrated by a 93% increase in recycling cost between the lowest (Bulk Moulding Compound, BMC) and highest (UPR infusion) cost waste types. Figure 4 shows that this variability in recycling cost is predominantly attributable to differences in direct operating costs of the FBR plant and, to a lesser extent, the capital investment. A substantial direct cost is electricity demand of the recycling process, which accounts, on average, for approximately 40% of direct costs. Despite having constant GRP mass throughput across Figure 4, the reactor cross sectional area is not fixed between waste types but rather determined by the reactor loading rate, which is assumed constant at 10 kg (GF/hr·m^2). This allows GRP waste stream with lower glass fibre weight fractions to be processed in reactors with small cross-sectional area, which in turn reduces the capital and operational costs.

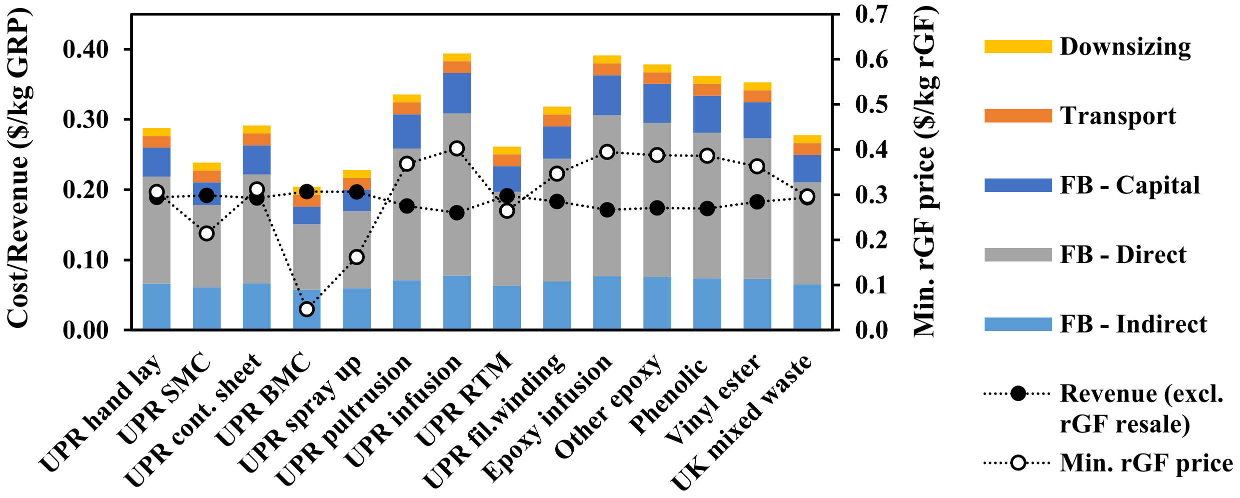

Figure 4. The associated recycling costs, revenue and minimum rGF resale price to break even for the range of GRP types in the UK mixed waste stream. FBR installed plant capacity and transportation distance are fixed at 20 kt GRP/yr and 200 km, respectively.

Figure 4 also gives the minimum rGF resale price, defined as the rGF resale price to establish breakeven conditions such that total recycling cost equals total revenue. This is found to increase with glass fibre weight fraction, which, given the higher recycling costs, is what may be anticipated conceptually. Under the conditions analysed in Figure 4, the minimum rGF resale prices remain significantly lower than vGF, conservatively estimated to have market value of $1.00/kg [19].

With the exception of “UK mixed waste”, the analysis in Figure 4 assumes processing a single waste type in isolation. Operating with a “mono-waste” feedstock allows the process to be optimised for the specific composition. For example, the reactor size can be minimised based on fibre content, which significantly reduces the direct operation costs and capital investment. In practice, this will not be feasible at the scales analysed in Figure 4 (≥20 kt GRP/yr), due to insufficient quantities of specific waste types generated each year. Figure 4 shows BMC to have significantly reduced minimum rGF resale price when compared to other waste types; however, this is assuming that the installed plant capacity of 20 kt GRP/yr is satisfied by BMC alone. In practice, it can be seen in Figure 2 that BMC only accounts for around 10 kt GRP/yr in the UK; therefore, in this region, supplementary feedstock GRP would be required to operate at this scale. Under these operating conditions, this will have deleterious effects on the resulting cost and rGF price competitiveness against virgin counterparts. These considerations are strictly dependent on the regional supply of waste GRP and the constituent composition. As such, a market analysis should be conducted within plant development regions, to estimate legacy and future waste GRP trends to inform the design criteria of the plant and ensure optimal operating conditions can be met.

In this work a weighted average of the UK GRP waste supply has been used to estimate the aggregated composition of mixed UK GRP waste, which can be used as a representation of waste feedstock for a UK FBR plant. This leads to a glass fibre weight fraction of approximately 30% and has a minimum rGF resale price of \$0.30/kg under the conditions analysed in Figure 4, which is considerably lower than the market value of even low-grade vGF.

3.2. Influence of installed plant capacity

Figure 5 gives the associated recycling costs, revenue and minimum rGF resale price to break even when recycling mixed GRP waste at a range of installed plant capacities. For reference, current total annual GRP waste in UK alone is estimated to be up to 80 kt/yr [4]. The cost of GRP recycling is substantially lowered by increasing the plant installed capacity because of lowering (relative to mass of GRP processed) labour and indirect costs associated with plant operation. The relative capital investment is also reduced significantly at higher plant capacities due to the non-linear scaling of plant capital cost in Eq 3. Similar trends were also found by Meng [11], reporting a minimum fibre resale price of 1.2 \$/kg when recycling CRP within a 5 kt/yr FBR plant.

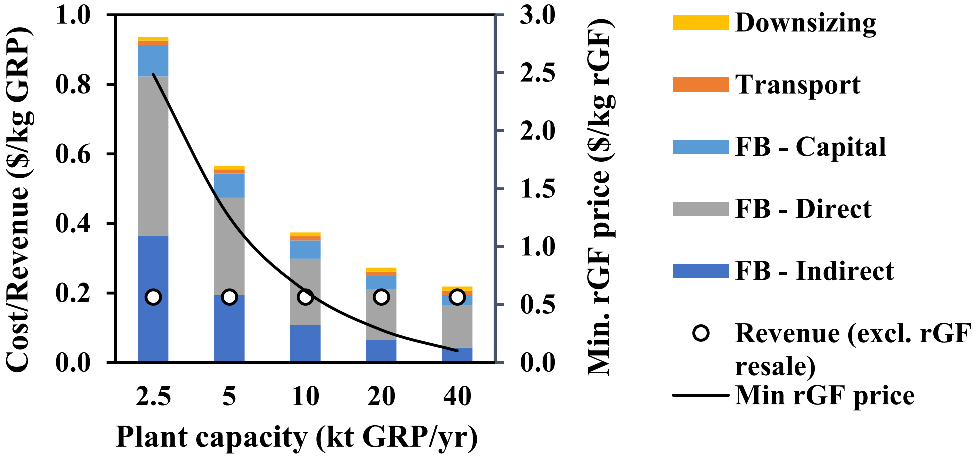

Figure 5. The associated recycling costs, revenue and minimum rGF resale price to break even recycling current UK mixed GRP waste at a range of installed plant capacities. Transportation distance is fixed at 200 km.

To reduce the cost of recycling, a FBR plant should be developed at a scale which maximises annual GRP throughput. This will inevitably determine the plant catchment areas and transportation distances to satisfy this demand; the impact of this on recycling costs is presented in Figure 8.

Figure 6 shows the minimum rGF resale price for the various GRP types in the UK mixed waste stream at a range of installed plant capacities. For installed plant capacities of 40 kt GRP/yr, it was found that low fibre content waste such as BMC and SMC have negative minimum resale prices. This indicates that the sum of other revenue sources, predominantly gate fee revenue, are greater than the total recycling costs; therefore, the recycling plant can break even without the need for fibre resale revenues. This only occurs for large capacity plants, which, while having lower capacity than annual UK GRP waste generation, would occupy a significant proportion of GRP waste available each year.

This study presents similar findings to those reported by Pickering et al. regarding plant capacity at breakeven [13]. If rGF retain 80% of their market value (0.8 $/kg), which was assumed by Pickering et al. in [13], Figure 6 shows that plant capacity at breakeven is expected to be slightly lower than 10 kt GRP/yr (depending on the waste types). This agrees with Pickering et al. [13], who estimated breakeven capacity of 9 kt GRP/yr when processing waste SMC.

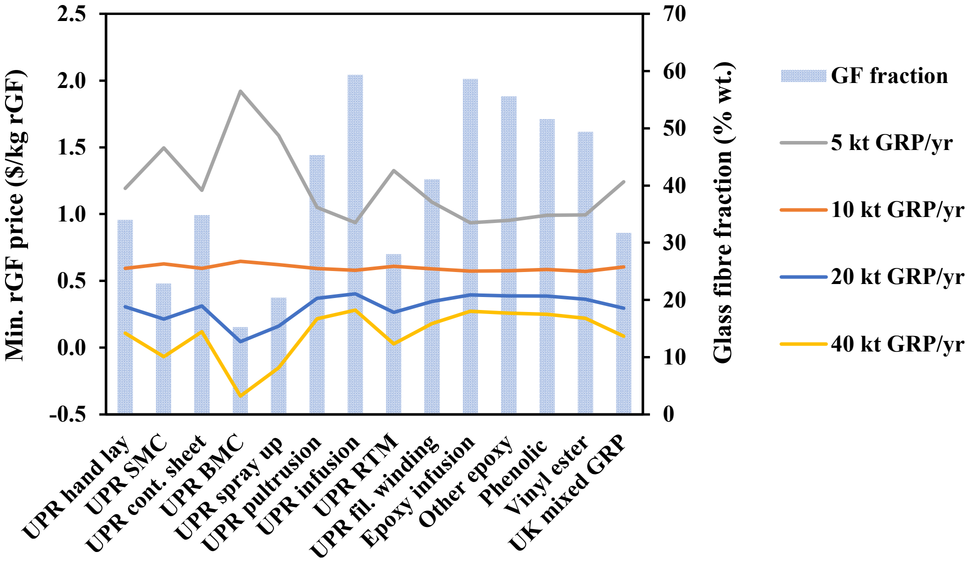

Figure 6. Minimum rGF resale price for the various GRP types in the UK mixed waste stream at a range of installed plant capacities. Transportation distance is fixed at 200 km.

3.3. Influence of plant operating capacity

In practice, it is unlikely that the plant will function at 100% fully installed capacity year-round; therefore, the effect of operating below maximum installed capacity has been investigated. Figure 7 gives the operating capacity at breakeven as a function of installed plant capacity for a range of rGF resale prices; this is given for both mixed GRP waste and EoL-WTB waste. Operating capacity is the actual mass of GRP processed each year within a FBR plant and is presented as a fraction of the installed plant capacity. The operating capacity dictates the number of hours the plant operates annually to achieve the required mass of GRP processed, where 100% operating capacity is equal to 8000 hr of operation. The installed capacity alone dictates the scale of the plant installed and consequently the initial capital investment, as shown in Figure 7. Operating below installed capacity therefore incurs addition cost to process GRP due to greater than required capital investment. Where operating capacity at breakeven was found to be greater than installed capacity, this was omitted from Figure 7.

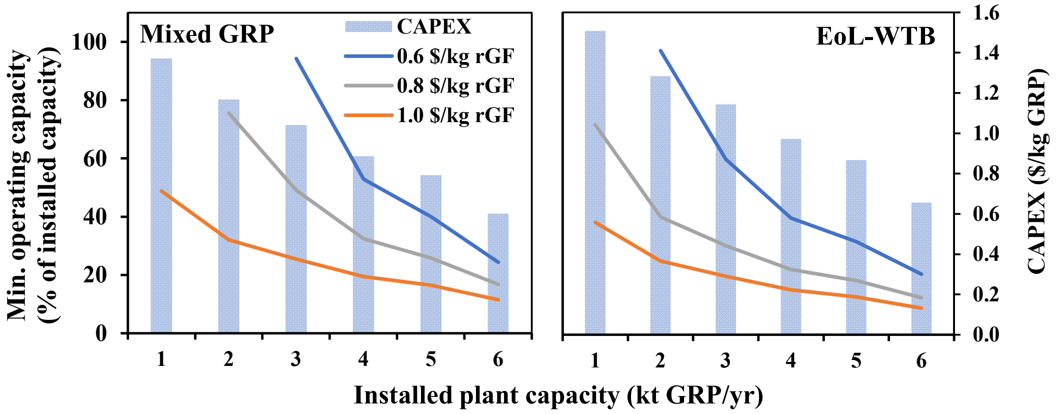

Figure 7. The operating capacity at breakeven as a function of installed plant capacity for a range of rGF resale prices and two GRP types: current UK mixed GRP waste and wind turbine blade waste. Transportation distance is fixed at 200 km.

Operating below installed capacity was found to only be viable for large plants or for scenarios where rGF resale price is high and approaching vGF cost. In all cases the relative operating capacity at breakeven decreases with increasing installed capacity, which suggests that larger plants are less sensitive to operating below the plant design point.

FBR plants processing EoL-WTB are less sensitive to changes in operating capacity at the lower range of installed capacities analysed. Figure 7 suggests that a plant dedicated to EoL-WTB recycling with installed capacity of 10 kt GRP/yr, could meet break-even conditions at operating capacity of just 40%, assuming rGF resale price of \$0.80/kg. This is particularly pertinent when designing for the future, where developing a plant to meet future anticipated waste volumes may be cheaper than ad hoc expansion of FBR plant with capacity no longer sufficient to maximise profits. The required operating capacity is however highly sensitive to rGF resale price and consequently rises to approximately 90% when reducing rGF resale price to \$0.60/kg, as shown in Figure 7.

The methodology used in Figure 7 assumes that operating below installed capacity is achieved by simply reducing the annual operating hours of the plant where full capacity is assumed to be met at 8000 hr/yr (e.g., operating at 50% capacity means 4000 hr/yr operation). Operating below the prescribed 8000 hr/yr will incur additional heat up/cool down periods that have not been considered. The operational costs both in terms of labour and utilities are therefore likely to be higher than is estimated in this model, given that workers would be required to be present during the heat up, which would also demand additional electricity costs. The operating costs to break even given in Figure 7 are therefore most likely an underestimation of the true value.

3.4. Influence of number of plants

Figure 8 gives the cost associated with recycling UK mixed GRP waste using FBR as a function of number of plants, particularly focusing on the impact on transportation costs. For each scenario, the total mass of GRP recycled is 81.2 kt/yr, which is the total current estimated annual mass of waste GRP in the UK. The scenarios differ in the number of plants located within the UK to processes this waste; therefore, the number of plants simultaneous varies (1) the individual plant installed capacities and (2) the required transportation distance. Transportation distance is inversely proportional to the number of recycling plants, with 1 and 10 plants requiring transportation distances of 772 and 150 km respectively. Similarly, plant installed capacity is also inversely proportional to the number of plants, with 1 and 10 plants requiring installed plant capacities of 81.2 and 8.12 kt GRP/yr, respectively, in order to facilitate the annual UK GRP waste volumes. Despite the significant increase in transportation distance, the transportation has minimal impact on the cost to recycle GRP. The transportation cost is inversely proportional to number of plants; however, the reduction in other recycling costs enabled by increasing installed plant capacity far outweigh savings in transportation cost, as is shown by total cost in Figure 8. Increasing plant capacity remains the largest impact on the cost to recycle using the FBR plant and should be maximised within the limits of available GRP waste feedstock, despite the additional transportation distance required to satisfy this demand. Figure 8 suggests that developing larger, national level FBR plants, as opposed to local or regional plants, is a preferable strategy to minimise costs and maximise rGF cost competitiveness.

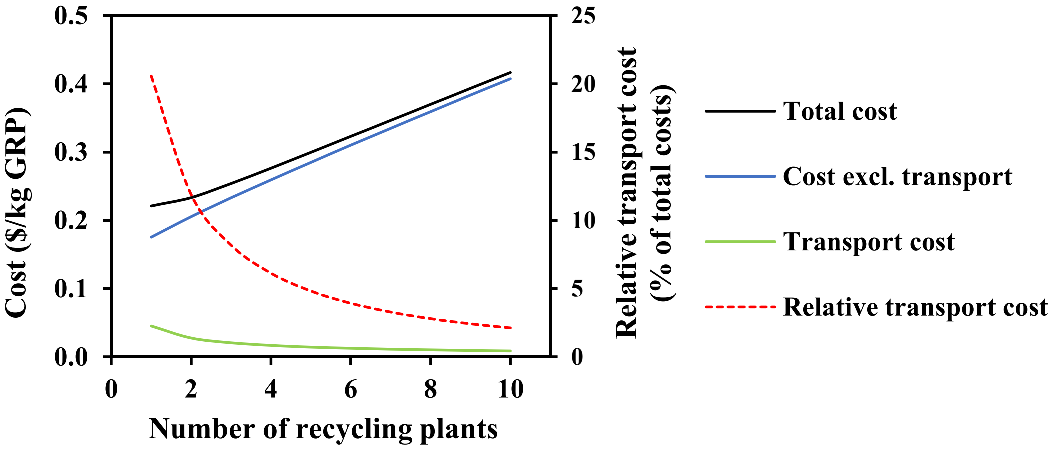

Figure 8. The influence of number of recycling plants, and by extension the transportation distance, on the cost to recycle current UK mixed GRP waste. Total waste recycled is assumed as 100% of current UK mixed GRP waste split equally between recycling plants.

3.5. Temporal analysis

The temporal analysis has been conducted to best reflect the long-term economic prospects of FBR plants within the UK and inform development strategies. In all cases an installed capacity of 40 kt GRP/yr was used across the scenarios investigated. Three scenarios are considered, each accepting different GRP waste streams, allowing for varying levels of annual waste throughput depending on waste availability each year.

- Scenario 1: EoL-WTB – The FBR plant only accepts EoL-WTB waste as feedstock, with all UK WTB waste generated over the period being processed in a single FBR plant. Due to limitations on waste availability, the plant initially operates far below installed capacity, as shown in Figure 9.

- Scenario 2: EoL-WTB + Manf. – The FBR plant accepts all UK EoL-WTB and is supplemented with UK manufacturing waste (15 kt GRP/yr) with an aggregated composition of UK GRP types.
- Scenario 3: EoL-WTB + Manf. + Mixed GRP – The FBR accepts all EoL-WTB + Manf. waste annually and is supplemented with enough mixed GRP waste to operate at 100% capacity each year.

The exact compositions of the waste in Scenarios 2 and 3 differ between years due to the variation in available EoL-WTB waste as shown in Figure 9. Table 2 gives input data for each of the scenarios which has been aggregated over the fifteen-year period analysed. It was assumed that for all scenarios, FBR plants accept waste from across the whole of mainland UK; therefore, the transportation distance was fixed at 772 km.

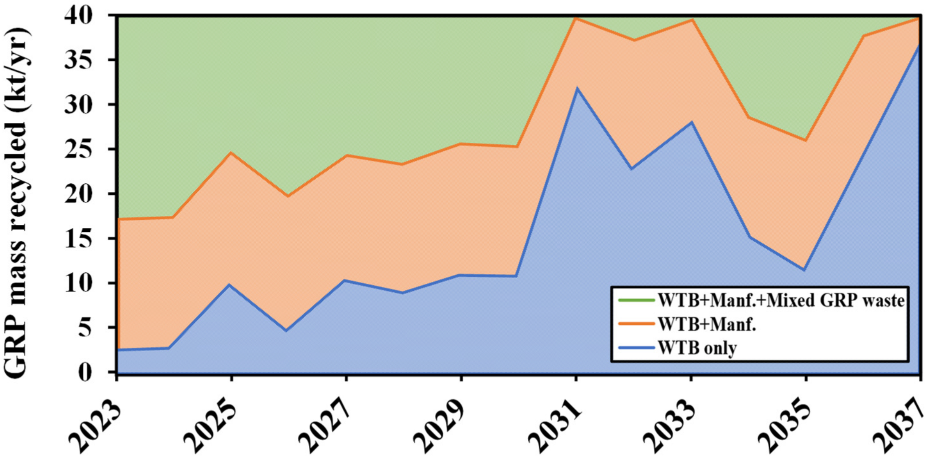

Figure 9. The mass of GRP from the different waste streams (WTB, manufacturing and mixed GRP waste) recycled over time for each of the scenarios analysed, where installed plant capacity is fixed at 40 kt GRP/yr.

Table 2. Input data for each of the scenarios analysed including the total mass of GRP recycled, operating capacity over the period and a breakdown of the composition of the waste processed aggregated over the fifteen-year period analysed.

Scenario	Installed capacity (kt/yr)	Mass recycled (kt)	Operating capacity (%)	GF weight fraction (%)		
				WTB	Manuf.	Mixed GRP
1	40	235	39	100.0	0.0	0.0
2	40	430	72	54.7	45.3	0.0
3	40	600	100	39.2	32.4	28.4

Figure 10 presents the minimum rGF resale prices for each of the scenarios analysed as a function of operating year. The bars in Figure 10 indicates the operating capacity relative to 40 kt installed plant capacity at three different scenarios. As would be expected, recycling only EoL-WTB initially has significantly higher rGF price due to operating far below installed capacity. As the anticipated volumes of EoL-WTB increase, a FBR plant under Scenario 1 can operate closer to installed capacity and more economically efficiently, ultimately reducing the revenue required from rGF sales to break even. By relying on a single waste type, however, the minimum rGF resale price remains highly dependent on EoL-WTB availability, as shown by irregular fluctuations in Figure 10. Developing a FBR plant with lower installed capacity to meet current waste demand would reduce recycling costs; however, it would quickly be insufficient in scale with the imminent rise in EoL-WTB waste. By supplementing with other waste streams, the rGF price found for Scenarios 2 and 3 are (1) consistently cost competitive with vGF and (2) less influenced by variation in EoL-WTB availability and therefore less volatile. From an economic perspective, it is always advantageous to have higher installed capacity, assuming waste demand can allow for maximised operating capacity; therefore, Scenario 3 presents the lowest minimum rGF resale price at breakeven.

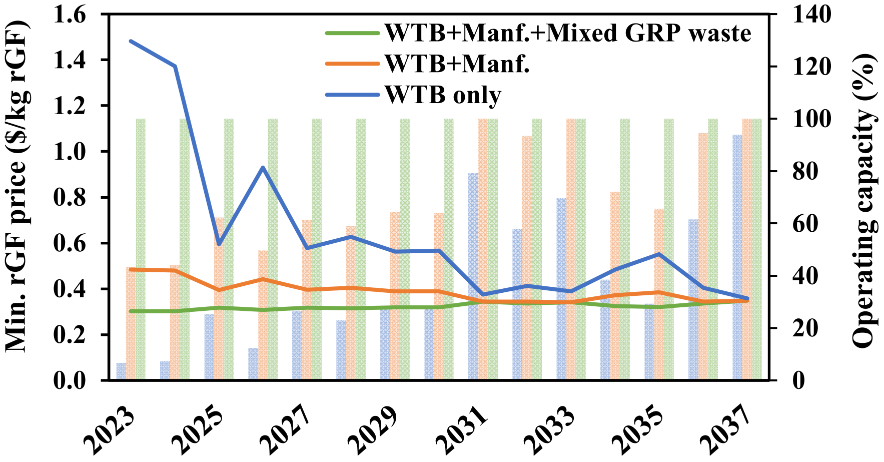

Figure 10. The minimum rGF resale price over time for each of the scenarios analysed. Installed plant capacity and transportation distance are fixed at 40 kt GRP/yr and 772 km, respectively.

Figure 11 gives the annual profit over time for each of the scenarios analysed assuming a rGF resale price 80% of vGF counterparts. Annual profits are particularly volatile for Scenarios 1 and 2, which heavily rely on EoL-WTB volumes and operate far below installed capacity when these are insufficient. Figure 11 shows that feedstock resilience will clearly influence the profitability of a FBR plant, with reliance on single source waste streams presenting challenges in this domain. From Figure 11 it was found that the total profits over the period analysed were $34M, $69M and $96M for Scenarios 1, 2 and 3, respectively. Clearly, there is strong economic incentive to develop plants capable of accepting mixed GRP waste streams to maximise the available profits. Single sources/types of feedstock, however, will likely have the advantages of consistency in composition, less/predictable contamination and requiring less sorting prior to processing. The cost associated with separating, sorting and managing mixed GRP waste streams has not been included in this analysis but would need to be overcome to accept mixed waste streams and may reduce the magnitude of profits given in Figure 11.

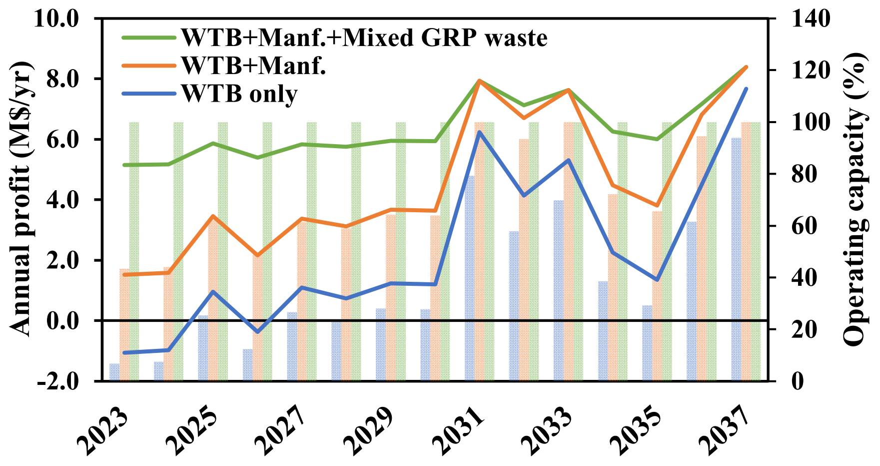

Figure 11. The annual profit over time for each of the scenarios analysed assuming rGF resale price 80% of vGF counterpart. Installed plant capacity and transportation distance are fixed at 40 kt GRP/yr and 772 km, respectively.

Figure 12 gives the real ROI over time for each of the scenarios analysed assuming rGF resale price 80% of vGF counterpart. Given the significantly higher profits in Figure 11, and comparable capital investment between scenarios, Scenario 3 has the highest ROI. This is due to lower operating cost (relative to mass of GRP recycled) and greater product output when operating closer to the maximum installed capacity of 40 kt/yr. Figure 12 shows that FBR plants supplementing with manufacturing and other mixed GRP waste can benefit from a threefold increase in ROI with comparable capital investment. Capital investment payback time can be found under conditions where ROI = 0%. From Figure 12 this was found to be approximately nine, six and four years for Scenario 1, 2 and 3 respectively, all of which is within the expected service life-expectancy of the equipment used in the FBR plant.

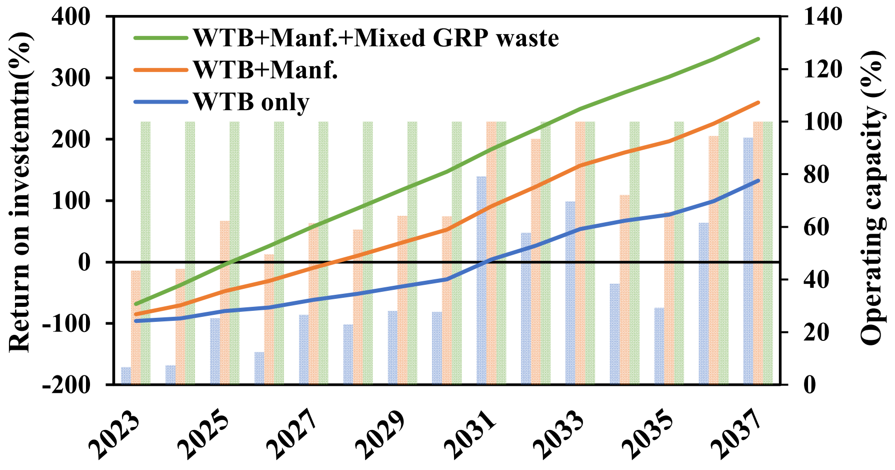

Figure 12. Real return on investment over time for each of the scenarios analysed assuming rGF resale price 80% of vGF counterpart. Installed plant capacity and transportation distance are fixed at 40 kt GRP/yr and 772 km, respectively.

Figure 13 expands on Scenario 1 and gives the total fifteen-year profit, ROI and payback time (yr) for FBR plants processing exclusively EoL-WTB at a range of installed capacities. The operating capacity is determined by the mass of EoL-WTB available which is in line with UK waste volumes in Figure 3. Figure 13 shows that while plants with installed capacities of 30–40 kt/yr provide greater lifetime profits, under the conditions analysed, ROI is maximised for 20 kt/yr FBR plants, and this scale presents a more efficient investment of capital. Installed capacity of 5 kt/yr provide a 3% ROI over fifteen years and is essentially the installed capacity at breakeven. At present, any FBR plant developed to process EoL-WTB alone would need to do so at a scale of ≥5 kt/yr to maintain profitability over the period analysed in Figure 13 (assuming rGF resale value of \$0.80/kg). Within the parameters investigated in Figure 13, payback time is relatively consistent for FBR plants with installed capacity greater than 5 kt/yr. It should be noted that payback time is an approximation, as it is always rounded up to the nearest whole year.

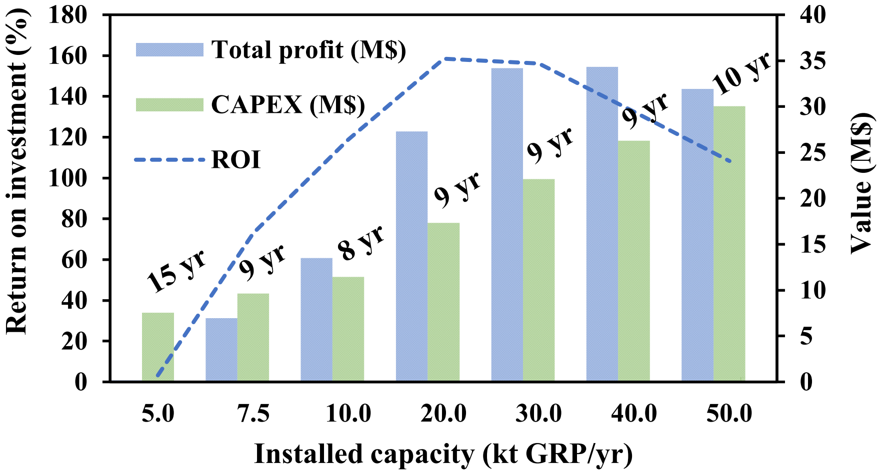

Figure 13. Total fifteen-year profit, return on investment and payback time for FBR plant processing exclusively EoL-WTB at a range of installed capacities. Transportation distance is fixed at 772 km.

Figure 14 plots the compounded present value and capital investment; showing that for all scenarios analysed, the compounded net present value is greater than the capital investment within the fifteen-year period. This demonstrates that investing in any of these plants would be preferred over the baseline alternative. The internal rates of return were found to be approximately 11%, 21% and 32% for Scenarios 1, 2 and 3 respectively. The internal rate of return gives the minimum discount rate required for the baseline alternative investment to be a preferred investment option; therefore, any other investment opportunity would need a rate greater than the respective internal rate of return to be a preferred venture over the recycling scenarios in Figure 14.

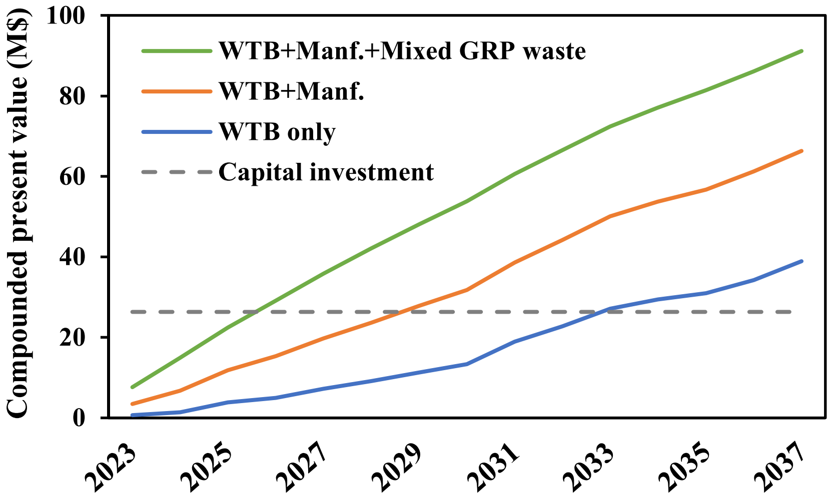

Figure 14. Compounded present value over time for each of the scenarios analysed assuming rGF resale price 80% of vGF counterpart and compared to capital investment. Installed plant capacity and transportation distance are fixed at 40 kt GRP/yr and 772 km, respectively.

4. Conclusions

This study examined the financial prospects of at scale FBR process as a means of recycling a litany of GRP types that comprise the current UK composites waste stream. Energy demands of the FBR process, in addition to a range of other operational and capital costs, were fed into a financial model which served as the foundation of the techno-economic analysis. Fourteen GRP waste types commonly produced in the UK were analysed, finding that fibre weight fraction within GRP waste was correlated with total recycling cost. Low fibre content GRP such as BMC/SMC can be more rapidly fed into a given reactor, ultimately reducing costs. On the other hand, revenue from recovered rGF is limited with low fibre content GRP. Minimum rGF price is highly dependent on both FBR plant installed capacity and composition of GRP processed, with smaller operations (≤10 kt/yr) favouring high fibre content GRP feedstocks such as EoL-WTB. FBR plant distribution across the UK was found to significantly impact the recycling cost, with fewer national scale plants providing optimal economics over many regional facilities. Costs saved at larger plant scales were found to outweigh the additional cost incurred with greater transportation distances, producing rGF product with lower minimum resale price. A temporal analysis over the coming fifteen years found that the FBR process could maintain profitability with rGF resale price significantly lower than vGF, regardless of the GRP feedstock processed. Developing FBR plant solely for EoL-WTB results in losses in the first few years of operation due to lower waste volumes available. Over the period analysed, however, it was found that profits of $35M could be achieved, which were optimal for plants with installed capacity of 30 kt/yr. EoL-WTB waste volumes are anticipated to vary annually, therefore, in years with less EoL-WTB available, full operating capacity of plants could be maintained with additional mixed GRP waste feedstocks. This was found to significantly increase fifteen-year profits to $96M, with just four-year payback time on initial capital investment. While processing mixed/multi-source GRP waste may present additional pre-processing steps, as well as inconsistency and uncertainty in waste composition, boosting capacity with this waste stream will likely significantly increase profitability and should be considered during commercial FBR plant development. Depending on waste types accepted, minimum rGF resale price to breakeven over the period analysed was found to be just 0.35–0.48 $/kg. This is significantly lower than cost of even low-grade vGF product, showing that the FBR process could be a commercially viable solution to GRP waste. Further work is required to demonstrate routes to market for rGF which will assist in establishing true market value of these materials and better inform future investment in this technology.

Use of AI tools declaration

The authors declare they have not used artificial intelligence (AI) tools in the creation of this article.

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Conflict of interest

All authors declare no conflicts of interest in this paper.

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