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Research article

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

Kyle Pender* and Liu Yang

University of Strathclyde, Department of Mechanical and Aerospace Engineering, 75 Montrose Street, Glasgow, G1 1XJ, United Kingdom

* **Correspondence:** Email: kyle.pender@nccuk.com.

Supplementary

1. Fluidised bed recycling

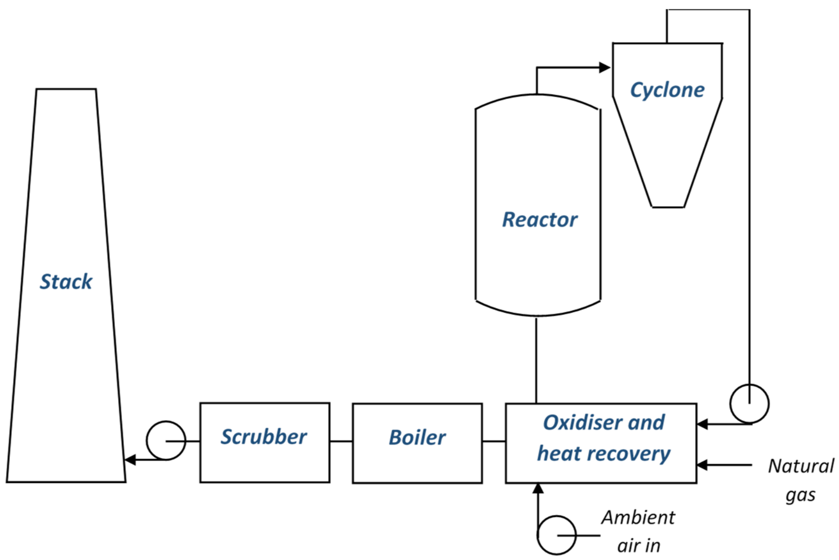

Figure S1. Schematic of FBR process used in model.

1.1. Operating parameters

The variable operating parameters are used to determine the required reactor cross sectional area of the fluidised bed reactor, as described in Eq 1.

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

The plant is assumed to operate commercially on a continuous basis with total annual operating time fixed at 8000 hr/yr. The superficial air velocity passing through the fluidised bed (fluidisation velocity) and flow through the pipes are 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. Plant layout and pipe lengths are scaled to allow for practical access to the various plant components while preventing excessive heat loss.

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

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

1.2. Energy model

Figure S2 shows the energy model of the fluidised bed process, including energy inputs through resin (Q_{resin}) and natural gas (Q_{NG}) combustion, electrical energy input and recovered materials (fibre and filler).

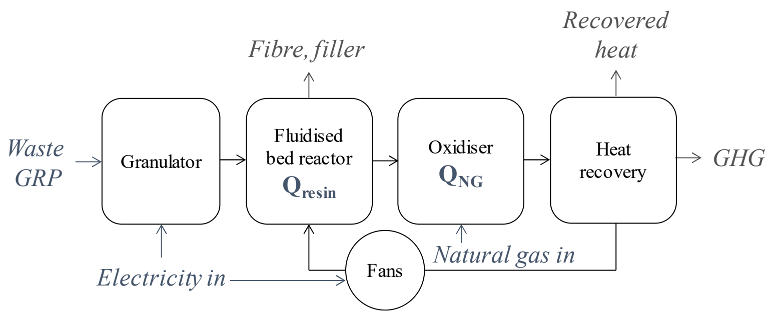

Figure S2. Schematic showing the fluidised bed process, including energy inputs through resin (Q_{resin}) and natural gas (Q_{NG}) combustion, electrical energy input and recovered materials (fibre and filler).

1.2.1. Heat model

The reactor temperature was fixed at 550 °C, which was previously found to be adequate to recover clean rGF from epoxy [1] and polyester [2], which are widely used in GRP products. The oxidiser temperature was set to 750 °C to ensure full oxidisation of volatiles prior to release through the stack. Heat loss throughout the system was modelled, considering internal and external convection, conduction through stainless steel component walls, insulation and cladding, as well as cladding surface radiation. Insulation thickness was selected to sufficiently reduce cladding outer surface temperature to within safe working limits (40 °C). Heat was supplied into the system through oxidation of the waste GRP polymer matrix in the reactor and natural gas oxidation in the oxidiser. The calorific value of the resin systems within the GRP waste stream was estimated using a modification of Dulong's formula which considers the carbon and hydrogen content of the materials and is given in Eq 2 [3].

$$CV_{resin}\left[\frac{MJ}{kg}\right] = \left(\frac{4.184}{1000}\right)(-2762.68 + 114.63C + 310.55H) \quad (2)$$

The relevant elemental contents and resulting calorific values of the resin systems used in this study are given in Table S1; these approximate experimentally obtained values of thermoset resin oxidation typically around 30 MJ/kg [2].

Table S1. Calorific values of resin systems derived from carbon and hydrogen content using modified Dulong's formula.

Resin	Fraction of resin (%)		Calorific value (MJ/kg resin)
	Carbon	Hydrogen	
UPR	71	6.1	30.2
Epoxy	74	7.8	33.9
Vinyl ester	81	7.3	36.6
Phenolic	67	6.7	29.2

It was assumed that all polymer heat energy was released within the reactor. In practice, full decomposition of the polymer does not occur within the reactor, meaning hydrocarbons are present in gases exiting the reactor [4]. The heat from these hydrocarbons is recovered in the oxidiser, where it can offset natural gas. On the other hand, less heat released in the reactor requires higher reactor inlet temperature, reducing the energy that can be recovered by the system. Overall, sensitivity study shows that under typical fluidised bed operating conditions, varying the amount of heat released within the reactor does not significantly affect overall energy demand of the system. Calorific value of natural gas was set to 39.5 MJ/m^3 based on UK grid average for 2018 [5]. Under steady state conditions, the high temperature heat exchanger efficiency was fixed, and the low temperature heat exchanger efficiency was varied to provided required fluidisation air temperature to maintain a bed temperature of 550 °C. Similarly, the energy input and corresponding flow rate of natural gas required to maintain the oxidiser temperature at 750 °C was found under steady state conditions using energy balance. It was assumed that the boiler has a thermal efficiency of 60%, with remaining heat in combustion gases being lost through the stack.

1.2.2. Electrical model

Fan electricity demand was determined as a function of the volume flow rate and necessary pressure rise, assuming an overall efficiency of 50%. Pressure losses through pipes, pipe bends, fluidised bed, cyclone, heat exchangers and oxidiser were considered with the pressure rise required for each fan established by fixing reactor gauge pressure to −500 Pa. The energy required to downsize GRP in preparation for recycling is calculated using data and methodology outlined in [6].

The energy demand of the recycling process is characterised in terms of (1) Energy input and (2) Net energy. Energy input is the required energy input to the recycling process to obtain rGF and is defined as the sum of the natural gas heat (Q_{NG}), fan electrical energy (E_{fans}) and downsizing electrical energy ($E_{downsizing}$), given in Eq 3. Heat energy is also supplied to the process through the resin matrix exothermic decomposition, but this energy source is a constituent of the GRP waste itself. Therefore only additional added energy is considered when calculating energy input in Eq 3.

$$Energy\ input = Q_{NG} + E_{fans} + E_{downsizing} \tag{3}$$

The net energy is defined as the energy to recycle GRP while displacing the production of resources using materials and heat recovered from the recycling process. This is given in Eq 4 as the energy input $\left(E_{input}\right)$ minus the energy offset and extracted by recycling GRP; sources of this are heat recovered from the system in the boiler (Q_{boiler}) and the energy required to manufacture vGF (E_{vGF}) and filler (E_{filler}).

$$Net\ energy = E_{input} - \left(Q_{boiler} + E_{vGF} + E_{filler}\right) \tag{4}$$

2. Financial model

Table S2. Cost and revenue input data for FBR plant financial model.

Capital costs	
Working capital	5% of plant capital
Capital investment	Plant capital + working capital
Direct costs	
Electricity (fans and downsizing)	0.15 $/kWh [7] (cost determined from energy analysis)
Natural gas	0.024 $/kWh [8] (cost determined from energy analysis)
Misc. materials	10% of maintenance
Maintenance	5% of capital cost
Operating labour	Assumed 3 staff during operation @ 31.32 $/h [9]
Supervision	15% operating labour
Lab charges	10% operating labour
Scrubber operation and maintenance	Annual cost: 32000 $/m^{3}s [10]
Indirect costs	
Plant overheads	60% operating labour
Insurance	0.5% of capital cost
Admin	25% of plant overheads
Distribution	5% of total indirect expenses
R & D	5% of total indirect expenses
GRP waste transport	Waste stream radius = 125 mile; Transport cost = 3.97 $/mile [11]
Revenue	
Gate fee (av. Dec 2020 UK landfill cost incl. tax)	154 $/tonne [12]
Process steam	0.009 $/kg
Filler (CaCO3)	50 $/tonne
Recycled fibre	Resale price est. as % of vGF cost (1 $/kg vGF) [13]
Exchange rates	1.25 $/£
	1.15 $/€

Eq 5 defines annual plant profit as the difference between the amount earned and the amount spent with one year. Corporation tax was assumed to be 19% on all earned profits [14].

$$Plant\ profit\ \left[{}^{\$}/_{yr}\right] = \left(\sum Revenue\ \left[{}^{\$}/_{yr}\right] - \sum CAPEX\ \left[{}^{\$}/_{yr}\right] - \sum OPEX\left[{}^{\$}/_{yr}\right]\right) - Corp.tax \tag{5}$$

Breakeven conditions occur when there is parity in spending and earning, or when profits equal zero, as shown in Eq 6. "Plant capacity at breakeven" is defined as the require plant capacity to satisfy the condition presented in Eq 6.

$$\sum Revenue\ \left[{}^{\$}/_{yr}\right] - \sum CAPEX\ \left[{}^{\$}/_{yr}\right] - \sum OPEX\left[{}^{\$}/_{yr}\right] = 0 \tag{6}$$

Return on investment is used to evaluate the efficiency of an investment or to compare the efficiencies of several different investments and is a ratio between net income and investment. A high return means the investment's gains compare favourably to its cost. Eq 7 gives the real return on investment which is adjusted for inflation, assuming an annual inflation rate of 1.4%.

$$Real\ return\ on\ investment[\%] = \left(\frac{\sum net\ cash\ flow\ [\$] - Capital\ investment\ [\$]}{Capital\ investment\ [\$] \times (1 + inflation\ rate\ [\%])}\right)^{operation\ year} \tag{7}$$

Net present value looks to assess the profitability of a given investment on the basis that currency in the future is not worth the same as today. Currency loses value over time due to inflation. However, money today can be invested and earn a return, making its future value possibly higher than an equivalent amount received at the same point in the future. Net present value seeks to determine the present value of an investment's future cash flows above the investment's initial cost by discounting the future cash flows to the present-day value. If subtracting the initial cost of the investment from the sum of the cash flows in the present-day is positive, then the investment is worthwhile. The discount rate is assumed to be a baseline alternative low risk stock investment with 6% interest rate. Eq 8 gives the net present value for a single operational year t.

$$Net\ present\ value\ [\$] = \frac{Net\ cash\ flow\ in\ operation\ year\ t\ [\$]}{(1 + discount\ rate\ [\%])^t} \tag{8}$$

Internal rate of return, given in Eq 9, is used to determine which discount rate makes the present value of future cash flows equal to the initial cost of the capital investment (i.e., the discount rate that causes the net present value of a project to be zero). If an investment will require capital that could be used elsewhere, the internal rate of return is the lowest level of return from the project that is acceptable to justify the investment. The baseline alternative is assumed to be a low-risk stock investment with 6% interest rate.

$$\sum_{t=1}^{t=no.of\ years} \frac{Net\ cash\ flow\ in\ operation\ year\ t\ [\$]}{(1 + Internal\ rate\ of\ return\ [\%])^t} = 0 \tag{9}$$

Equation 10 gives the conditions required for capital payback, which states that the total net earnings over time t must be greater than the initial capital investment. Payback period is defined as the minimum value for N which satisfies Eq 10.

$$\sum_{t=1}^{t=N} Net\ cash\ flow - Capital\ investment > 0 \tag{10}$$

For the “steady-state” analysis, the capital investment is spread over the life expectancy of the plant in order to determine the CAPEX cost contribution to product cost (this is analogous to the depreciated cost), shown in Eq 11

$$Annual\ CAPEX = \frac{Total\ capital\ investment}{Plant\ life\ expectancy} \tag{11}$$

3. Transportation

Assuming an even distribution of GRP waste across UK, recycling plant intake areas required to encompass mainland UK for a given number of plants was estimated, as shown in Figure S3.

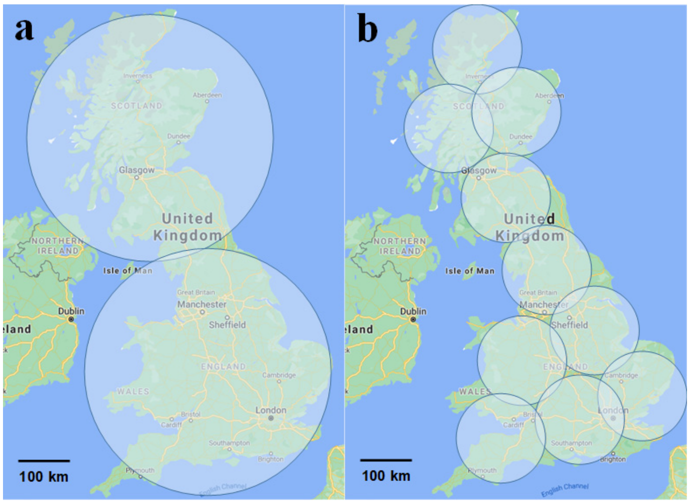

Figure S3. Example of potential recycling plant intake areas for (a) 2 plants and (b) 10 plants used to determine straight line transportation distances.

For uniform waste GRP distribution within a circular intake area, the average straight line transportation distance of GRP to the recycling plant located at the centre is given as $\frac{2R}{3}$, where R is the intake radius. This straight-line distance was doubled to account for outbound and inbound journeys. The actual transport distance was found using Eq 12, which accounts for transportation via road networks not being direct [15].

$$\frac{Actual\ transport\ distant}{Straight\ line\ transportation\ distant} = 1.42 \tag{12}$$

Figure S4 gives the actual transportation distance for up to ten recycling plants in the UK which can be closely approximated by a power curve with an R^2 of 0.99.

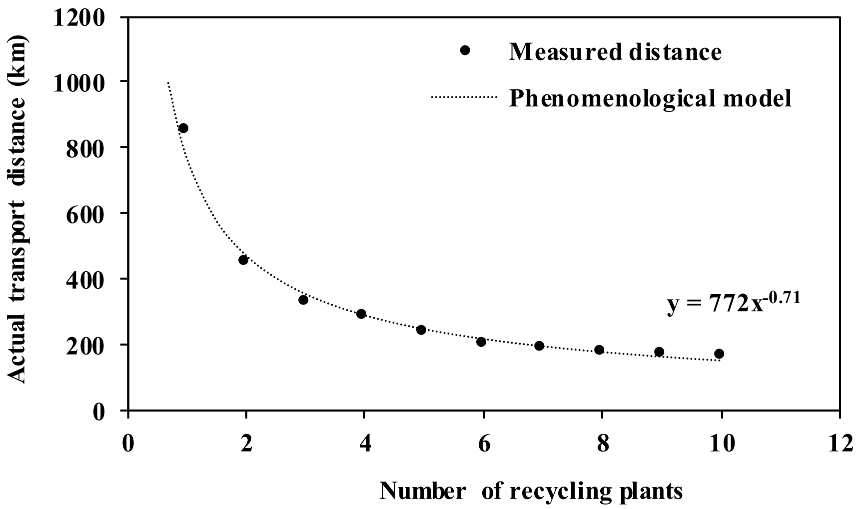

Figure S4. Measured and modelled transportation distances as a function of number of recycling plants.

Where there is a fixed total annual mass of GRP waste available, the plant capacity, defined as the annual GRP throughout of a single recycling plant, is also dictated by the number of plants. Using the power model in Figure S4, transport distance, number of recycling plants, plant capacity and total annual GRP waste mass can be expressed in Eq 13.

$$Actual\ transport\ distance = 772(No. of\ plants)^{-0.71} = 772\left(\frac{Total\ available\ annual\ GRP\ waste\ mass}{Plant\ capacity}\right)^{-0.71} \quad (13)$$

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