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The Effects of Glass Reinforced Plastic Disposal in Energy from Waste Plants

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Abstract

The production volume of fibre reinforced plastic (FRP) has increased massively since its initial creation and as such the volume of waste associated with these materials has also increased. As it stands the most prevalent means of disposal for waste FRP is by landfill, but as countries seek to divert waste material from landfill sites, pressure is mounting on industries to devise suitable and cost-effective disposal methods. Fibre reclamation technologies are currently being researched and show great promise but as of yet, no technologies are available at the scale which is necessary to combat the problem. Energy from waste (EfW) technology provides an alternative to landfill, by incinerating waste it is possible to reclaim a portion of the energy expended on its creation, whilst dramatically reducing the volume of said waste.

This report investigates the effect on EfW when glass reinforced plastic (GRP is added into the waste stream. Using a complex mathematical model, the potential effect on outputs from EfW such as power generation capability, energy efficiency, bottom ash production and greenhouse gas emissions are analysed. To add robustness, several forms of GRP materials are investigated at various fibre concentrations. The key findings include that a decrease in CO₂ emissions can be seen with all GRP materials investigated and that different compositions of GRP can have profoundly different effects on the systems energy generation capabilities.

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Table of Contents

1.0	Introduction	14
2.0	Objectives & Scope.....	17
3.0	Literature Review	18
3.1	Composite recycling.....	18
3.1.1	Emerging Technologies.....	18
3.2	Energy from Waste	20
3.2.1	Description of process.....	20
3.2.2	State of technology.....	25
3.2.3	Composites in EfW.....	25
3.3	Incentives & Barriers.....	26
4.0	Methodology	27
5.0	Method.....	27
5.1	Model Construction.....	27
5.1.1	Energy Density.....	28
5.1.2	Air Requirements.....	30
5.1.3	Boiler Power	34
5.1.4	Turbine Power	36
5.1.5	Useful Heat	36
5.1.6	Additional Losses	37
5.2	Bottom Ash	38
5.3	Emissions	39
5.4	Matrix Materials	40
6.0	Sensitivity Analysis.....	42
6.1	Introduction	42
6.2	Effect of Air Temperatures on Net Efficiency	42
6.1	Boiler Efficiency	44
6.2	Effect of Air Temperatures on Fan Power Requirements	44
6.3	Turbine Efficiency effect on Net Efficiency in a CHP System.....	45
6.4	Ambient and Primary Air Preheat Temperatures	46
7.0	Results & Discussion	48
7.1	Introduction	48
7.2	Assumptions & Limitations.....	48
7.3	Energy Content of Matrix Materials.....	49

7.4	GRP Resin Comparison.....	49
7.5	Potential Emissions related to GRP incineration.....	51
7.5.1	CO2 Production.....	51
7.5.2	NOx Production.....	56
7.5.3	Summary.....	58
7.6	Bottom Ash.....	58
7.7	Investigation into Common GRP Formations.....	59
7.7.1	Energy Density.....	60
7.7.2	Bottom Ash.....	60
7.7.3	Emissions.....	61
7.7.4	Energy Generation.....	62
7.8	Comparison of emissions with traditional energy generation methods and grid.....	63
8.0	Conclusions.....	65
9.0	Further Study.....	66
10.0	References.....	67
11.0	Appendices.....	72
11.1	Appendix 1 – Superheated Steam Enthalpy Table (56).....	72
11.1	Appendix 2 – Specific Heat Capacity of Air (56).....	72
11.2	Appendix 3 – Air density table (56).....	73

List of Figures

Figure 1 - Wind turbine blade fragments being buried in Wyoming, USA (3).	14
Figure 2 - Waste hierarchy (8)	16
Figure 3 - Common FRP fibre recovery technologies	18
Figure 4 -- Example layout of an EfW incineration plant (18).....	21
Figure 5 - Schematic of a reciprocating grate (19)	22
Figure 6 - Simplified schematic of a CHP EfW system showing all major components necessary for modelling.....	28
Figure 7 – Air temperature Vs. net efficiency, showing decline in efficiency at higher boiler outlet temperatures and lower furnace temperatures	42
Figure 8 – Air temperature vs. net efficiency, axes switched to show extreme effect of changing furnace temperature	43
Figure 9 - Effect of boiler efficiency on fan power requirements, showing increase in fan power as boiler efficiency increases alongside an increase in useful energy extraction.....	44
Figure 10 - Effect of changing air temp after boiler on fan power requirements, indicating improved fan efficiency at higher furnace temperatures.....	45
Figure 11 - Effect of turbine-generator efficiency on power generation, showing no impact on overall efficiency.....	46
Figure 12 - Effect of changing air regeneration temps on energy extraction from useful heat	47
Figure 13 – Calorific value comparison of GRP at varying matrix content. ..	50
Figure 14 - Comparison of energy density with matrix fraction and GRP/MSW fraction for polyester resin GRP, showing decline in overall calorific value with decreased matrix content.	50
Figure 15 - Effect of GRP combustion at 50% matrix on CO ₂ production....	52
Figure 16 - Effect of GRP combustion at 75% matrix on CO ₂ production of mixed waste.....	52
Figure 17- Rate of change in CO ₂ production and calorific value for polyester GRP at a matrix fraction of 75%.....	53
Figure 18- Rate of change in CO ₂ production and calorific value for polyester GRP at a matrix fraction of 25%.....	53
Figure 19- Rate of change in CO ₂ production of polyester GRP when matrix fraction is at minimum requirements to prevent loss in calorific value. Showing decreased CO ₂ production without adverse effect to calorific content of mixed fuel.....	54
Figure 20 - Decrease in CO ₂ production from adding GRP whilst maintaining overall energy density of mixed fuel.....	55
Figure 21 - Impact of 50% matrix GRP incineration on the production of NO ₂ furnace gases. Indicates that lower initial nitrogen content of fuels leads to lower NO ₂ emissions	56
Figure 22 - Impact of phenolic resin on NO _x production showing increased NO _x production when calorific value is maintained.....	57

Figure 23 - Impact of epoxy resin on NO _x production showing decreased levels of NO _x when calorific value is maintained.	58
Figure 24 - Bottom ash production at varying levels of matrix within GRP showing steep increase in ash production with decreased matrix content. ...	59
Figure 25 - Bottom ash production of common GRP constructions at different GRP/MSW fractions.	60
Figure 26 - CO ₂ production in common GRP constructions showing increased CO ₂ production in low matrix fraction constructions.	61
Figure 27- NO ₂ production in common GRP constructions showing gradual elimination of NO ₂ production in GRP constructions with no nitrogen content.	62
Figure 28 - Power Generation vs. GRP Content by GRP Type	62
Figure 29 - Net efficiency of EfW plant with addition of common GRP constructions showing steep decline in efficiency after around 30% bulk/sheet moulding compound is added to the mixed fuel source.	63
Figure 30 - GHG production comparison with traditional energy generation showing decrease in GHG emissions through addition of GRP	64

List of Tables

Table 1 - Common matrix compositions (37) (38) (39).....	40
Table 2 - Molar mass of elements (40)	40
Table 3 - Total elemental composition of resin types	41
Table 4 - Summary of set points for modelling.....	48
Table 5 - Energy content of matrix material from ultimate analysis.....	49
Table 6 - Maximum fibre mass fraction required to prevent lowering mixed fuel energy density.....	51
Table 7- Calculated figures show decrease in CO ₂ production at matrix fractions which do not decrease overall energy content of mixed fuel	55
Table 8 - Composition of common composite materials (48) (49) (50) (51) (52) (53) (54).....	59
Table 9 - Calorific value of common GRP constructions, the calorific value for MSW is 11.21MJ/kg	60

List of Equations

Eq. 1 – Waste throughput rate	28
Eq. 2 – Calorific content from elemental analysis “Modified Dulong’s Formula”	29
Eq. 3 – Conversion of Kcal/kg to GJ/t	29
Eq. 4 – Energy density of GRP	29
Eq. 5 - Combined energy density of mixed fuel source	30
Eq. 6 – Reactor energy output	30
Eq. 7 – Stoichiometric oxygen volume	31
Eq. 8 – Stoichiometric oxygen volumetric flow rate	31
Eq. 9 – Stoichiometric dry air volumetric flow rate	31
Eq. 10 – Stoichiometric wet air volumetric flow rate	32
Eq. 11 – Adjustment of volumetric flow rate to real air conditions using Charles’ law	32
Eq. 12 – Required excess air ratio	33
Eq. 13 – Actual volumetric flow rate with excess air.	33
Eq. 14 – Mass flow rate of primary air.....	33
Eq. 15 – Post combustion air volume.....	34
Eq. 16 – Mass flow rate of boiler working fluid.	35
Eq. 17 – Electrical output of turbine/generator	36
Eq. 18 – Energy extracted for regeneration	37
Eq. 19 – Available energy for useful heat extraction	37
Eq. 20 – Energy extracted as useful heat	37
Eq. 21 – Work done by fans.....	38
Eq. 22 – Mass of bottom ash generated by mixed GRP/MSW fuel.....	38
Eq. 23 – Annual carbon emissions from fuel source	39
Eq. 24 – adjusted carbon emissions to account for mixed fuel	39
Eq. 26 – adjusted NO ₂ emissions to account for mixed fuel	39
Eq. 27 - Example of calculation used to generate elemental composition of matrix materials.....	40

Nomenclature

<u>Symbol</u>	<u>Description</u>	<u>Units</u>
\dot{m}_{waste}	Waste throughput rate	<i>t/hour</i>
u_{fuel}	Calorific content of a fuel source	<i>GJ/tonne</i>
C	Carbon content	%
H	Hydrogen content	%
O	Oxygen content	%
N	Nitrogen content	%
u_{matrix}	Calorific content of matrix	<i>GJ/tonne</i>
u_{grp}	Calorific content of GRP	<i>GJ/tonne</i>
x_{matrix}	Fraction matrix within GRP	
x_{grp}	Fraction GRP within fuel source	
u_{msw}	Calorific value of MSW	<i>GJ/tonne</i>
u_{total}	Calorific content of GRP/MSW mixed fuel	<i>GJ/tonne</i>
$Q_{reactor}$	Energy through combustion	<i>MW</i>
$x_{unburnt}$	Unburnt fuel fraction	
$V_{O(stoich)}$	Stoichiometric oxygen volume requirements	<i>m³/kg</i>
$\dot{V}_{O(stoich)}$	Stoichiometric oxygen volume flow rate	<i>m³/hour</i>

$\dot{V}_{air(dry)}$	Stoichiometric volume flow rate of dry air	$m^3/hour$
$\dot{V}_{air(normal)}$	Stoichiometric volume flow rate of wet air (normal)	$m^3/hour$
AH	Absolute Humidity	$kg H_2O/kg air$
ρ_{air}	Density of dry air	kg/m^3
ρ_{H2O}	Density of water vapour	kg/m^3
$\dot{V}_{air(real)}$	Stoichiometric volume flow rate of wet air (real)	$m^3/hour$
η_{boiler}	Boiler efficiency	
λ	Excess air ratio	
Cp_{air}	Specific heat capacity of air	$kJ/kg K$
T_{inlet}	Temperature at boiler inlet	$^{\circ}C$
T_{outlet}	Temperature at boiler outlet	$^{\circ}C$
\dot{V}_{air}	Volumetric flow rate with excess air	$m^3/hour$
$\dot{m}_{air(intake)}$	Mass flow rate of air at intake	kg/s
V_{CO2}	CO ₂ volume within combustion gas	m^3
V_{SO2}	SO ₂ volume within combustion gas	m^3
V_{N2}	N ₂ volume within combustion gas	m^3
V_{H2O}	Water volume within combustion gas	m^3
$V_{excess O2}$	O ₂ volume within combustion gas from excess air	m^3
w	Fuel water content	$\%$

\dot{m}_{boiler}	Mass flow rate of working fluid through the boiler	kg/s
h_{out}	Enthalpy at boiler outlet	kJ/kg
h_{in}	Enthalpy at boiler inlet	kJ/kg
W_{elec}	Electrical power generated	MW
Q_{boiler}	Energy recovered in boiler	MW
$\eta_{turbine/generator}$	Total direct efficiency of the turbine/generator	
Q_{regen}	Energy extracted for preheating primary air	MW
Q_{cond}	Energy content at inlet to condenser	MW
Q_{heat}	Useful heat exported	MW
ΔP	Sum of pressure drops across the system	Bar
\dot{V}_{fan}	Volumetric flow rate of air across the fan	$m^3/hour$
W_{fan}	Work done by the fan	MW
$m_{bottom\ ash}$	Mass of post-combustion bottom ash	$Tonnes$
C_{MSW}	Carbon content of MSW	$\%$
C_{GRP}	Carbon content of GRP	$\%$

1.0 Introduction

By design, fibre reinforced polymers (FRP's) are necessarily resistant to degradation from mechanical, thermal, and chemical processes. These materials provide massive design benefits for a large array of applications and have allowed designers to create larger and lighter structures than it is possible to create from traditional materials such as metal or wood. It therefore stands to reason that since the advent of FRP's, their popularity has grown steadily. In the UK alone, over 100,000 tonnes of glass fibre reinforced plastics (GRP) are currently produced every year (1).

The popularity of these materials has led to a dilemma regarding the nature in which they are disposed. During the early years, little consideration was given to the end of life of FRP's and now as their prevalence increases, as does the need to create viable options for their disposal. Currently, around 67% of all GRP waste (the most common form of FRP waste) processed is sent to landfills or dedicated burial sites similar what is shown in figure 1. Only around 2% of GRP is incinerated and 19% is reused or recycled (2).



Figure 1 - Wind turbine blade fragments being buried in Wyoming, USA (3).

As outlined by CompositesUK (1) in their 2018 circular economy report, the UK currently generates an estimated 6,200 tonnes of GRP production waste per year and 75,000 tonnes of further waste attributed to end of life GRP. A further 1,600 can be accredited to production waste from carbon fibre reinforced plastic (CFRP)

manufacturing and although there is a negligible quantity of CFRP currently generated from end of life products, this is set to change to several thousand tonnes per year in the coming years – as waste from decommissioning within the aerospace and automotive industries begins to become more prevalent. The volume of waste is set to increase considerably in the future as GRP from today's wind power industry reaches decommissioning age (1). As of 2018 approximately 118,000 tonnes of GRP is produced annually (1), all of which will eventually require disposal.

As the EU looks to reduce the volume of municipal waste which is sent to landfill to 10% by 2030 (4), options for the reclamation and reuse of FRP waste are currently being researched intensively and whilst there are potential technologies -such as fluidised bed, pyrolysis and chemical recovery technologies – emerging, there are currently no plants operating at the scale necessary to process the levels of FRP required to meet these targets.

The polymer matrix of an FRP generally has a calorific value of around 30MJ/kg which is comparable to fossil fuels used in traditional energy generation (5,6). This means that there is scope for energy reclamation through incineration of these waste products in energy from waste (EfW) plants, in fact this method is already being employed on a limited scale.

Energy reclamation through incineration is not an ideal method of recycling - there is an argument that it should not be considered a recycling technology at all and that EfW plants may discourage alternative forms of material recycling (7). Much of the problems associated with traditional fossil fuel energy generation are still present within this technology such as the emission of greenhouse gases, particulate matter, and other environmentally harmful substances.

Figure 2 displays the hierarchy of waste management, in descending order of desirability from top to bottom. As can be seen from the image, energy recovery is one of the least desirable options for waste management, second only to disposal.

The reality is that there will always be some degree of waste which cannot be dealt with by any other means than energy recovery or disposal.



Figure 2 - Waste hierarchy (8)

This study sets out to investigate the impacts of adding or increasing GRP waste within the waste streams currently employed in EfW plants using a thermodynamic modelling technique. The model is designed to provide a better understanding of the effects which an increased use of this disposal method has on the operation of pre-existing plants, the emissions which the plants generate and the waste streams generated by the plants themselves in the form of grate ashes. These results can then be used as a comparison for other disposal techniques which look to increase process efficiency by recovering materials from FRP.

2.0 Objectives & Scope

The aim of this project is to present insightful information regarding the impact which the addition of GRP into an EfW waste stream will have with regards to the operational performance of a combined heat and power (CHP) EfW plant. This includes the plants ability to generate power; the production of waste materials such as bottom ash and the level of environmentally harmful gases emitted from the plant. Parallel to these aims, the report will investigate how different materials used in the creation of GRP affect these parameters.

The objectives are as follows:

- Perform a literature review to gather pertinent information regarding the current state of GRP waste management within the UK and the EU.
- Gather information regarding competing technologies as a potential alternative to GRP incineration in EfW plants.
- Thoroughly research the EfW process and gather technical information which will aid in the modelling process.
- Create a working mathematical model of an operational EfW plant using data gathered during the research phase of the project, the model should be easily manipulated and include outputs regarding energy generation ability and waste and emission production.
- Perform a robust sensitivity analysis on all adjustable parameters to identify which parameters influence the performance of the system to the greatest degree.
- Use justified parameters to generate useful data regarding the performance of the EfW system at different degrees of GRP/MSW fraction and for different GRP materials.
- Apply a case study to the model to see the impact of common GRP formations on the EfW system.
- Produce a list of clear conclusions and suggest areas of further study.

3.0 Literature Review

3.1 Composite recycling

GRP composites have been used in the construction of various components since the 1930's due to various advantages over classical materials such as metals and wood (9). The weight savings involved by moving to composite technologies allowed the aviation industry to build larger and more efficient airplanes for commercial air travel. Over time, advances in these materials have piqued the interest of engineers for applications in a wide array of products including within the energy, maritime and automotive industries.

It is estimated that around 1.69 gigatonnes of GRP was generated in Europe in 2015 and that this number was set to increase annually by 5.4% between 2015 and 2020 (10). GRP waste in Europe at the end of 2015 had reached 304,000 tonnes/year (10) and by 2020, the UK generated around 100,000 tonnes of GRP waste annually (1). The most common disposal techniques are landfilling and incineration (10), with the former accounting for around 67% of GRP processed in the UK (2).

3.1.1 Emerging Technologies

EU initiatives have become increasingly stringent with regards to curbing the use of landfills, among other things this has helped drive research into potential recycling technologies for FRP, some of which are presented in figure 3 (11). These technologies can largely be grouped into three categories from which, there are several emerging strategies. It should be noted that as it stands, there are little to no large-scale plants providing cost effective applications of these processes (12).

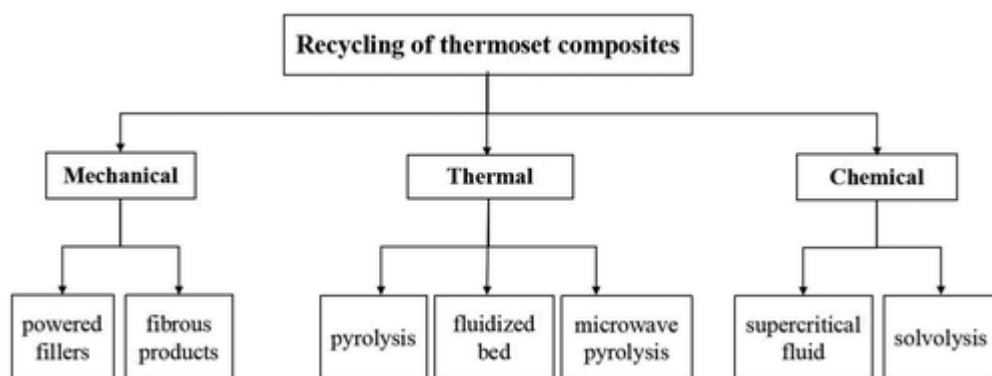


Figure 3 - Common FRP fibre recovery technologies

3.1.1.1 Mechanical Recycling

Mechanical recycling generally involves milling FRP waste into fine powders or shredding the waste which can then be reused as reinforcing filler in raw materials such as cements (13). The process is a relatively low-cost option however much of the beneficial properties of the initial FRP are lost as a result and therefore the products of the process are of a greatly diminished value. Ribeiro et al postulate that mechanically recovered GRP pultrusion wastes can contribute to increased material strength when used as a replacement for traditional filler or aggregates in cement production (10).

3.1.1.2 Thermal

Thermal recycling is a blanket term for recycling methods which use heat energy to recover the fibre content of a material whilst sacrificing the polymer matrix. EfW does not qualify as a thermal recycling process as although some energy is recovered within an EfW plant, the material constituents of the original FRP are lost. Common methods in development currently include pyrolysis, microwave pyrolysis and fluidised bed recycling.

In the pyrolysis recycling method the resin matrix of the FRP is heated to a high temperature within an oxygen free environment, leading to the gasification of the resin without causing significant damage to the fibres (13). CFRP recovered using this method has been shown to retain 90% of its original strength, the results for glass fibre recovered using this strategy are less successful, with only around 20% of the strength retained (13,14). Coupled with the loss in strength, the relative low cost of glass fibres is likely to have an impact on the uptake of pyrolysis for glass fibre recovery.

The fluidised bed process passes hot air through a bed of sand (silica) at a high velocity, essentially turning the sand into a fluid (14). Chopped FRP waste is placed within the reactor where the polymer matrix is decomposed, the remaining fibres are blown from the reactor and collected.

3.1.1.3 Chemical

Chemical recycling refers to the recovery of material from FRP by use of chemical agents and solvents. Chemical recycling has been shown to be more effective though more difficult and expensive than mechanical recycling. Frontrunners within this branch of technology include supercritical fluid recovery and solvolysis.

Supercritical fluid recycling involves placing waste material within a fluid – generally water or alcohol – which is raised to a pressure and temperature wherein the fluid becomes supercritical, therefore exhibiting properties of both a liquid and a gas. Whilst in this state, the supercritical fluid displays a high degree of solubility and can decompose polymers into their constituent parts - this method can therefore recover not only the fibre content of the waste material but also to a degree, components of the polymer matrix (13). This method has been shown to have excellent matrix removal ability with very little degradation in the recovered fibres – as high as 99% of the original strength for recovered carbon fibre.

Solvolytic is the method of depolymerising the matrix fraction of FRP using chemical solvents such as nitric acid. The toxicity of solvents and their relative cost call into question the level of sustainability which these processes can operate at (13). Nevertheless, the process shows a good matrix removal ability with losses in strength of recovered carbon fibre as low as around 1%.

3.2 Energy from Waste

EfW technologies convert MSW into energy through incineration, much in the same way as conventional fossil fuel energy technologies (15), the heat generated in incineration is used to power a traditional Rankine steam cycle. Unlike traditional fossil fuels, the MSW fuel source is largely heterogeneous and there are additional issues which must be considered in an EfW plant such as ensuring that the waste is sufficiently mixed to create as uniform an energy source as possible (15).

In the UK in 2009, around 500kg of MSW was generated per person per year, roughly half of which was sent to landfill (15). There is reason to consider that although landfill and incineration are both low on the hierarchy of recycling, landfill has the larger ecological impact (16). Incineration generates a high volume of greenhouse gases but energy regenerated from waste displaces emissions from other fossil fuel generation methods on the grid whilst reducing emissions caused from landfill sites simultaneously by eliminating the need for landfill (16).

3.2.1 Description of process

A basic example of the layout of an EfW plant is shown in figure 4. EfW plants will differ in some aspects but all essentially abide to the same basic principles outlined (17):

- Waste is collected and stored within the plant.
- Waste is then combusted to release the internal chemical energy and produce heat
- The energy produced during combustion is converted into a transportable energy source, usually in the form of electricity and heat.
- Emissions from the combustion process are dealt with, this includes waste gases and bottom ash which requires further processing to ensure minimising environmental impact

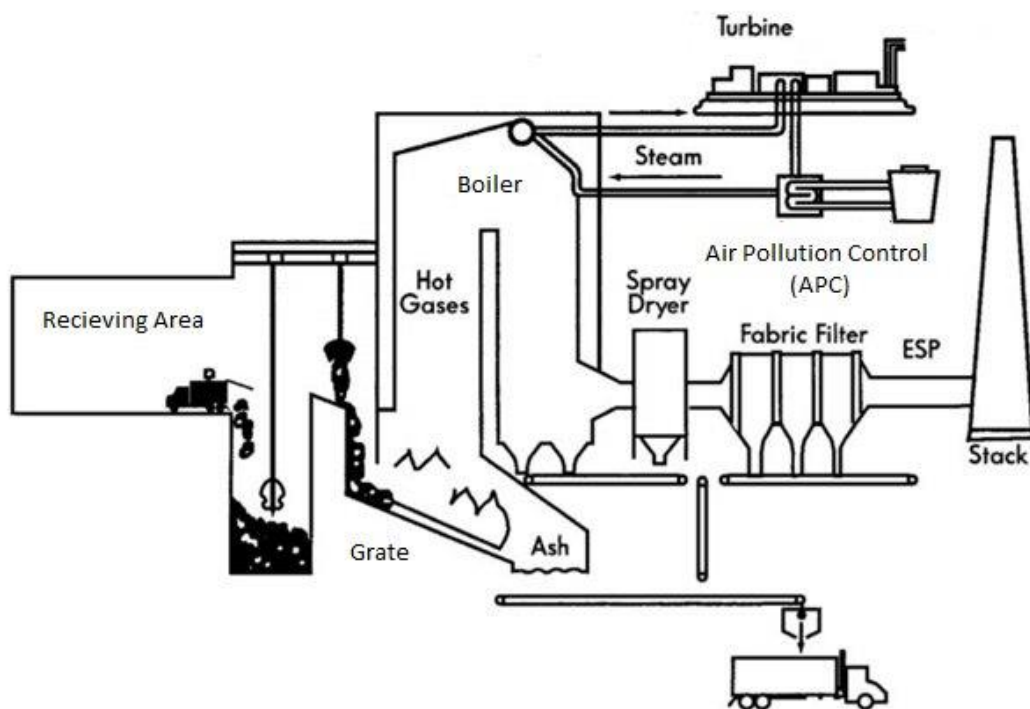


Figure 4 -- Example layout of an EFW incineration plant (18).

3.2.1.1 Waste storage

MSW is delivered to the EFW facility by the same means as when delivered to landfill – usually directly by the refuse collection vehicle. The waste is deposited onto the tipping floor from which it is transferred to a storage pit (6). Like traditional energy generation, EFW plants operate as continuous a process as possible and therefore a 4 day supply of fuel is generally present to ensure this (19). Combustion air is generally drawn from the storage pit to maintain a negative pressure and help contain fumes and odour.

Mixing is an important process prior to combustion. MSW is a heterogeneous fuel source with the energy content varying highly from one household to another and

mixing ensures as uniform an energy source as possible therefore reducing complications in the combustion process (15). Mixing also helps to dry the MSW which also aids in combustion. The moisture content of MSW is between 25%-40% of its mass requires evaporation before the waste can be successfully incinerated – although mixing helps in this process the majority of this drying occurs within the furnace (6).

An overhead crane is in place for a multitude of purposes. As well as mixing the fuel, it is used to feed the fuel into a hopper and charge the furnace (19).

3.2.1.2 Combustion

The combustion of waste takes place in stages over the course of 45-60 minutes. After entering the furnace, the waste must first dry for combustion to take place. Following this the fuel source ignites and is gradually burnt out as it moves through the furnace.

The most common means of transporting burning waste through the furnace is via a moving grate (20). Moving grates can come in various constructions including reciprocating grate as shown in figure 5 which moves waste along the furnace using reciprocating pushing motion. At the end of the furnace, bottom ash is usually deposited into a quenching pit to reduce its temperature before being moved for further processing and transportation.

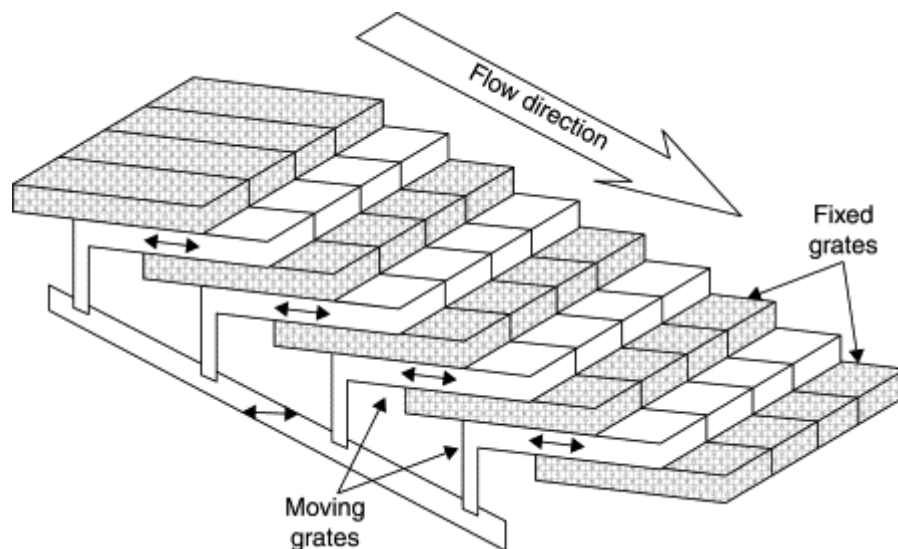


Figure 5 - Schematic of a reciprocating grate (19)

Air is introduced into the furnace in two locations. Primary (under fire) air is blown up through the grate system, the advantages here are twofold as the air helps to cool the moving grate system as well as forcing air into the fuel source which aids

combustion (21). Secondary (over fire) air is added above the combusting waste to ensure full oxidisation of gases released by increasing oxygen availability and by creating turbulence in the furnace air flow. The air flow then forces hot gases to the boiler stage of the EfW plant. The minimum rate at which air must be added to ensure complete combustion can be calculated from the elemental analysis of the fuel source although excess air is usually required to ensure enough oxygen is available and to control temperatures within the furnace system (19).

3.2.1.3 Boiler system

A boiler is a requirement of an EfW plant in order to convert the heat generated in during combustion into energy within a useful working fluid. Energy transferred in the boiler is used to power a traditional Rankine steam cycle. The efficiency of a boiler in an EfW plant is lower than that of traditional energy plants due to temperature and pressure limitations imposed to prevent corrosion associated with affluent products of MSW combustion, plants usually operate with a steam boiler pressure of around 40 bar and a temperature of around 400°C resulting of boiler efficiencies in the area of 83% (15,22).

3.2.1.4 Energy utilisation

EfW incinerator plants typically operate in one of three modes: electricity generation only; heat generation only or combined heat and power generation.

In electricity only operation, the steam generated in the boiler drives a turbine which is connected to an electrical generator. The power generated is transported to the grid much like a traditional power plant however due to low operating temperatures and pressures, the thermal efficiency of electricity only EfW plants is around 25%-30% (15), for reference a traditional thermal plant can operate at a thermal efficiency of over 35% (23) .

In heat only mode there is no turbine present, instead the heat energy transferred is utilised for domestic or commercial heating use. CHP mode utilises both electrical generation and a useful heat output thereby extracting more energy and increasing the overall efficiency of the system to as high as 85% when prioritising heat production (24).

3.2.1.5 Emission control

MSW is a chemically complex fuel source and as such the potential for post combustion gases to contain environmentally damaging and toxic pollutants is

significant. These materials include among others: particulate matter; nitrogen oxides (NO_x); sulphur dioxide; hydrogen chloride; heavy metals; and other organic compounds which have a negative impact on the environment. Emission controls are therefore an essential part of the EfW process (20).

Flue gas can be used in order to limit the levels of nitrogen present within the combustion furnace, limiting the potential for the formation of nitrogen oxides (20). This has the added advantage of lowering the level of primary air needed to maintain air flow through the system. Nitrogen oxide levels can be lowered further with the use of selective and non-selective catalytic reduction wherein a reagent – predominantly urea or ammonia – is added to the flue gas to react with and lower the level of nitrogen oxide pollutants. Effective application of catalytic reduction methods can lower NO_x emissions by 90%.

Acid gases such as sulphur dioxide and hydrogen chloride can be removed by a process of wet scrubbing with hydrated lime (20). The hydrated lime is sprayed into a tall tower through which flue gas is passed, reacting with acid gases and removing them from the flue gas. The spent lime can then be collected and recycled for use in building materials.

Heavy metals like lead and mercury are removed from the flue gases through the addition of fine particles of activated carbon into the gas stream. The metals present in the gas attach to the carbon particles and are filtered from the carbon through a particle filter.

Particulates have been proven to cause damaging to human health when inhaled (20). There are several tactics employed to remove particulate matter including the use of an electrostatic precipitator which uses high voltages passed through oppositely charged plates, inducing a static charge in the particulate matter, causing it to stick to the plates. The plates are regularly cleaned by mechanical rapping causing the particulate matter to fall to the bottom of the device where it is collected (25).

3.2.1.6 Bottom Ash

Bottom ash is generated at a rate of between 0.15-0.25 tonnes for each tonne of MSW incinerated (26) although the volume is reduced by around 90% (15). Metals present within the ash are removed for resale as scrap. Ferrous metals are processed using magnetic separation and more valuable non-ferrous metals such as aluminium and copper can be removed using eddy current separation.

The utilisation of bottom ashes varies heavily from country to country (26). The ash itself has been shown to behave in a similar manner to traditional building materials and is often used in countries such as the UK, Belgium and The Netherlands in the construction of roads, the latter two countries recycling over 90% of EfW bottom ash.

3.2.2 State of technology

As of 2018, there are 58 EfW plants operating in the UK which in 2018 generated 3.6TWh of energy, this value increased 5.5% from the previous year (27). This upward trend can be seen throughout the whole of the century – in 2005 there were only 22 waste incinerators in the UK (15).

The majority of EfW plants operate with electrical energy recovery only which - given the limitations on boiler temperature and pressure arising from corrosion issues - operate at a low efficiency relative to traditional generation methods (15), generally EfW plants have an electrical efficiency of between 18% and 25% although more modern plants have managed to increase efficiency to above 30% (15). In comparison, coal and oil powered generation can reach electrical efficiencies of around 37% (28).

Plants operating in combined heat and power (CHP) mode can increase the overall plant efficiency to as much as 60% by utilising waste heat which would otherwise be lost to the environment in the condenser (15,29). The implementation of such a plant requires the necessary heat distribution infrastructure to deliver the useful heat extracted to the end user, this can be in the form of a district heating network.

3.2.3 Composites in EfW

Little information was found regarding the implications of introducing FRP into the waste stream of EfW plants, though Composites UK suggest that GRP can be sent to EfW plants and that the bottom ash from plants can be used in the production of aggregates and in construction applications (4).

The effectiveness of adding GRP to EfW fuel is largely dependent on the proportion of matrix material to fibre and filler within the composite (30). The polymer matrix of GRP has a high calorific value but fibre and filler are inorganic and therefore incombustible, if said material has a high fibre and filler content relative to the matrix material then the overall energy content per unit mass is diminished (30).

A recommendation was made to prepare fuel with a 10% blend of GRP to MSW (31), Unfortunately further details on the original study are unavailable to the author as it was published in Swedish and unobtainable online at the time of writing although, it is referenced in a further study (31).

3.3 Incentives & Barriers

The UK regards EfW as a better option than landfill so long as the plant is efficient and that the waste incinerated has a high enough renewable fraction (17). The UK therefore offers grants to EfW developers in order to aid the diversion of waste from landfill sites.

The EU acknowledges the role which EfW plays in aiding a transition to a circular economy and leaves decisions regarding the implementation of EfW to member states while suggesting countries with high reliance on landfill seek to implement measures to curb this (32).

4.0 Methodology

Following a thorough literature review, it was deemed necessary to generate a representative mathematical model of an EfW plant as a means of calculating potential outputs from the plant when GRP was added into the fuel stream. A mathematical model has the advantage of allowing a system to be analysed without the time and cost restraints associated with a physical analysis of the system.

Microsoft Excel was selected as suitable software for the purpose of mathematical modelling. The model uses the established laws of thermodynamics where possible although prior proven modelling techniques which have been uncovered within the literature review have been used at times, such as the use of Dulong's formula to gather data regarding the calorific value of a fuel source.

Once the model had been successfully created, a sensitivity analysis was carried out to ascertain which variables had the greatest effect on the performance of the system and therefore minimise uncertainties. The outputs from the sensitivity analysis are verified against observed data. Results were generated by changing variables pertaining to several aspects of GRP itself and the concentration of GRP within a mixed EfW fuel source. These variables were changed independently to see the effect on the outputs being investigated.

5.0 Method

5.1 Model Construction

A visualisation of the construction of the EfW plant model can be seen in figure 6. This represents a simplified version of a CHP EfW plant for the purposes of modelling. In reality the plant will be much more complex than this, for example, the turbine may be made up of several stages of varying pressure, each stage may have steam re-entering the boiler section to maximise efficiency. This project aims however to take a more generalised approach to the EfW model by reducing the system down to its key elements.

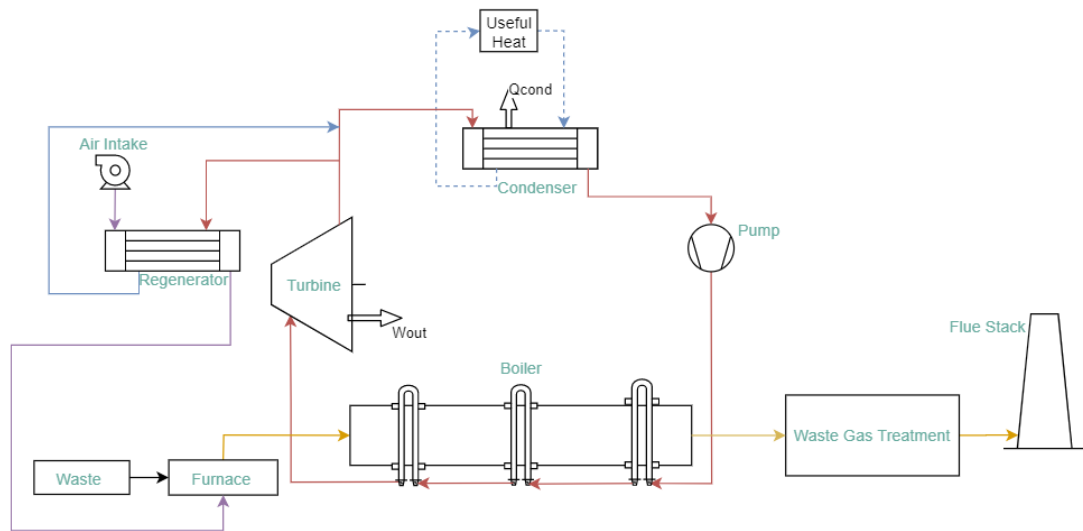


Figure 6 - Simplified schematic of a CHP EfW system showing all major components necessary for modelling.

5.1.1 Energy Density

Plant capacity & operational hours are first selected, from which the required waste throughput is then calculated, these values can be changed according to requirements. Eq. 1 shows the calculation used, for the purpose of this investigation, 8000 annual operational hours were assumed:

$$\dot{m}_{waste} = \frac{\text{Annual Plant Capacity (tonnes)}}{\text{Annual Operational Hours}} \quad t/\text{hour}$$

Eq. 1 – Waste throughput rate

Where:

$$\dot{m}_{waste} = \text{Mass flow rate of waste}$$

The ultimate analysis of MSW & GRP Matrix material is entered. This is presented as a proportional elemental breakdown of the materials in use. As there are several potential GRP resin materials available, the study considers 4 of these materials which can be entered according to requirements. Garg, A. et al provide the elemental analysis of MSW in the UK which is used in this study (33).

The calorific content of MSW & Polymer Matrix is calculated using a modified “Dulong’s Formula” (34) which is shown in Eq. 2. The calorific value generated is shown to correlate with reported calorific values (35).

$$u_{fuel} = -2762.68 + 114.63C + 310.55H \quad kcal/kg$$

Eq. 2 – Calorific content from elemental analysis “Modified Dulong’s Formula”

Where:

u_{fuel} = Calorific content of the fuel source

C = Carbon fraction of fuel source

H = Hydrogen fraction of fuel source

This is then converted to GJ/t using Eq. 3.

$$1Kcal/kg = \frac{4.184}{1000} GJ/t$$

Eq. 3 – Conversion of Kcal/kg to GJ/t

The calorific value of the matrix of the composite does not represent the calorific value of the GRP, as there is an inorganic fraction made up from fibre and filler content. The addition of fibre-filler to a GRP lowers the overall calorific content as it is inorganic and incombustible.

The energy density of the whole composite is then calculated in Eq. 4, accounting for the inorganic fraction:

$$u_{grp} = u_{matrix} \cdot x_{matrix} \quad GJ/t$$

Eq. 4 – Energy density of GRP

Where:

u_{grp} = Calorific value of GRP

u_{matrix} = Calorific value of matrix material

x_{matrix} = Fraction of matrix/fibre-filler

The fraction of MSW to waste can now be entered into Eq. 5, allowing the overall calorific value of the mixed fuel source to be calculated.

$$u_{total} = u_{grp} \cdot x_{grp} + u_{msw}(1 - x_{grp}) \quad GJ/t$$

Eq. 5 - Combined energy density of mixed fuel source

Where:

- u_{total} = Calorific value of the combined fuel source
- x_{grp} = Fraction at which GRP is added to the fuel source
- u_{msw} = Calorific value of MSW

The reactor energy output calculation is shown in Eq. 6. At this point the unburnt fraction of the fuel source is accounted for as it will have an effect on the ability of the furnace to convert the fuel source into useful energy.

$$Q_{reactor} = \frac{u_{total} \cdot \dot{m}_{waste} \cdot (1 - x_{unburnt})}{3.6} \quad MW$$

Eq. 6 – Reactor energy output

Where:

- $Q_{reactor}$ = Energy generated by the furnace
- $x_{unburnt}$ = Unburnt fuel fraction

5.1.2 Air Requirements

The overall elemental analysis is calculated based on the ultimate analysis of both MSW and Matrix material and the fraction of each within the waste flow rate. From this, the combustion gas requirements are calculated in Eq. 7-15. First the stoichiometric oxygen volume requirements at normal conditions (1 bar, 0°C, Dry.) is calculated.

$$V_{O(stoich)} = 22.41 \cdot \left(\frac{C}{12} + \frac{H}{4} + \frac{S - O}{32} \right) \text{ m}^3/\text{kg fuel}$$

Eq. 7 – Stoichiometric oxygen volume

Where:

$V_{O(stoich)}$ = Stoichiometric oxygen volume requirements

C = % Carbon in fuel source

H = % Hydrogen in fuel source

S = % Sulphur in fuel source

O = % Oxygen in fuel source

The stoichiometric oxygen volumetric flow rate is dependent on the waste throughput.

$$\dot{V}_{O(stoich)} = V_{O(stoich)} \cdot \frac{\dot{m}_{waste}}{1000} \text{ m}^3/\text{hour}$$

Eq. 8 – Stoichiometric oxygen volumetric flow rate

Where:

$\dot{V}_{O(stoich)}$ = Stoichiometric oxygen volume flow rate

The stoichiometric volumetric air flow rate can then be calculated, assuming that Oxygen accounts for 20.9% of atmospheric air

$$\dot{V}_{air(dry)} = \frac{\dot{V}_O}{0.209} \text{ m}^3/\text{hour}$$

Eq. 9 – Stoichiometric dry air volumetric flow rate

Where:

$\dot{V}_{air(dry)}$ = Stoichiometric volume flow rate of dry air

This air flow rate must be modified to account for moisture within the ambient air. As the density of water vapour is lower than that of dry air, the volumetric air flow requirements increase with humidity. For simplicity, this study assumes a constant absolute air humidity of 0.01 kgH₂O/kgAir, which is the value present at 25°C and 50% relative humidity. The air flow rate is adjusted using the following formula:

$$\dot{V}_{air(normal)} = \dot{V}_{air(dry)} \left(1 + AH \frac{\rho_{air}}{\rho_{H_2O}} \right) \text{ m}^3/\text{hour}$$

Eq. 10 – Stoichiometric wet air volumetric flow rate

Where:

$\dot{V}_{air(normal)}$	= Stoichiometric volume flow rate of wet air (normal)
AH	= Absolute Humidity
ρ_{air}	= Density of dry air
ρ_{H_2O}	= Density of water vapour

The value is then adjusted using Charles' Law to the actual ambient air intake temperature which is set by the model operator.

$$\dot{V}_{air(real)} = T_{air(real)} \frac{\dot{V}_{air(normal)}}{T_{air(normal)}} \text{ m}^3/\text{hour}$$

Eq. 11 – Adjustment of volumetric flow rate to real air conditions using Charles' law

Where:

$\dot{V}_{air(real)}$	= Stoichiometric volume flow rate of wet air (real)
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In reality, a furnace will operate with a surplus of air to ensure that combustion is as complete as possible. The proportion of excess air to the stoichiometric air can be used to control parts of the combustion process including managing the temperature reached within the furnace.

The excess air required is calculated by determining the flow rate necessary to maintain set temperatures at both the inlet and outlet of a boiler with a given efficiency.

Using the boiler efficiency, the energy extracted is first calculated and then divided by the equivalent extraction which would occur at a stoichiometric air flow level in

the following equation. The specific heat capacity is extracted from a table shown in Appendix 2

$$\lambda = \frac{Q_{reactor} \cdot \eta_{boiler}}{Cp_{air}(T_{inlet} - T_{outlet}) \cdot \rho_{air} \cdot \dot{V}_{air(stoich)}}$$

Eq. 12 – Required excess air ratio

Where:

η_{boiler}	= Boiler efficiency
λ	= Excess air ratio
\dot{Q}	= Boiler energy (kW)
Cp_{air}	= Specific heat capacity of air
T_{inlet}	= Temperature at boiler inlet
T_{outlet}	= Temperature at boiler outlet

The actual volumetric air flow rate is then calculated using the excess air ratio.

$$\dot{V}_{air} = \lambda \cdot \dot{V}_{air(real)} \quad m^3/hour$$

Eq. 13 – Actual volumetric flow rate with excess air.

Where:

\dot{V}_{air}	= Volumetric flow rate with excess air
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The mass flow rate of the air at the intake is then calculated by multiplying the volumetric flow rate by the wet air density (appendix 3) at the intake.

$$\dot{m}_{air(intake)} = \frac{\dot{V}_{air} \cdot \rho_{air}}{3600} \quad kg/s$$

Eq. 14 – Mass flow rate of primary air

Where:

$\dot{m}_{air(intake)}$	= Mass flow rate of air at intake
ρ_{air}	= Air density at intake temperature

As a result of combustion, the mass flow rate of the air will increase as gases are released from the fuel source - this is important to calculate as it will affect the mass flow rate of gas over the boiler. Eq. 15 shows the method used to model the volume of combustion gases while including the addition of excess air.

$$\begin{aligned}
 V_{combustion} = & \underbrace{\left(22.41 \cdot \frac{C}{12}\right)}_{V_{CO_2}} + \underbrace{\left(22.41 \cdot \frac{S}{32}\right)}_{V_{SO_2}} + \underbrace{\left(22.41 \cdot \frac{N}{28}\right) + 0.79 \cdot \lambda \cdot V_{air}}_{V_{N_2}} \\
 & + \underbrace{\left(22.41 \cdot \left(\frac{H}{2} + \frac{W}{18}\right) + 1.61 \cdot \lambda \cdot x \cdot V_{air}\right)}_{V_{H_2O}} \\
 & + \underbrace{\left(0.21 \cdot (\lambda - 1) \cdot V_{air}\right)}_{V_{excess O_2}} \quad m^3/kg \text{ fuel}
 \end{aligned}$$

Eq. 15 – Post combustion air volume

Where:

V_{CO_2}	= CO ₂ volume within combustion gas
V_{SO_2}	= SO ₂ volume within combustion gas
V_{N_2}	= N ₂ volume within combustion gas
V_{H_2O}	= Water volume within combustion gas
$V_{excess O_2}$	= O ₂ volume within combustion gas from excess air
W	= Fuel water content

This is simply multiplied by the fuel throughput to calculate the volumetric flow rate within the furnace assuming normal conditions. Again, Charles' Law is used to calculate the true flow rate dependant on the required furnace temperature input.

5.1.3 Boiler Power

The boiler is assumed to operate at 40 bar and a temperature of 400°C, this is a common arrangement for a boiler in a MSW furnace due to restrictions arising from corrosion. The relatively low pressure and temperatures limit the power which can be generated from the turbine.

The steam table in appendix 1 shows that superheated water vapor leaves the boiler at an enthalpy of 3213.6 kJ/kg. Neglecting pump work at this stage, the enthalpy at the intake of the boiler is equal to that at the outlet of the condenser. Assuming that the fluid is a saturated liquid at a pressure of 0.08 bar, from steam tables then, the enthalpy at the boiler inlet is at 173.88 kJ/kg.

The amount of energy extracted by the boiler is set by multiplying the furnace power with the direct efficiency of the boiler which can be set by the model operator. This allows for the mass flow rate of water within the boiler/turbine system to be calculated as shown in Eq. 16.

$$\dot{m}_{boiler} = \frac{Q_{reactor} \cdot \eta_{boiler}}{h_{out} - h_{in}} \text{ kg/s}$$

Eq 16 – Mass flow rate of boiler working fluid.

Where:

\dot{m}_{boiler} = Mass flow rate of working fluid through the boiler

h_{out} = Enthalpy at boiler outlet

h_{in} = Enthalpy at boiler inlet

5.1.4 Turbine Power

Like the boiler, the turbine generator power is calculated using the overall efficiency of the component which can be multiplied by the power extracted in the boiler to calculate the overall electrical power as shown in Eq. 17.

$$W_{elec} = Q_{boiler} \cdot \eta_{turbine/generator} \quad MW$$

Eq 17 – Electrical output of turbine/generator

Where

W_{elec} = Electrical power generated

Q_{boiler} = Energy recovered in boiler

$\eta_{turbine/generator}$ = Total direct efficiency of the turbine/generator

5.1.5 Useful Heat

Following the extraction of electrical power, the remaining energy in the system is extracted for useful heat applications. A CHP plant such as the one modelled in this study exports this low-grade heat to be used for direct heating applications as part of a district heating system.

A primary air heater is also considered in this model. This part of the system pre-heats air being added to the furnace via a heat exchanger placed between the steam turbine outlet and the condensing heat exchanger.

The amount of energy extracted depends on the primary air heat requirements which can be set within the model. The energy extraction rate is dependent on the specific heat capacity of the air, for simplicity, this value is interpolated as the midpoint between the ambient air inlet temperature and the required primary air temperature from a datasheet (appendix 2).

The amount of energy extracted to heat the primary air can therefore be determined by Eq. 18:

$$Q_{regen} = \dot{m}_{air} \cdot C_{p_{air}} \cdot \Delta T \quad MW$$

Eq 18 – Energy extracted for regeneration

Where:

Q_{regen} = Energy extracted for preheating primary air

ΔT = Temperature difference between ambient and regenerated air

The energy content of steam entering the condensing heat exchanger is calculated in Eq. 19 as the energy content at the boiler outlet minus the energy extracted by the turbine and the energy extracted by the primary air pre-heater.

$$Q_{cond} = Q_{boiler} - W_{elec} - Q_{regen} \quad MW$$

Eq 19 – Available energy for useful heat extraction

Where:

Q_{cond} = Energy content at inlet to condenser

The remaining energy can then be collected using a condensing heat exchanger. The energy available is calculated using equation 20.

$$Q_{heat} = Q_{cond} - Q_{boiler\ inlet} = Q_{cond} - (\dot{m}_{boiler} \cdot h_{in}) \quad MW$$

Eq 20 – Energy extracted as useful heat

Where:

Q_{heat} = Useful heat exported

5.1.6 Additional Losses

In addition to losses incurred through component efficiencies, several other losses were considered. Losses from fan power were calculated using the fan power equation.

$$W_{fan} = \dot{V}_{fan} \cdot \Delta P \quad MW$$

Eq 21 – Work done by fans

Where:

- ΔP = Sum of pressure drops across the system
- \dot{V}_{fan} = Volumetric flow rate of air across the fan
- W_{fan} = Work done by the fan

The number of fans within the system are simplified to two fans, one for primary air (PA), and another for the induced draft (ID) fan. In reality, several separate fans would likely be in place for these two purposes.

Charles' Law is used to calculate the volumetric flow rate at the PA and ID fan locations. Choudhury, S. provides details on approximate pressure drops within a EfW system (36).

The losses from feedwater and wet scrubber pumps are given as a function of the waste throughput and heat losses are entered as a percentage of input energy.

5.2 Bottom Ash

Bottom ash in this context refers to the waste left after the combustion process is complete. For classic MSW power plants, around 20% of the original mass of waste is left following the incineration process as bottom ash. This ash contains a mixture of materials including metals as well as the unburnt fraction of combustible waste.

With the addition of GRP to the waste stream, this value will increase as GRP contains high levels on incombustible inorganic materials such as the glass fibres themselves and filler material which may also be added.

To calculate the effect of GRP addition on the bottom ash, the following Eq. 22 is applied.

$$m_{bottom\ ash} = 0.2(1 - x_{grp}) + x_{grp} [(0.2 \cdot x_{matrix}) + (1 - x_{matrix})] \quad tonnes/tonnes\ waste$$

Eq 22 – Mass of bottom ash generated by mixed GRP/MSW fuel

Where:

- $m_{bottom\ ash}$ = Mass of post-combustion bottom ash

The waste throughput is then used to calculate the effect on the system being modelled.

5.3 Emissions

Carbon emissions for a single fuel can be calculated using Eq. 23

$$Emmissions = C \cdot m_{fuel} \cdot \frac{44}{12} \text{ tonnes cabon/year}$$

Eq 23 – Annual carbon emissions from fuel source

This equation must be modified slightly as GRP and MSW have different carbon contents and are mixed at a pre-decided ratio, with GRP having an incombustible fraction as seen in Eq. 24.

$$Emmissions = \frac{44}{12} m_{fuel} [(1 - x_{GRP})C_{MSW} + x_{GRP} \cdot x_{matrix} \cdot C_{GRP}] \text{ tonnes cabon/year}$$

Eq 24 – adjusted carbon emissions to account for mixed fuel

Where:

C_{MSW} = Carbon content of MSW

C_{GRP} = Carbon content of GRP

In Eq. 25 the NO₂ emissions are also considered, they are adjusted according to their relative global warming potential to that of CO₂, this is assumed to be 1000%

$$Emmissions = 10 \cdot \frac{14}{46} m_{fuel} [(1 - x_{GRP})N_{MSW} + x_{GRP} \cdot x_{matrix} \cdot N_{GRP}]$$

tonnes NO₂/year

Eq 25 – adjusted NO₂ emissions to account for mixed fuel

5.4 Matrix Materials

The matrix compositions used in this analysis are shown in table 1. By using the molar mass of the chemical elements from table 2, it is possible to produce an ultimate analysis of the combined resin material from the mass fraction of each molecule within the cured resin.

	MOLECULE	FORMULA	MASS FRACTION
EPOXY RESIN	Bisphenol A diglycidyl ether (DGEBA)	C ₂₁ H ₂₄ O ₄	0.87
	Isophorone Dianmine (IPD)	C ₁₀ H ₂₂ N ₂	0.13
PHENOLIC RESIN	Phenol	C ₆ H ₆ O	0.69
	Formaldehyde	CH ₂ O	0.18
	Hexamine	C ₆ H ₁₂ N ₄	0.13
VINYL ESTER RESIN	DGEBA	C ₂₁ H ₂₄ O ₄	0.36
	BPA	C ₁₅ H ₁₆ O ₂	0.11
	Methacrylic acid	C ₄ H ₆ O ₂	0.09
	Styrene	C ₈ H ₈	0.44
	MEKP	C ₈ H ₁₈ O ₆	0.01
POLYESTER RESIN	Unsaturated polyester resin (UPR)	C ₁₈ H ₁₈ O ₉	0.59
	Styrene	C ₈ H ₈	0.40
	MEKP	C ₈ H ₁₈ O ₆	0.01

Table 1 - Common matrix compositions (37) (38) (39)

This is done by multiplying together the mass fraction, the number of a given element within the molecule and the molar mass of that element, then dividing by the total molar mass of the molecule. This process is repeated for each molecule present within the resin then summed.

ELEMENT	MOLAR MASS
CARBON	12
OXYGEN	16
HYDROGEN	1
NITROGEN	14

Table 2 - Molar mass of elements (40)

For example, the carbon content of epoxy – where there are 21 carbon molecules in DGEBA with a mass fraction of 0.87 and 10 carbon molecules in IPD with a mass fraction of 0.13 – is calculated in Eq. 26.

$$C = \frac{0.87 \times 12 \times 21}{340} + \frac{0.13 \times 12 \times 10}{170} = 73.66\%$$

Eq 26 - Example of calculation used to generate elemental composition of matrix materials

This is repeated for all resin types and elements to produce the elemental analysis shown in table 3.

	CARBON	OXYGEN	HYDROGEN	NITROGEN
EPOXY RESIN	73.66%	16.38%	7.82%	2.14%
PHENOLIC RESIN	66.84%	21.22%	6.72%	5.22%
VINYL ESTER RESIN	80.70%	12.87%	7.34%	0.00%
POLYESTER RESIN	71.09%	22.93%	5.97%	0.00%

Table 3 - Total elemental composition of resin types

6.0 Sensitivity Analysis

6.1 Introduction

A sensitivity analysis was undertaken to identify which areas of the model were most influenced by user input. This is an important stage to follow the model construction as it helps outline the nature of further modelling as well as testing the validity of the model itself. Each independent variable available to the user was changed in turn to generate a series of figures.

6.2 Effect of Air Temperatures on Net Efficiency

Changing the furnace and boiler outlet temperatures has a notable effect on the net efficiency of the plant. The net efficiency of the system is plotted against the boiler outlet temperature in figure 7. The graph indicates that efficiency is increased greatly by creating a higher temperature differential across the boiler. This is expected as the temperature drop is indicative of the energy transferred from the furnace gases to the working fluid within the boiler. A larger drop in temperature indicates a larger transfer of energy and therefore a more efficient system.

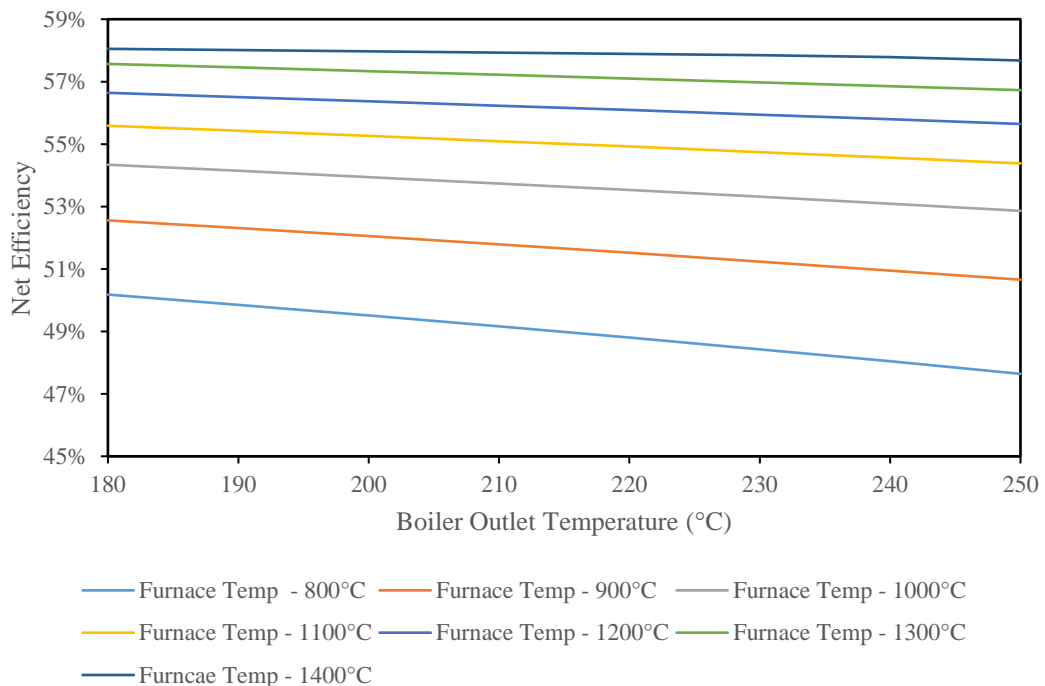


Figure 7 – Air temperature Vs. net efficiency, showing decline in efficiency at higher boiler outlet temperatures and lower furnace temperatures.

In figure 8, the net efficiency of the plant is plotted as function of furnace temperature for a range of boiler outlet temperatures. Changing the furnace temperature has a much more pronounced effect on the efficiency of the system than changing the boiler outlet temperature.

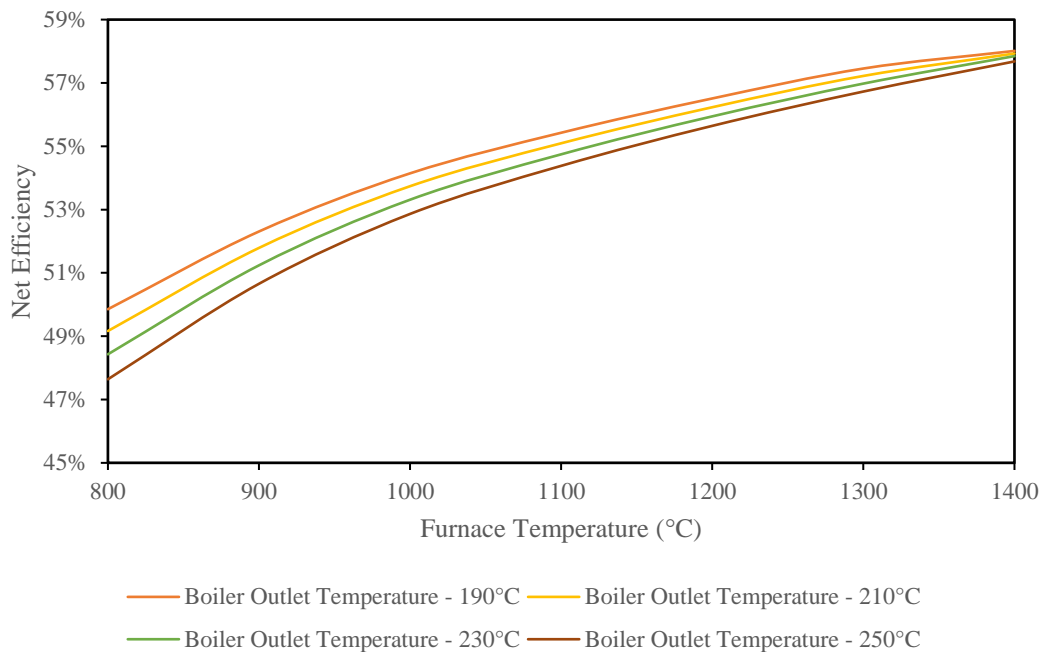


Figure 8 – Air temperature vs. net efficiency, axes switched to show extreme effect of changing furnace temperature

This effect is caused by the difference between potential temperature ranges for each end of the boiler. At the outlet - to maximise efficiency – the temperature should be as low as possible, compounding this is that there is a maximum temperature restriction in place for air entering the gas scrubbing section of the plant which follows the outlet of the boiler. Branchini, L. states that gases exiting the boiler are between 180°C -250°C although lower values are possible in advanced boiler arrangements which generally operate at higher boiler pressures and temperatures than the majority of EfW plants (15).

The furnace temperature is not subject to such stringent limits. The minimum allowable furnace temperature is constrained by regulations in the EU to 850°C (1100°C for hazardous waste) (14), this constraint is in place to minimise the NO_x and other emission forming potential of waste incineration . It is required of plants to have a means in place to maintain the temperature of the furnace above this temperature – typically through the use of of natural gas burners (15). The upper limits imposed on the furnace temperature stem firstly from the material limits of components within the furnace and boiler and are also managed to minimise corrosive effects on the boiler system (15). A moving grate furnace such as that modelled in this report, can tolerate temperatures up to around 1250°C (14).

For the purposes of further modelling, adiabatic temperatures of 1200°C and 200°C for the furnace temperature and boiler outlet temperature are respectively assumed.

6.1 Boiler Efficiency

The efficiency of the boiler influences the useful energy extracted from the hot furnace gases directly – if the boiler has a direct efficiency of 85%, then 85% of the energy is passed into the steam loop of the model – as inefficiencies are accounted for at a later stage in the model. The air flow rate required to maintain the inlet and outlet boiler temperatures set by the model operator is derived from the boiler efficiency. An increase in air flow rate corresponds to an increase in fan power as can be seen in figure 9.

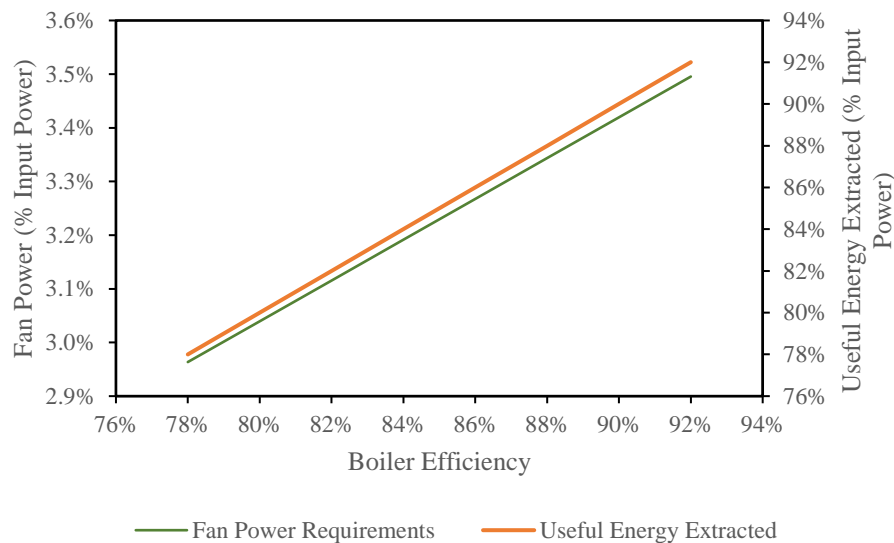


Figure 9 - Effect of boiler efficiency on fan power requirements, showing increase in fan power as boiler efficiency increases alongside an increase in useful energy extraction

Fan requirements do increase as a function of boiler efficiency however the degree at which they do is far less than that of the useful energy extracted. Boiler efficiencies are lower in EfW plants, at around 83% (22) compared to traditional power plants in which boilers can reach efficiencies above 90% due to higher permissible operating temperatures and pressures.

6.2 Effect of Air Temperatures on Fan Power Requirements

Figure 10 outlines the effect of changing furnace and boiler air temperatures on fan efficiency. The results here may seem counterintuitive at first glance as one may expect the effect of increased temperature on gas density to increase the energy demand of the fans. In-fact although a lower energy density may increase the velocity of the fan blades, it does not affect the energy required by the fans.

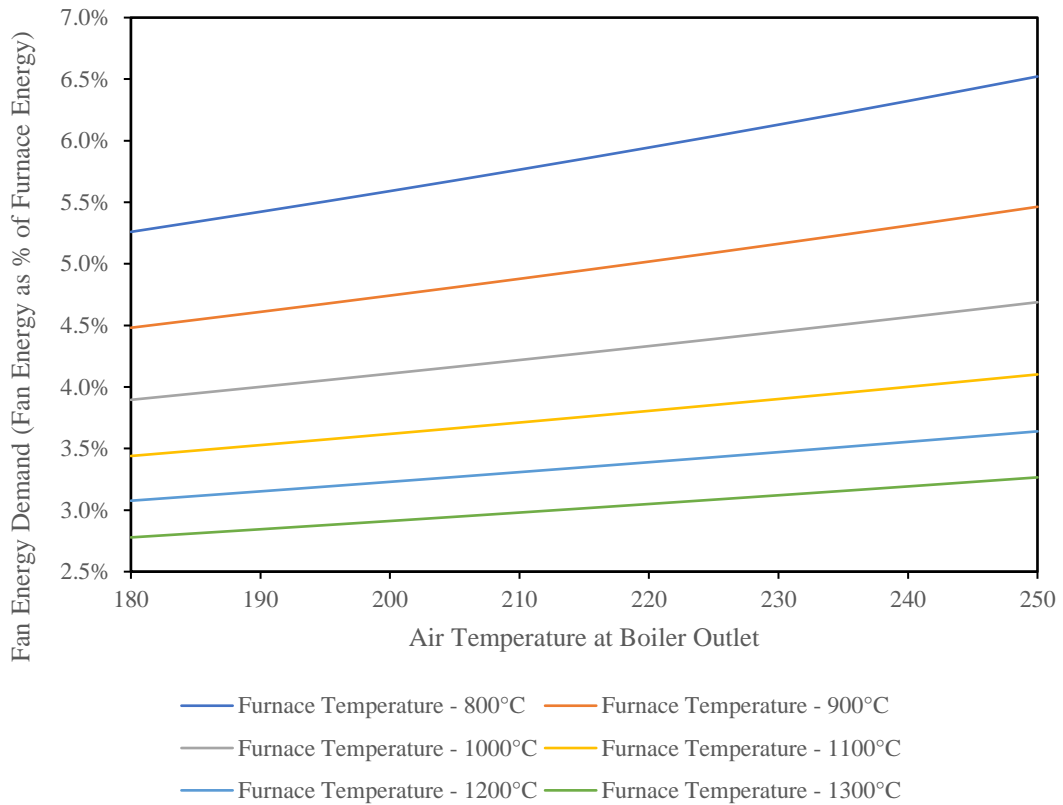


Figure 10 - Effect of changing air temp after boiler on fan power requirements, indicating improved fan efficiency at higher furnace temperatures

The function of the fans - along with providing oxygen for combustion - is to manage the temperature of the furnace hence, by allowing the furnace to reach a higher temperature the workload of the fans is actually decreased.

The numbers presented correlate with observations made by Godichon, A. identifying that the total power consumption of fans represents 2-4% of energy generated by a plant (41). At a boiler efficiency of 83% and temperatures assumed in section 6.2 the energy consumption of all fans in the model 3.04%, which lies halfway within that range.

6.3 Turbine Efficiency effect on Net Efficiency in a CHP System

In figure 11 the electrical and heat energy exported are plotted as a function of turbine efficiency. The sensitivity analysis shows that there is no effect on energy generation as a result of fluctuating the steam turbine generator efficiency. Figure 11 outlines an obvious limitation inherent in the model. As turbine efficiency decreases, less electrical energy is utilised, essentially this means that steam leaving the turbine has a higher energy content which is subsequently utilised as useful heat.

This is likely not the case in practice as each component will cause entropy changes at different rates although it does outline a key advantage of the CHP arrangement as

a means for maximising the efficiency of an EfW plant, wherein energy lost through inefficiencies in the steam generation is captured as useful heat and therefore utilised anyway, albeit in a different form.

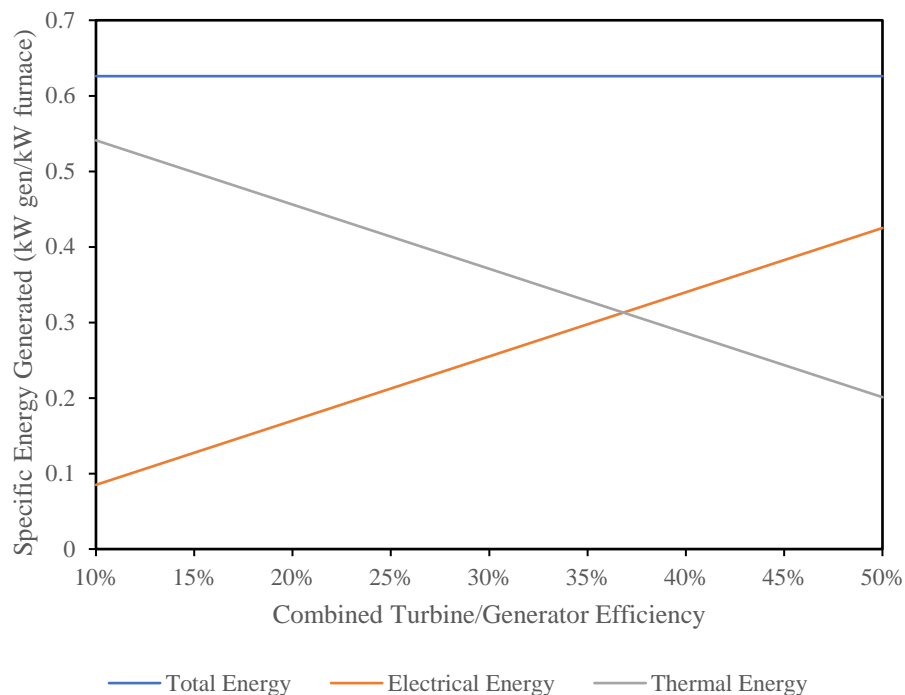


Figure 11 - Effect of turbine-generator efficiency on power generation, showing no impact on overall efficiency

6.4 Ambient and Primary Air Preheat Temperatures

As can be seen in figure 12 the changes in ambient air temperature have a negligible effect on the amount of energy extracted whilst preheating the primary air for the furnace. A much larger effect can be seen by the primary air preheat temperature. The extent of air preheating requirements will depend on the needs of an individual EfW plant, but typically plants have been shown to preheat air to 150°C (42), assuming an ambient air temperature of 15°C this puts the useful heat available at 0.79 MWh/tonne waste.

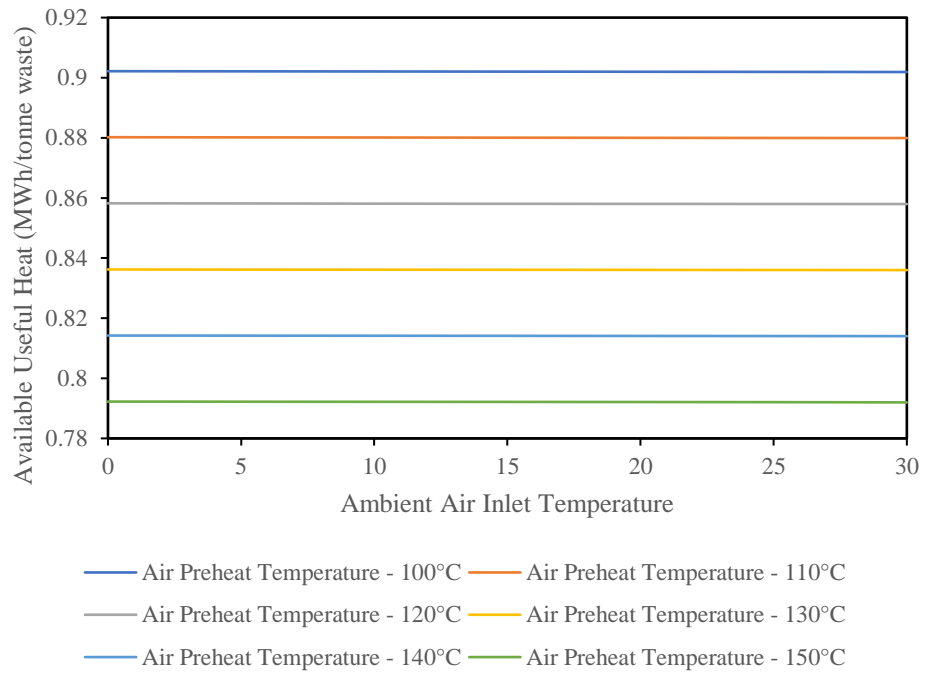


Figure 12 - Effect of changing air regeneration temps on energy extraction from useful heat

7.0 Results & Discussion

7.1 Introduction

The results from modelling are discussed in this section of the report. A comparison of the calorific value of different matrix materials is presented followed by an investigation into the impact which the inorganic fraction of a GRP has on the calorific value. The CO₂ and NO_x emissions were calculated for each material in order to investigate the effect on emission production at various GRP/MSW and Matrix/fibre-filler fractions. Bottom ash production was then investigated. Finally, a case study regarding the effect on all the aforementioned variables of the addition common GRP constructions was undertaken.

The parameters used for system components were gathered in the literature review and sensitivity analysis sections of this report and are summarised in table 4.

<i>Parameter</i>	<i>Set Point</i>
<i>Plant capacity</i>	100,000 t/year
<i>Operational hours</i>	8000 hours
<i>Unburnt fraction</i>	20%
<i>Required furnace temperature</i>	1200°C
<i>Boiler pressure</i>	400 Bar
<i>Condenser pressure</i>	0.08 Bar
<i>Boiler direct efficiency</i>	83%
<i>Boiler air outlet temperature</i>	200°C
<i>Primary air reheat temperature</i>	150°C
<i>Turbine-generator efficiency</i>	30%
<i>Feedwater & wet scrubber pump energy</i>	0.015MW/t-fuel
<i>Heat losses</i>	1.5% of input energy

Table 4 - Summary of set points for modelling

7.2 Assumptions & Limitations

- The model assumes that the EfW plant operates at a steady state.
- The model does not account for fluctuations in MSW elemental composition, therefore incremental changes to air flow requirements and calorific value through time are not considered
- The boundary of the system is set at the point which material waste enters the EfW facility, therefore additional energy requirements associated with transport and pre-processing of waste are not considered.
- Results are only indicative for the GRP materials analysed in section 5.4 of this report.

7.3 Energy Content of Matrix Materials

The energy contents of common matrix materials are outlined in table 5. The calorific values were calculated using an adapted Dulong's equation as outlined in Eq.2. Vinyl Ester resin is shown to have the highest calorific value, likely due to the high carbon content of the material. Vinyl ester composites display a high degree of chemical resistance and as such are commonly used in maritime applications such as boat hulls (43).

<i>Matrix Material</i>	<i>Calorific Value (MJ/kg)</i>
<i>Phenolic Resin</i>	29.18
<i>Polyester Resin</i>	30.29
<i>Epoxy Resin</i>	33.88
<i>Vinyl Ester Resin</i>	36.62

Table 5 - Energy content of matrix material from ultimate analysis

Epoxy resin delivers the second highest calorific value of the materials investigated. This is important to know as the epoxies are commonly used in high stress components such as wind turbine blades as well as in the aviation industry.

The calorific content of polyester resin is of most note as it is the most common material used in GRP, mainly due to its low relative cost and ease of use. When incorporated into an EfW waste stream, it is likely to have the biggest impact on the overall energy density of waste at a national or international scale (44).

Phenolic resin is the least common of the materials investigated. It is generally used for small rigid components where heat resistance is of most concern (45). The low calorific value of this material is therefore of little concern as it is unlikely to have a large impact in comparison to more common materials.

The energy density of MSW is calculated using the same method to be 11.21MJ/kg, this figure correlates with observed experimental values (35).

7.4 GRP Resin Comparison

Given the disparity between the calorific values of Matrix resins and MSW, the assumption would be that by increasing the level of GRP within the waste stream, the overall energy produced through incineration would increase, the results show that this is not strictly the case.

Figure 13 shows the variance of calorific value corresponding to each resin investigated by plotting the calorific content against matrix fraction of each GRP material. There is a linear correlation between the addition of an incombustible

fraction made up from fibre and any additional filler present within the composite and the overall calorific value of the GRP.

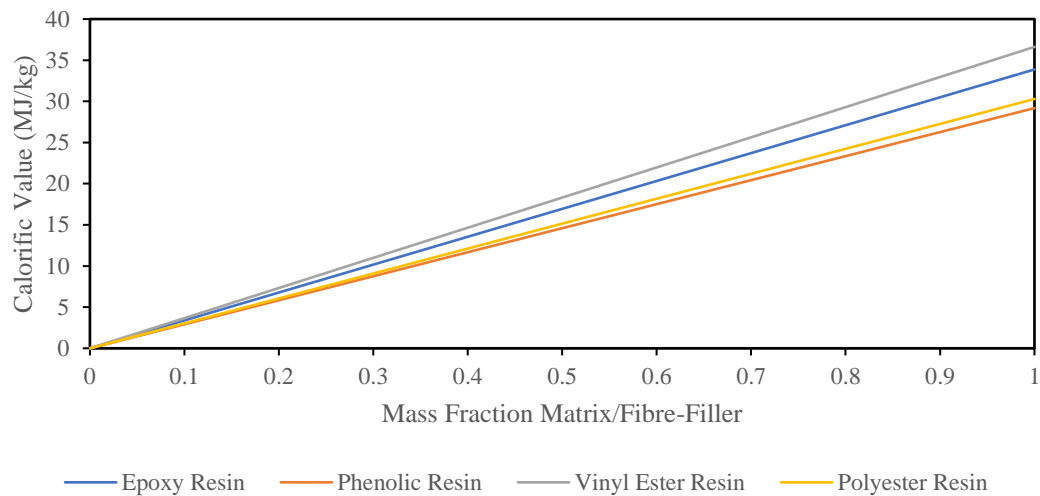


Figure 13 – Calorific value comparison of GRP at varying matrix content.

The impact which decreasing the matrix content of a GRP material on the overall energy density of the combined fuel source can be seen in figure 14 where the calorific value is plotted as a function of organic fraction of the GRP material for each of the investigated matrix materials. This is the first indication of a problem which can arise from using GRP as a fuel source in an EfW plant, when the fibre content of the GRP is high enough to lower the calorific content of the GRP to such a level that it is less than that of MSW, resulting in a reduction of the overall energy density of the combined fuel.

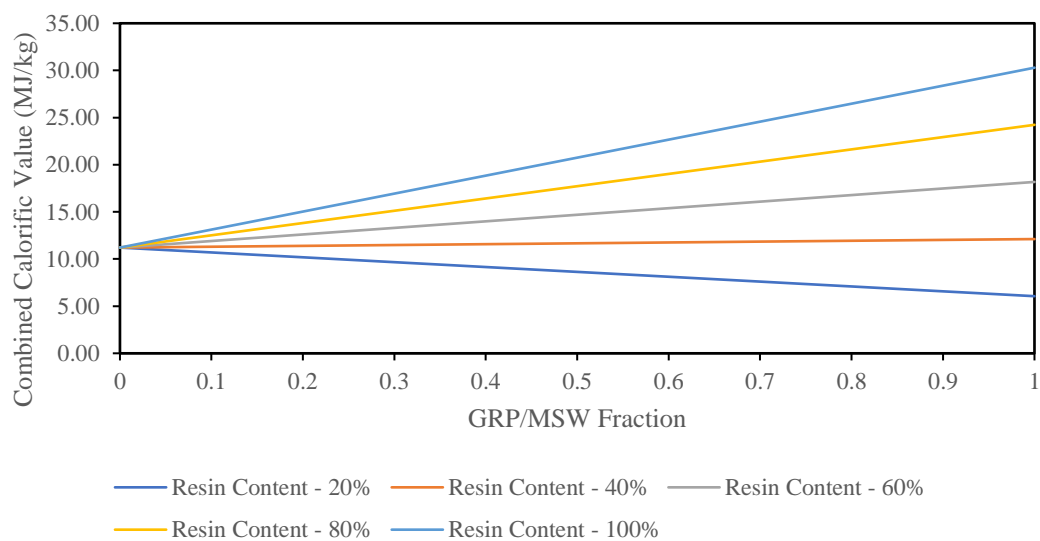


Figure 14 - Comparison of energy density with matrix fraction and GRP/MSW fraction for polyester resin GRP, showing decline in overall calorific value with decreased matrix content.

The extent to which this effect could impact the performance of the plant comes down to the constitution of the GRP materials which are being incinerated as well as the fraction of total waste they make up. The possible implications of a high fibre content material passing through the EfW system at a high concentration are many. The system may be unable to maintain the necessary operating temperatures and air flow rates as the available fuel within the furnace diminishes in calorific value.

This effect should be a consideration of EfW operators when selecting the volume of GRP which should be mixed into the plants waste stream. Table 6 shows the maximum inorganic fraction of waste which is permissible in order to prevent a loss in the overall energy density of the mixed fuel. The values assume the previously stated calorific value of 11.21MJ/kg for MSW

Matrix Material	Maximum Inorganic Fraction
<i>Epoxy Resin</i>	66.90%
<i>Phenolic Resin</i>	61.58%
<i>Vinyl Ester Resin</i>	69.38%
<i>Polyester Resin</i>	62.98%

Table 6 - Maximum fibre mass fraction required to prevent lowering mixed fuel energy density

Many common GRP materials such as small boat hulls are unlikely to contain levels of fibre/filler at these levels however waste materials from wind turbine blades or bulk moulding compound contain a very high fibre-filler volume fraction and may have some impact.

7.5 Potential Emissions related to GRP incineration

For the purposes of this study, the emission levels of greenhouse gases were calculated to see the effect which GRP may have on their production. In the EU, strict limits are in place on environmentally harmful emissions released through the flue stack (32). The concentration of gases formed within the furnace can be calculated from the elemental analysis of the fuel type. CO₂ and NO_x concentrations were calculated for various fuel types.

7.5.1 CO₂ Production

The CO₂ output of standalone MSW incineration was calculated to be 1.28 kgCO₂/kgWaste, This value corresponds with UK government guidance, which predicts a CO₂ production rate of between 0.7-1.7 kgCO₂/kgWaste (46). In figures 15 & 16 a plot of specific CO₂ emission production vs. the GRP fraction of the fuel source is presented for matrix fractions of 50% & 75%. CO₂ production rates are

shown to increase as the matrix fraction is increased. This increase in CO₂ emissions corresponds with the increase in calorific value outlined in section 7.4.

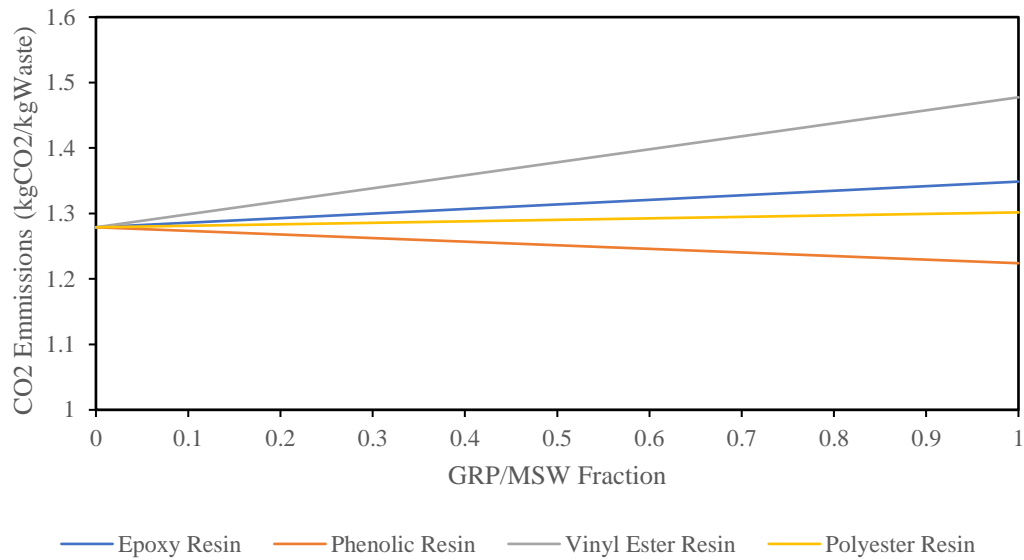


Figure 15 - Effect of GRP combustion at 50% matrix on CO₂ production

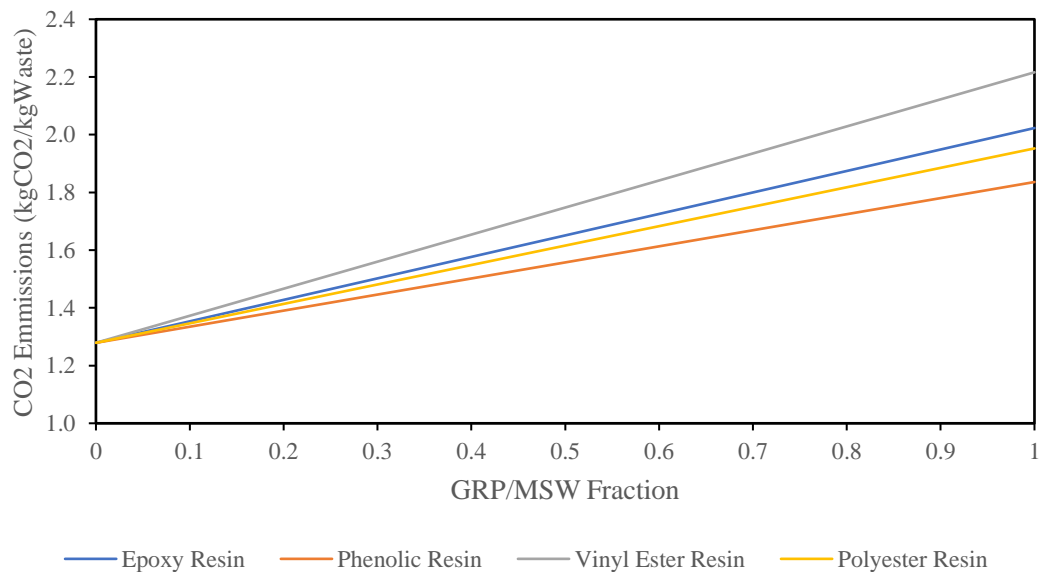


Figure 16 - Effect of GRP combustion at 75% matrix on CO₂ production of mixed waste

Looking now specifically at polyester, the rate at which emissions and calorific value change relative to MSW only incineration was investigated at matrix fractions of 75% and 25% as shown in figures 17 & 18, respectively. These figures have been normalised to show the level of change from 0% GRP addition for emissions and calorific value.

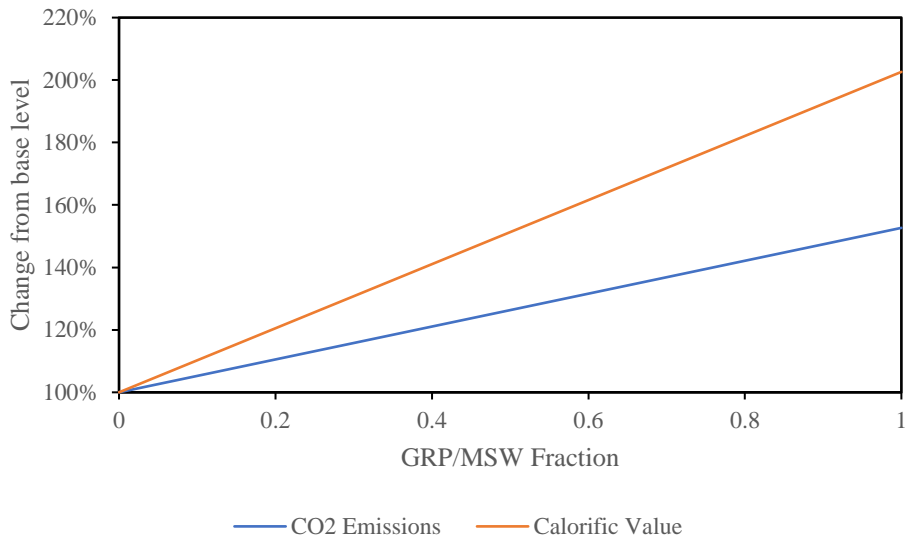


Figure 17- Rate of change in CO₂ production and calorific value for polyester GRP at a matrix fraction of 75%

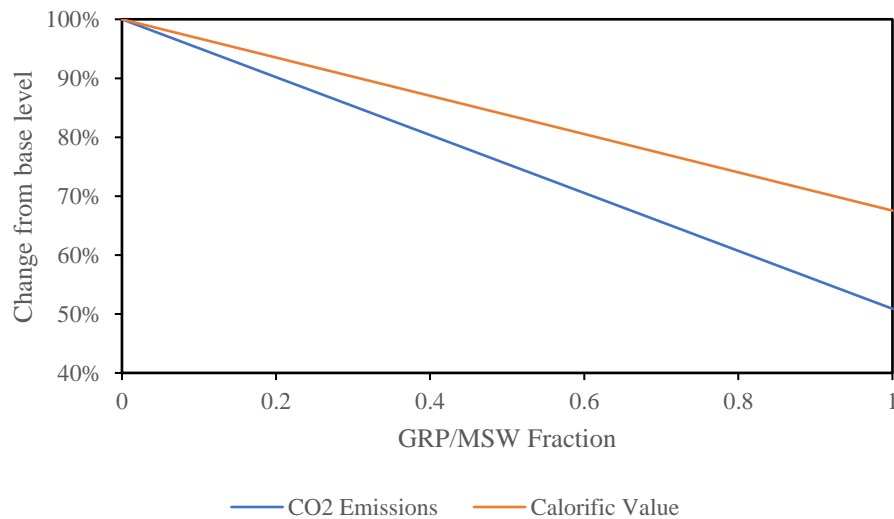


Figure 18- Rate of change in CO₂ production and calorific value for polyester GRP at a matrix fraction of 25%

The results show that although CO₂ production changes with calorific value, the rate at which this happens is divergent, indicating that overall CO₂ emissions per unit of energy generated is decreased substantially as polyester GRP is added, including when the overall calorific value of the fuel is decreased. Polyester based GRP is the most common form of GRP waste so there may be scope for it to be used as a method of reducing CO₂ production in an operational EfW plant.

Figure 20 shows the extent of this effect when the fibre-filler fraction is set to the minimum value set out in table 6. The addition of GRP at this matrix fraction of

36.2% has no adverse effect on the energy density of the fuel source whilst decreasing the rate of CO₂ emissions. At a GRP/Matrix fraction of 0.1, CO₂ emissions are lowered by around 2.5%.

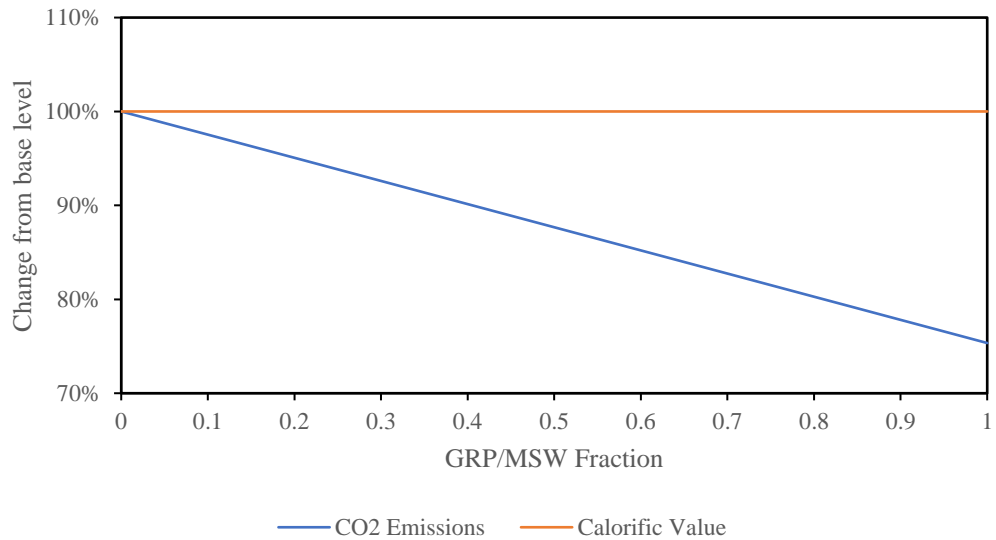


Figure 19- Rate of change in CO₂ production of polyester GRP when matrix fraction is at minimum requirements to prevent loss in calorific value. Showing decreased CO₂ production without adverse effect to calorific content of mixed fuel

Table 7 and figure 20 show that this trend is true for all of the resin types investigated. It is most prevalent in epoxy resin, where the reduction in CO₂ production is around 3% at a 10% GRP fuel concentration.

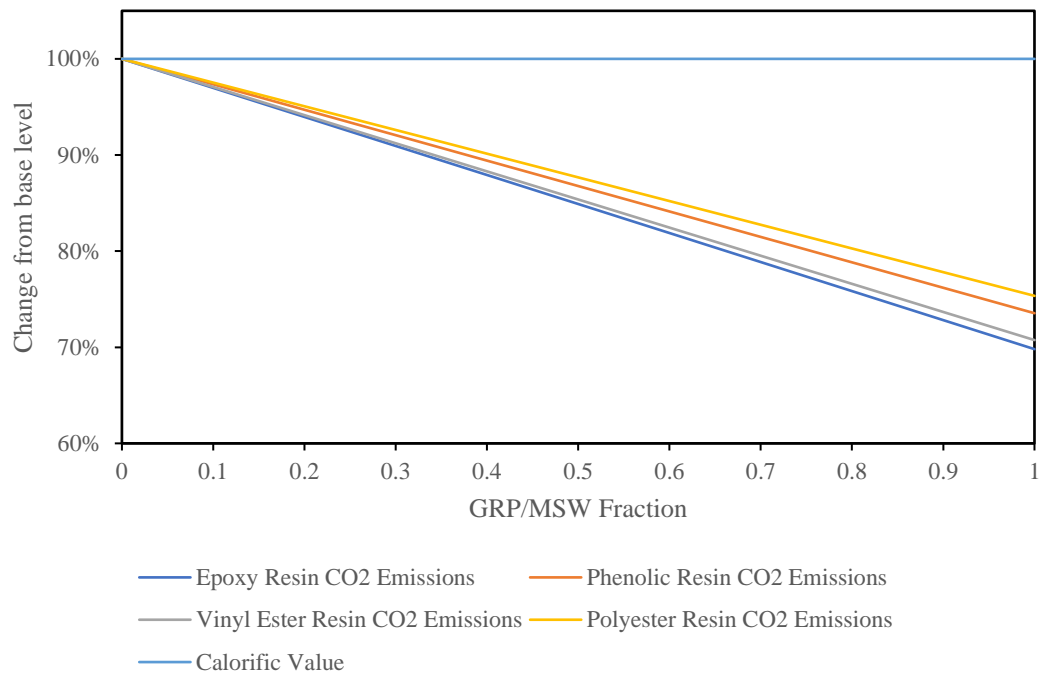


Figure 20 - Decrease in CO₂ production from adding GRP whilst maintaining overall energy density of mixed fuel.

GRP/MSW Fraction	Epoxy Resin CO ₂ Emissions	Phenolic Resin CO ₂ Emissions	Vinyl Ester Resin CO ₂ Emissions	Polyester Resin CO ₂ Emissions
0	100.0%	100.0%	100.0%	100.0%
0.1	97.0%	97.4%	97.1%	97.5%
0.2	94.0%	94.7%	94.1%	95.1%
0.3	90.9%	92.1%	91.2%	92.6%
0.4	87.9%	89.4%	88.3%	90.1%
0.5	84.9%	86.8%	85.4%	87.7%
0.6	81.9%	84.1%	82.4%	85.2%
0.7	78.9%	81.5%	79.5%	82.7%
0.8	75.8%	78.8%	76.6%	80.3%
0.9	72.8%	76.2%	73.7%	77.8%
1	69.8%	73.5%	70.7%	75.3%

Table 7- Calculated figures show decrease in CO₂ production at matrix fractions which do not decrease overall energy content of mixed fuel

7.5.2 NO_x Production

Fuel NO_x is created within the furnace when ionised nitrogen is released from the fuel source and is oxidised by the surrounding air. There are an array of NO_x gases that are created as a result of combustion however NO₂ is the most common of these (47). NO₂ is not a greenhouse gas directly however it has an impact on ozone levels over time and leads to the formation of greenhouse gases.

Calculations performed regarding NO₂ production assume that all nitrogen from the fuel source is converted into NO₂ when in reality a small amount of nitrogen will be converted into other gases such as NO. The base production level of NO₂ emissions when no GRP is added to the waste stream is calculated as 0.031 tonneCO₂e/tonneMSW.

Figure 21 gives insight into NO₂ production in the furnace by plotting NO₂ production against the GRP fraction for all resin types. The only matrix material shown to generate a notable increase on NO₂ production is phenolic resin, the least common of all matrix materials investigated (47).

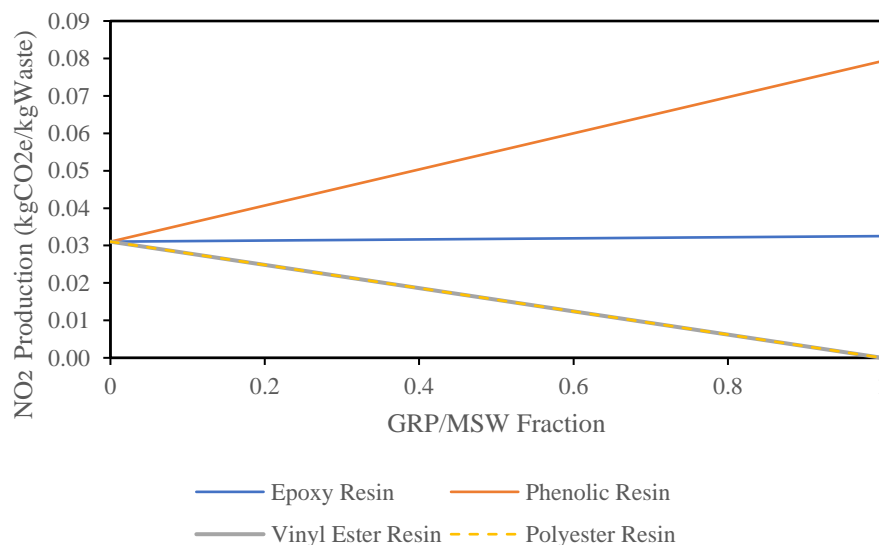


Figure 21 - Impact of 50% matrix GRP incineration on the production of NO₂ furnace gases. Indicates that lower initial nitrogen content of fuels leads to lower NO₂ emissions

Epoxy resin does produce a small increase, but it is negligible in comparison to other matrix materials and is therefore unlikely to generate a noticeable difference in NO₂ production in the furnace – especially when considering fluctuations in the nitrogen content of MSW.

Vinyl Ester and Polyester generate no NO₂ whatsoever as the materials contain no nitrogen to react with oxygen when combusted. What is seen in the case of these two

materials is therefore a steady decline in NO₂ production as their concentration in the fuel source is increased. This result is valid assuming that the materials in use adhere exactly to the elemental compositions calculated earlier in this report. In reality there are many different formations of each of these materials, some of which could contain nitrogen and even in nitrogen free materials, there would likely be some degree of nitrogen present due to contamination.

Figures 22 & 23 show that when normalised to maintain a steady calorific value within a mixed GRP/MSW fuel, phenolic resin is the only matrix material investigated which increases NO₂ production. Although the epoxy resin showed a slight increase in NO₂ production at a 50% matrix fraction, the calorific value of the fuel at that level would increase, therefore increasing the energy generated within the furnace, the NO₂ produced per unit energy would therefore decrease.

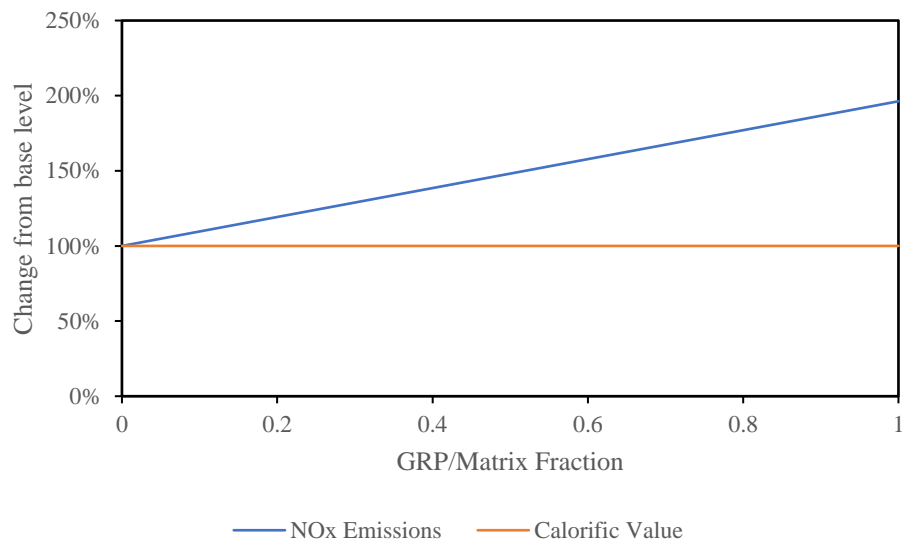


Figure 22 - Impact of phenolic resin on NO_x production showing increased NO_x production when calorific value is maintained.

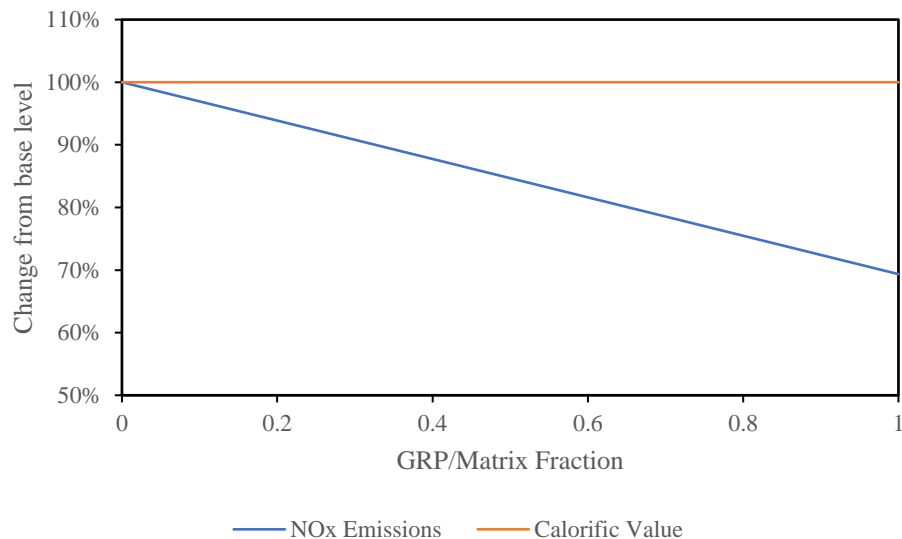


Figure 23 - Impact of epoxy resin on NOx production showing decreased levels of NOx when calorific value is maintained.

7.5.3 Summary

An investigation into the impact of CO₂ and NO₂ production when adding GRP into a EfW waste stream has shown that all matrix materials investigated cause a drop in CO₂ production relative to their effect on the energy density of the fuel source. The greatest drop in CO₂ production recorded was for epoxy resin although all fuel sources performed well in this regard.

Phenolic resin was the only matrix material shown to increase NO₂ production relative to its effect on the energy density of the mixed fuel source. It is therefore concluded from these results that the addition of GRP into the waste stream results in desirable effects in terms of emission management.

7.6 Bottom Ash

Bottom ash refers to the unburnt fraction of material which is left over following the incineration process. In MSW incineration this is comprised mainly of carbon but contains other incombustible materials present in MSW such as metals. Due to the high inorganic fractions found in many GRP materials, an investigation was undertaken to better understand the effect which GRP incineration would have on the levels of bottom ash generated in an EfW process.

Assuming that the combustible fraction of each GRP type will leave the same ash mass as residual waste, the impact of GRP incineration can be seen in figure 24 where bottom ash generation is plotted against the GRP fraction of the fuel.

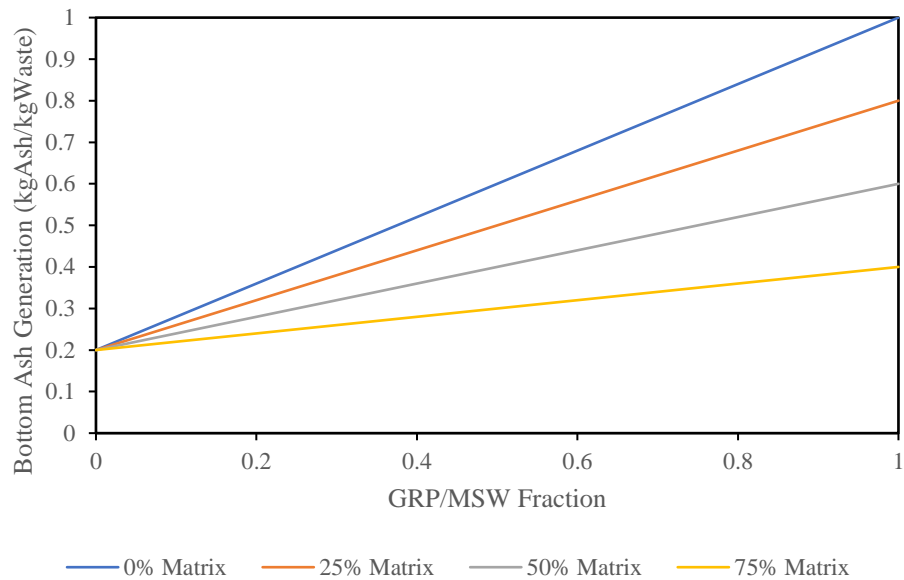


Figure 24 - Bottom ash production at varying levels of matrix within GRP showing steep increase in ash production with decreased matrix content.

Bottom ash production increases as GRP is added at all matrix concentrations. This suggests a need for extra considerations in terms of end waste management as GRP addition will produce ash with a high glass fibre content. Ash materials can be used by the construction materials in the production of aggregates for roads (26). Currently there is little knowledge regarding how high levels of glass fibre within the bottom ash will affect the usage of bottom ash as a construction material. This matter requires further investigation on its effect on each individual application of bottom ash.

7.7 Investigation into Common GRP Formations

Case studies were analysed to see the real-world impact of the incineration of some common GRP constructions. Some common arrangements of varying resin material and fibre fraction are presented in table 8.

<i>Application</i>	<i>Matrix Material</i>	<i>Matrix Fraction</i>
<i>Boat Hull</i>	Vinyl Ester Resin	0.75
<i>Pressure Vessel</i>	Epoxy Resin	0.52
<i>Pipe</i>	Epoxy Resin	0.90
<i>Wind Turbine Blade</i>	Epoxy Resin	0.30
<i>Bulk/Sheet Moulding Compound</i>	Polyester Resin	0.25

Table 8 - Composition of common composite materials (48) (49) (50) (51) (52) (53) (54)

7.7.1 Energy Density

Table 9 shows the calorific values of the investigated GRP compositions. Those compositions which fall below the calorific value of MSW will have a negative impact on the overall calorific value of the mixed fuel. In the context of this study, this includes high fibre-filler content materials such as bulk/sheet moulding compound and wind turbine blades.

<i>Application</i>	<i>Matrix Material</i>	<i>Calorific Value (MJ/kg)</i>
<i>Boat Hull</i>	Vinyl Ester	27.46
<i>Pressure Vessel</i>	Epoxy Resin	17.75
<i>Pipe (woven)</i>	Epoxy Resin	30.42
<i>Wind Turbine Blade</i>	Epoxy Resin	10.16
<i>Bulk/Sheet Molding Compound</i>	Polyester Resin	8.47

Table 9 - Calorific value of common GRP constructions, the calorific value for MSW is 11.21MJ/kg

7.7.2 Bottom Ash

The levels of bottom ash generated relate to the level of inorganic material found within the GRP construction. This can be seen in figure 25 which displays that there is a far greater increase in bottom ash production associated with wind turbine blades and bulk/sheet loading compound than with the boat hull and woven pipe constructions which have higher matrix fractions.

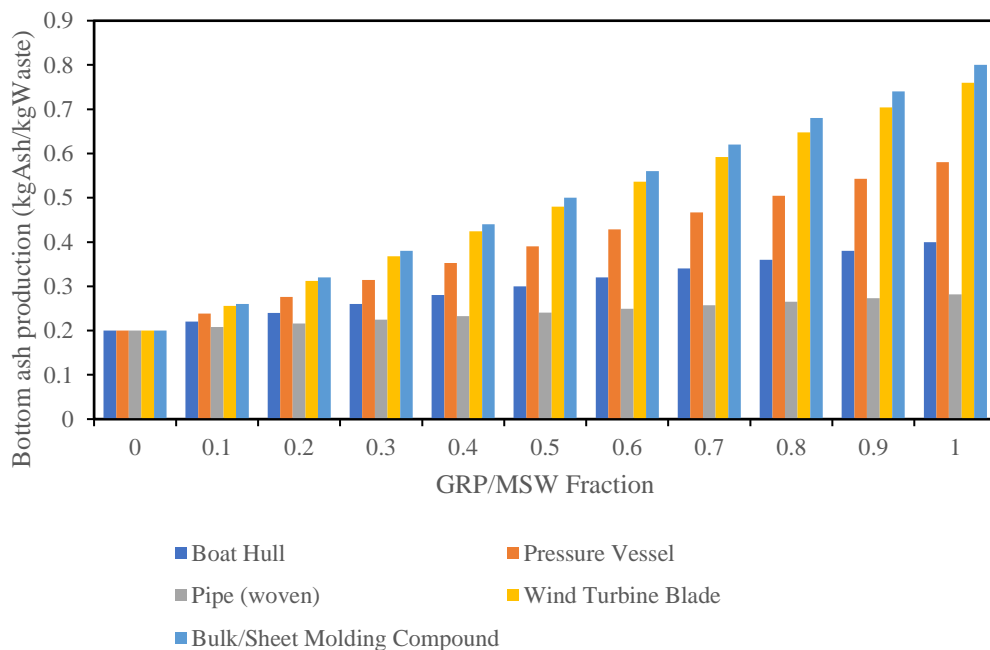


Figure 25 - Bottom ash production of common GRP constructions at different GRP/MSW fractions.

7.7.3 Emissions

7.7.3.1 CO₂ Production

The production of CO₂ for each example GRP construction can be seen in figure 26 and indicates that the incineration of bulk moulding compound and wind turbine blades result in lower CO₂ emissions in comparison materials with larger matrix fractions such as boat hull or woven pipe.

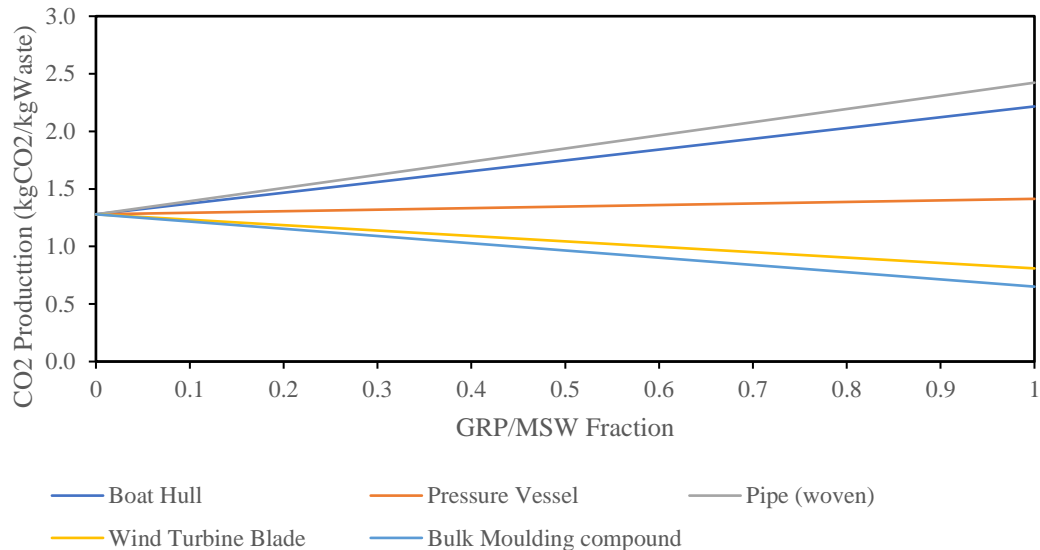


Figure 26 - CO₂ production in common GRP constructions showing increased CO₂ production in low matrix fraction constructions.

7.7.3.2 NO₂ Production

The bulk/sheet moulding compound and boat hulls use polyester and vinyl ester as a matrix material, neither of these materials contain any nitrogen and therefore lead to a decrease in NO₂ production as their concentration within the fuel source increases, as seen in figure 27 which compares NO₂ production with GRP fraction within the mixed waste source. The remaining three constructions employ epoxy resin as a matrix material therefore the concentration of resin within these materials corresponds to their NO₂ generating potential.

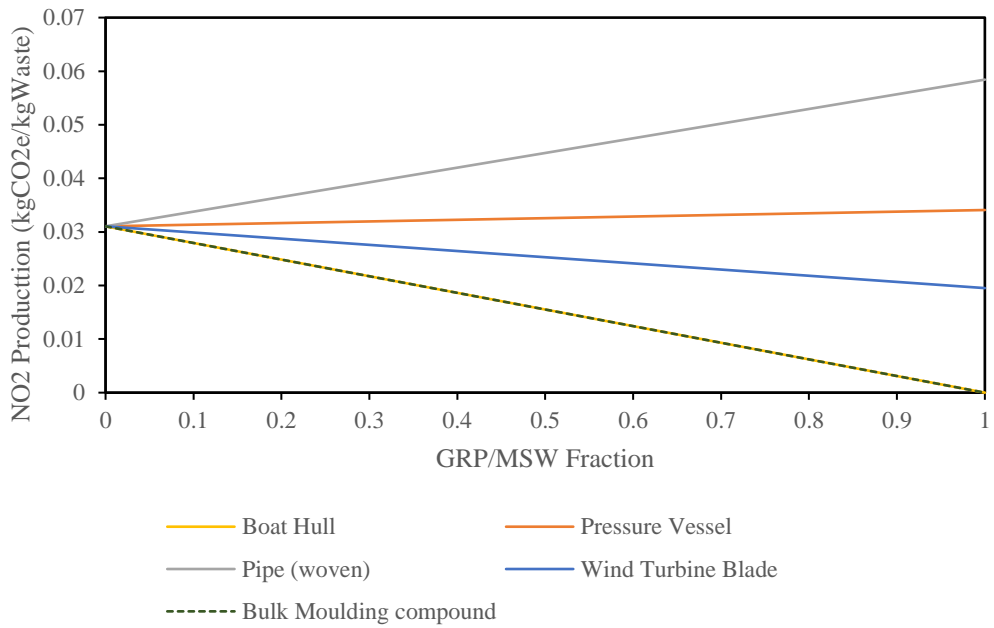


Figure 27- NO2 production in common GRP constructions showing gradual elimination of NO2 production in GRP constructions with no nitrogen content.

7.7.4 Energy Generation

Using the constraints laid out in the methodology section of this report, the total useful energy output of the EfW plant can be calculated for the addition of each example construction, for a plant running with 100% MSW this figure amounts to 1.36MW/tonne-fuel with a net efficiency of 48.5%. Figure 28 shows the effect which the GRP examples have on the overall output by comparing the energy output of the plant with the GRP content of the fuel source.

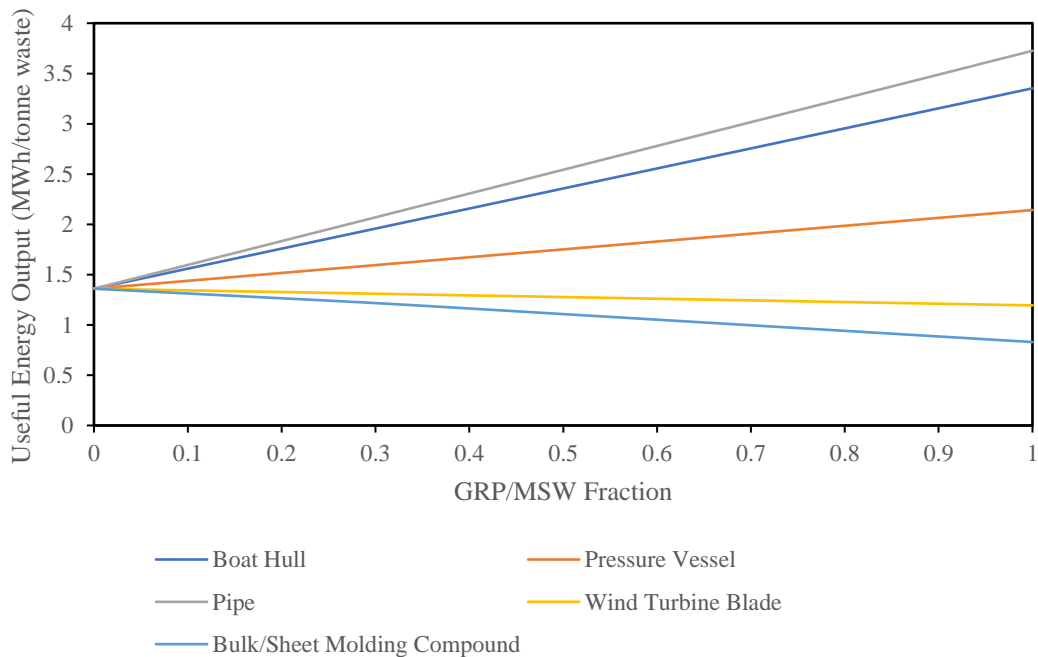


Figure 28 - Power Generation vs. GRP Content by GRP Type

As expected, constructions for which the calorific content of the material is lower than that of MSW produce a steady decrease in energy generation as they are added into the mixed fuel source.

A more striking finding as shown in figure 29 is that there is a limit at which the energy requirements of auxiliary functions within the plant begin to decrease at a much slower rate than the decline in energy generated. This leads to a rapid decrease in the plants net efficiency and can be seen in the results for the bulk/sheet moulding compound due to its low matrix content. It should be noted that it is unlikely GRP would be added at the rate which is required for such an effect to present itself – as previously indicated, a recommendation is for GRP to be added to the waste stream at 10% and at this rate the change in efficiency for all materials remains less than 1%.

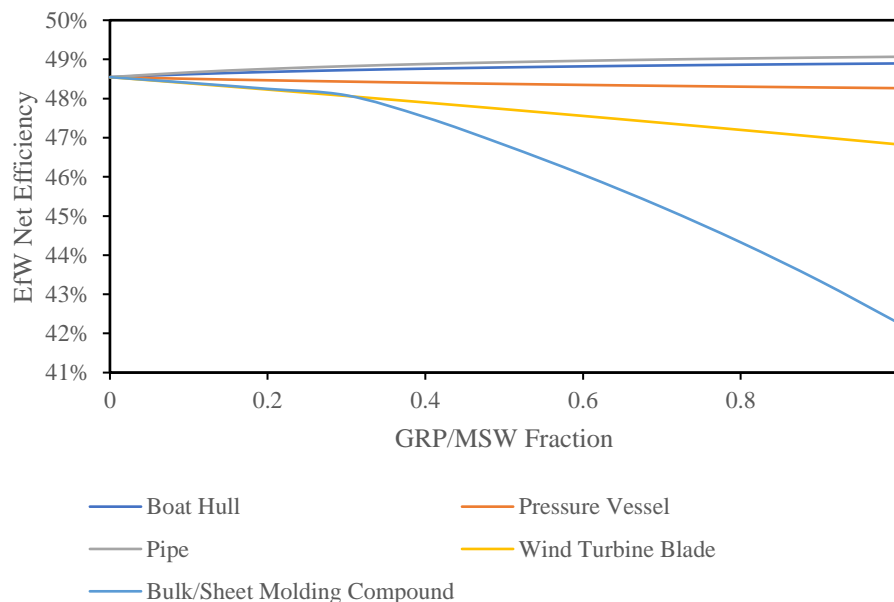


Figure 29 - Net efficiency of EfW plant with addition of common GRP constructions showing steep decline in efficiency after around 30% bulk/sheet moulding compound is added to the mixed fuel source.

7.8 Comparison of emissions with traditional energy generation methods and grid.

Figure 30 shows how greenhouse gas emissions from EfW compare with traditional fossil fuel generation methods when GRP is added to the EfW fuel source. The figure shows that EfW performs similarly to coal generation with 0% GRP added. There is a steady decline in GHG production with the addition of some common GRP types. At around 40% boat hull addition, the level of GHG emissions is comparable with that of energy generation using oil as a fuel source this shows the benefit in terms of

GHG emissions from using GRP within the fuel source. The emissions associated with EfW are still very high however, even when compared to generation using natural gas.

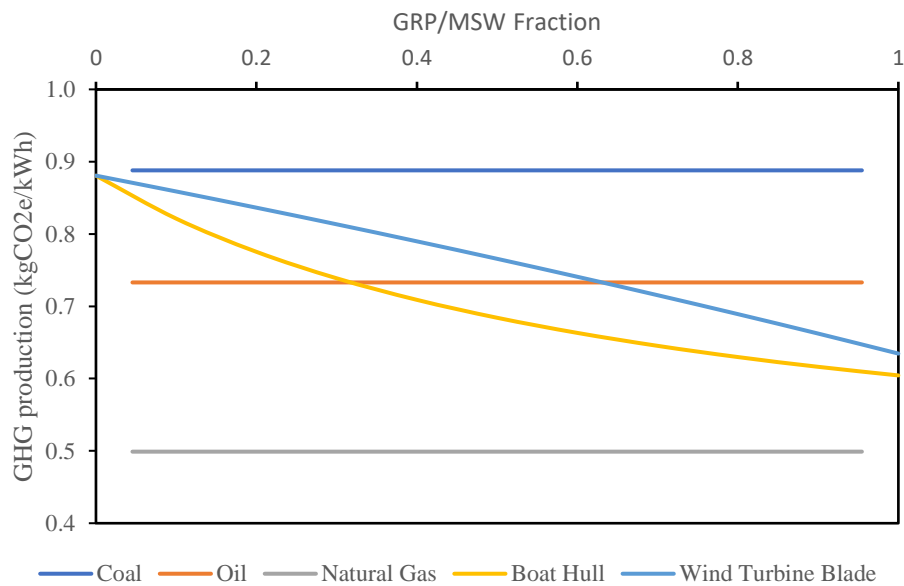


Figure 30 - GHG production comparison with traditional energy generation showing decrease in GHG emissions through addition of GRP

The grid in the UK has a relatively low level of GHG emissions at 0.2773 gCO₂e/kWh (55). This means that even with the addition of GRP, EfW would increase the carbon intensity of the grid. In many areas such as certain states within the USA and Australia, the carbon intensity of the grid is much higher (55) and the use of EfW with additional GRP could be seen as a means of lowering grid carbon intensity.

8.0 Conclusions

From the results section of this report, the following can be concluded:

- Vinyl ester and epoxy resin have highest calorific value and therefore, the most benefit in terms of energy generation.
- The concentration of inorganic compounds within the matrix material has a direct effect on its overall calorific value
- The minimum inorganic concentrations required to ensure no decrease in calorific value of a mixed GRP-MSW fuel were calculated as per the calorific content of MSW used in this project
- High fibre materials such as wind turbine blades and bulk/sheet moulding compound were shown to have an adverse effect on energy generating potential although these effects were minimal at less than 10% GRP concentration of the fuel source
- All GRP formations investigated were shown to reduce CO₂ production of the plant. The greatest example of this effect was seen in epoxy resin.
- The addition of nitrogen free resins Vinyl Ester and Polyester to the fuel source led to a decrease in NO_x production levels while the addition of epoxy resin showed little effect. Only phenolic resin was seen to create an increase in NO_x production
- Bottom ash production is drastically increased with the addition of high inorganic fraction GRP even at small concentrations of GRP in the fuel source.
- A case study revealed that common GRP constructions produce varying results. Relatively common low fibre materials such as vinyl ester boat hulls provide large increases in useful energy generated but do result in higher CO₂ emissions - albeit not relative to the energy increase.
- Comparing GHG emissions of EfW traditional methods, it was shown that emissions from EfW are still higher than oil and natural gas generation at small GRP fractions although some materials are shown to have lower emissions than oil at GRP concentrations above 30%
- Even when lowered by the addition of GRP, GHG emission rates from EfW were still much higher than the UK grid carbon intensity.

9.0 Further Study

During the production of this report, some key areas were shown to be lacking in research.

- The effect which increased fibre content of bottom ash has on the desirability of bottom ash as a usable building material
- Further studies are required regarding the effect which GRP has on the EfW process, particularly those which review the effects within a working EfW plant.
- A similar study to this one could include MSW compositions from areas other than the UK, allowing for more broad conclusions to be drawn. As well as more robust modelling of the interaction between turbine efficiency and useful heat extraction.

10.0 References

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11.0 Appendices

11.1 Appendix 1 – Superheated Steam Enthalpy Table (56).

40 Bar	
<i>t</i> (°)	<i>h</i> (kJ/kg)
Sat	2801.4
280	2901.8
320	3015.4
360	3117.2
400	3213.6
440	3307.1
500	3445.3
540	3536.9
600	3674.4
640	3766.6
700	3905.9
740	3999.6

11.1 Appendix 2 – Specific Heat Capacity of Air (56)

<i>t</i> (°c)	<i>C_p</i> (kj/kgk)
0	1.006
6.8	1.006
15.5	1.006
26.8	1.006
46.8	1.007
66.8	1.009
86.8	1.01
106.8	1.012
126.8	1.014
226.8	1.03
326.8	1.051
426.8	1.075
526.8	1.099
626.8	1.121
826.8	1.159
1226.8	1.21
1626.8	1.241

11.2 Appendix 3 – Air density table (56)

t (°C)	ρ (kg/m ³)
0	1.292
5	1.269
10	1.246
15	1.225
20	1.204
25	1.184
30	1.164
35	1.145
40	1.127
45	1.109
50	1.092
60	1.059
70	1.028
80	0.9994
90	0.9718
100	0.9458
120	0.8977
140	0.8542
160	0.8148
180	0.7788
200	0.7459
250	0.6746
300	0.6158
350	0.5664
400	0.5243
450	0.488
500	0.4565
600	0.4042
700	0.3627
800	0.3289
900	0.3008
1000	0.2772
1500	0.199
2000	0.1553