THE FEASIBILITY OF ENERGY-FROM-WASTE SYSTEMS IN THE UK – A TECHNO-ECONOMIC MODEL

A thesis submitted to Cardiff University for the degree of

Master of Philosophy

By

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DECLARATION

This work has not previously been accepted in substance for any degree and is not concurrently submitted in candidature for any degree.

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SUMMARY

This thesis aims at interpreting the issues surrounding the implementation of small-scale EfW systems in the UK. To investigate these issues a case-study area was used and a techno-economic model has been applied to define the feasibility parameters of a modern Advanced Thermal Treatment process for around 20,000 tonnes of waste per year. Previous literature suggested the use of sensitivity and scenario analysis as an adequate method for research of these systems.

A waste classification was performed in a typical rural environment. The waste streams analysed were MRF residues (end-of belt residue, trommel residue and ballistic separator residue) resulting from household waste and recycling waste. This data was fed into the techno-economic model.

The results of the techno-economic model show that this type of facility is sensitive to variations in fuel properties, tonnages, operation and operational availability. Ideally a waste derived fuel would have high calorific value and low moisture content. However the analysis of municipal waste properties reveals that only a small part of the waste has these characteristics. Thus it is necessary to manipulate the calorific value in the overall waste stream in order to increase its potential for use in Advanced Thermal Treatment processes.

Investment analysis included NPV (net present value) and IRR (internal rate of return) analysis of five scenarios which particularly reflected the impact on capital cost repayment. Results showed that the most attractive option for investment is the nominal situation which presented values of 17% IRR. All of the scenarios investigated returned a lower IRR, with values ranging from 6% to 15%, which reflects its associated risk.

The results obtained from the techno-economic model show that nominal scenario is economically feasible. However, alterations to chemical properties of the waste and operation of the thermal treatment processes impacts greatly on economic feasibility which reflects the high risk associated to investments of this nature.

ACKNOWLEDGEMENTS

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Introduction

1. Background

Waste production has been a constant in History since the first communities emerged in the Neolithic Era. Waste, mainly composed of food and animal remains, would be deposited outside these settlements. It can be assumed that very quickly the need for disposing of waste in an adequate way was established in order to avoid the spread of disease and odour. Ancient civilizations developed specific recipients where waste would initially be deposited before final disposal. Early records from Ancient Greece point to the onset of the first waste disposal regulations at around 300 B.C. which shows that waste management has been a constant concern since the onset of civilization (Bilitewski, 1997).

In more recent times, records show an increase in waste production associated to the industrial revolution (circa 1750 – 1800). In the UK, as industrial areas developed, the idea of establishing norms for the cleaning of towns began to emerge by the mid 18th century. Early examples of waste management legislation were first implemented in London with the publication of the 1846 Nuisance removal and Disease prevention act. The Public Health Act of 1875 was the first piece of legislation created to establish waste management norms.

Further industrial development resulted in an increase in waste production which resulted in the introduction of waste disposal methods, such as landfill and incineration, which are still in use today. The term energy-from-waste describes waste management techniques that produce energy. Thermal treatment in particular refers to incineration, gasification and pyrolysis. The two last terms are also referred to as advanced thermal treatment as these are newer techniques that have a more positive environmental impact.

Over the next sections a more detailed description of these two methods will be provided. Other disposal methods such as recycling, composting and anaerobic digestion will also be discussed.

In recent years, environmental matters have gained greater relevance both in the UK and at European Union level. This increased awareness lead to the publication of the European Union waste management directive providing guidance on transport, collection, recovery and disposal of waste (EU Waste Framework Directive, 2008). This piece of legislation aims at encouraging prevention and waste reduction, recovery of waste through re-cycling, reusing or reclamation and finally recovery of energy.

The waste hierarchy, shown in figure 1, sets the order of waste disposal methods to adopt. According to these regulations energy recovery before final disposal is a more favourable method because it provides energy from a renewable source. These regulations set out that anaerobic digestion is preferable to composting since it provides the expectation of energy recovery. Furthermore, it establishes that recycling is preferable to energy from waste, which is preferable to landfill.

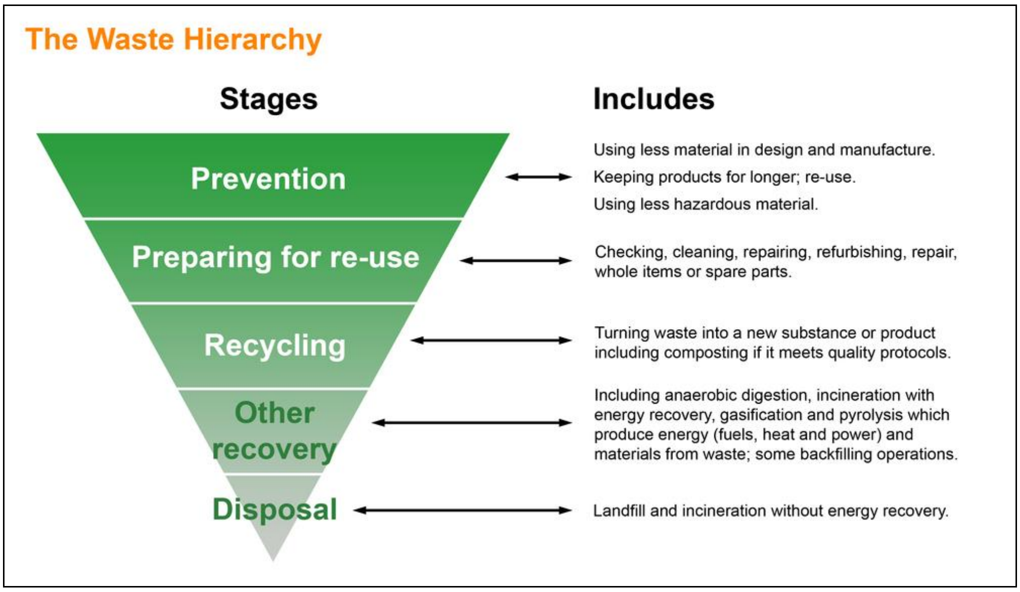


Figure 1. Waste hierarchy in http://northumberland.limehouse.co.uk/portal/planning/core_strategy/csio?pointId=s1335436077029 [accessed on 31/10/2013].

The waste hierarchy provides a classification of waste disposal methods by order of environmental impact. The three first stages of the waste hierarchy (prevention, re-use and recycling) aim at reducing the amount of waste produced and at giving a new use to materials instead of disposing of them. Although it is possible to re-use and recycle materials, residual waste subsists. As shown in the waste hierarchy these materials should go through a process of energy recovery before final disposal. These processes are (depending on the type of waste): anaerobic digestion and thermal treatment. Over the next sections these disposal methods will be analysed in greater detail.

Table 1 gives shows waste arisings by method and gives a perspective of the most common disposal methods. The number of sites permitted and the quantity of waste processed per method shows that landfill was preferred to incineration. The data also shows that the use of incineration increased from 2011 to 2012.

Table 1. Waste arisings by method in England and Wales in 2012, Environment Agency in http://www.environmentagency.gov.uk/research/library/data/150322.aspx [accessed online on 24th February 2014]

Waste management method	Sites permitted at end 2012	Sites that accepted waste in 2012	Millions tonnes managed in 2012	Percentage change from 2000 to 2012	Percentage change from 2011 to 2012
Landfill	510	380	43.9	-48.0	-6.3
Transfer	3,478	2,677	41.2	1.6	-0.9
Treatment	2,319	1,649	46.3	309.9	11.0
Metal recycling	2,662	1,316	15.3	58.5	-6.3
Incineration	123	82	7.1	-	7.7
Use of waste	219	163	4.0	-	110.2
Land disposal	199	114	8.6	-	220.7
Total	**9,510**	**6,381**	**166.4**	**-**	**5.5**

2. Waste Disposal Methods

2.1 Recycling

Recycling is defined as the process of transforming waste into new material so that it can be given a new use. There is evidence to suggest that ancient civilizations would reuse metals during times of resource depletion such as during a war (Bilitewski, 1997). Victorian records present evidence of domestic materials such as tin cans that would be applied to other situations after being used. Nowadays, recycling has become an increasingly important disposal method as a result of the implementation of environmental legislation. Recycling targets imposed by EU legislation have been increasing over time (Incineration of Municipal Solid Waste, 2013).

2.2 Composting and Anaerobic digestion

Composting is a waste management method in which the biological material is converted into a new use in agriculture. This method, which is also considered an energy-from-waste technology is applied only to biological material and its main end application is in agriculture. In anaerobic digestion, biological mater is broken down (in a similar process to composting). The resulting biogas from the process can then be used as a fuel in energy recovery processes (Anaerobic Digestion Strategy and Action Plan, 2011).

2.3 Thermal treatment

Thermal treatment or energy-from-waste (EfW) is a waste treatment method that makes use of a chemical reaction between waste (as a fuel) and oxygen. This method, as mentioned before, is particularly relevant as it sits on the penultimate stage of the waste hierarchy where energy recovery takes place and thus it is a preferred option to landfill disposal. Another important aspect of thermal treatment is that it reduces the mass of waste thus taking up less space on the final stage of disposal. Thermal treatment processes can be divided into two major categories: Incineration and Advanced thermal treatment (Soderman, 2003).

The difference between these two methods is the quantity of oxygen involved in the chemical reaction with the waste. Figure 2 reflects the quantity of oxygen associated to thermal treatment systems.

Appropriate waste characteristics include high calorific value and low moisture content. These aspects will be further described over the next section.

Incineration involves a reaction with excess oxygen that will ensure complete combustion. Pyrolysis and gasification are defined as advanced thermal treatment because these processes require less oxygen than what is needed to combust the fuel. Pyrolysis takes place in an oxygen starved environment whilst gasification takes place in partial air.

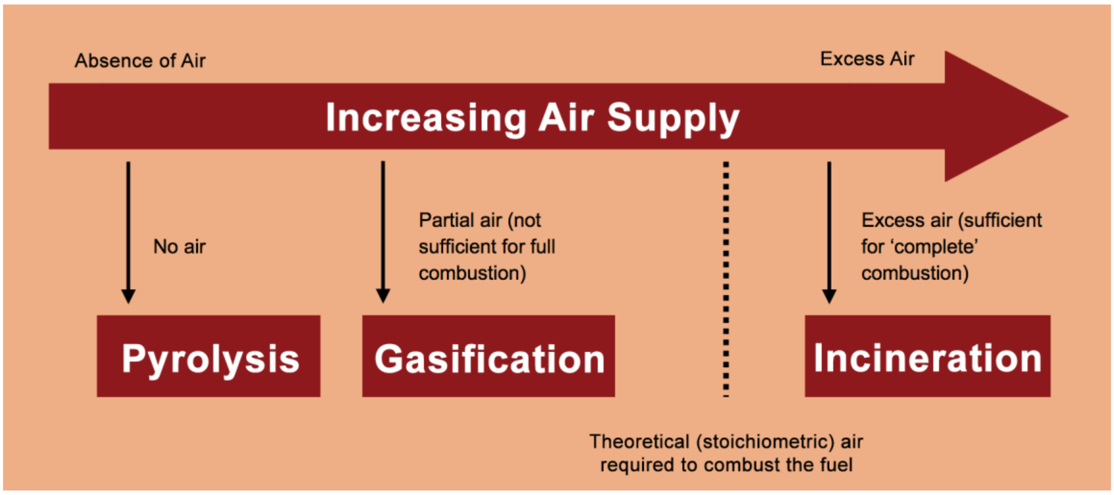


Figure 2. Relationship between level of oxygen and thermal treatment technology (adapted from DEFRA report on Incineration of Municipal Solid Waste, February 2013)

2.3.1 Incineration

Incineration involves a chemical reaction between waste and excess oxygen. This type of system may have an energy system associated to it or not. In the UK, all operating incinerators have an energy recovery system in place (Fichtner, 2004). In incineration systems the waste is fully oxidised which requires greater quantities of oxygen to ensure the process. Typically, incineration plants operate at 850°C or above. Inert materials are collected at the final stage of the process as bottom ash (Incineration of Municipal Solid Waste, 2013).

Incineration consists of the combustion of waste in an oxygen rich environment. The image on figure 3 shows a diagram of a typical incineration plant and its main component parts.

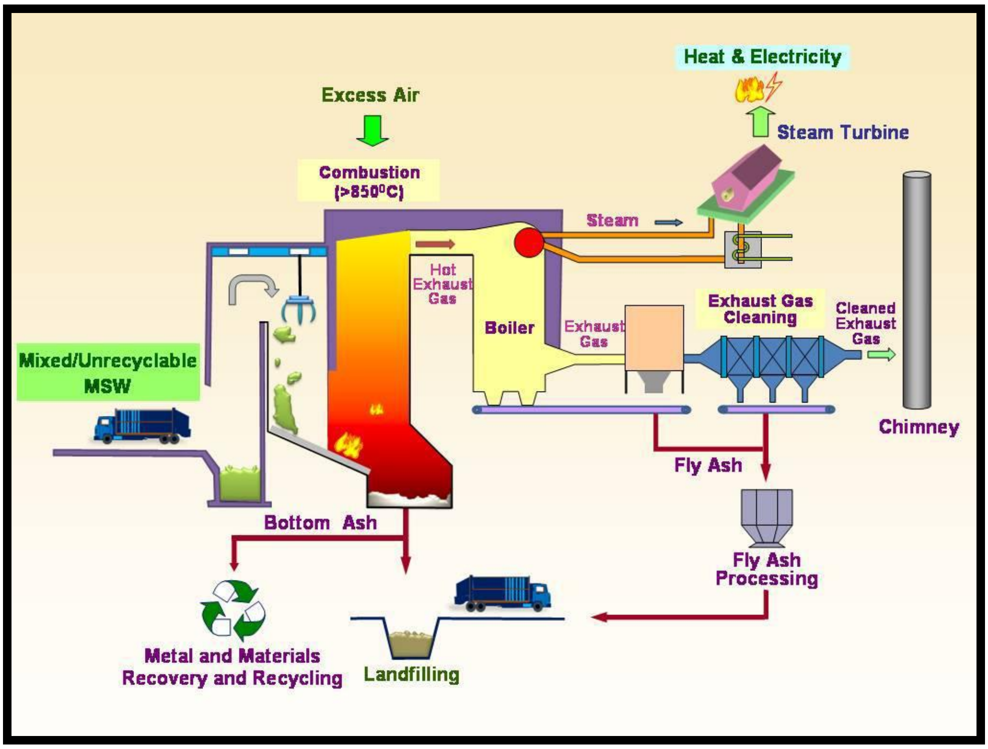


Figure 3. Typical incineration flowchart. Environmental Protection Department of Hong Kong, in http://www.epd.gov.hk/epd/english/environmentinhk/waste/prob_solutions/WFdev_IWMFtech.html [accessed: 7th November 2011]

The various parts of an incineration plant can be summarised as follows:

The waste is tipped into the reception pit. This ensures a constant quantity of waste is always available to maintain the thermal process.

The waste is then tipped into the combustion chamber. At this stage the air enters the system as primary then secondary air. The primary air enters the chamber through openings under the grates while the secondary air enters the chamber through an opening located above the area where combustion takes place. These components ensure complete combustion of the waste and manipulate the orientation and intensity of the flame created. Controlling these characteristics will prevent damage to the walls of the combustion chamber, which, otherwise, could result in blockage of the openings through excessive production of chars and other particles.

There are three types of grate: roller grate, reciprocating grate and reversed feed grates.

The chamber can also have different design configurations: counter-flow firing, middle-flow firing or parallel-flow firing. The design of the grate will influence the flame direction. The gases created from this stage ascend in the chamber and pass through the boiler.

The steam resulting from this stage goes through a steam turbine where electricity is produced. It is also possible to recover heat from the EfW process and these systems occur in a range of settings including sole electricity production and combined electricity and heat production also known as combined heat and power (CHP).

The resulting gases go through a series of cleaning components before being realised into the atmosphere. These vary accordingly to the type of system, pollutants present and emissions control regulations imposed on the industry. Figure 4 shows the necessary steps for gas cleaning. Air pollution control (APC) considers the removal of dioxins and fly ash. APC include electrostatic precipitator, pre-collector, wet scrubber and fabric filter.

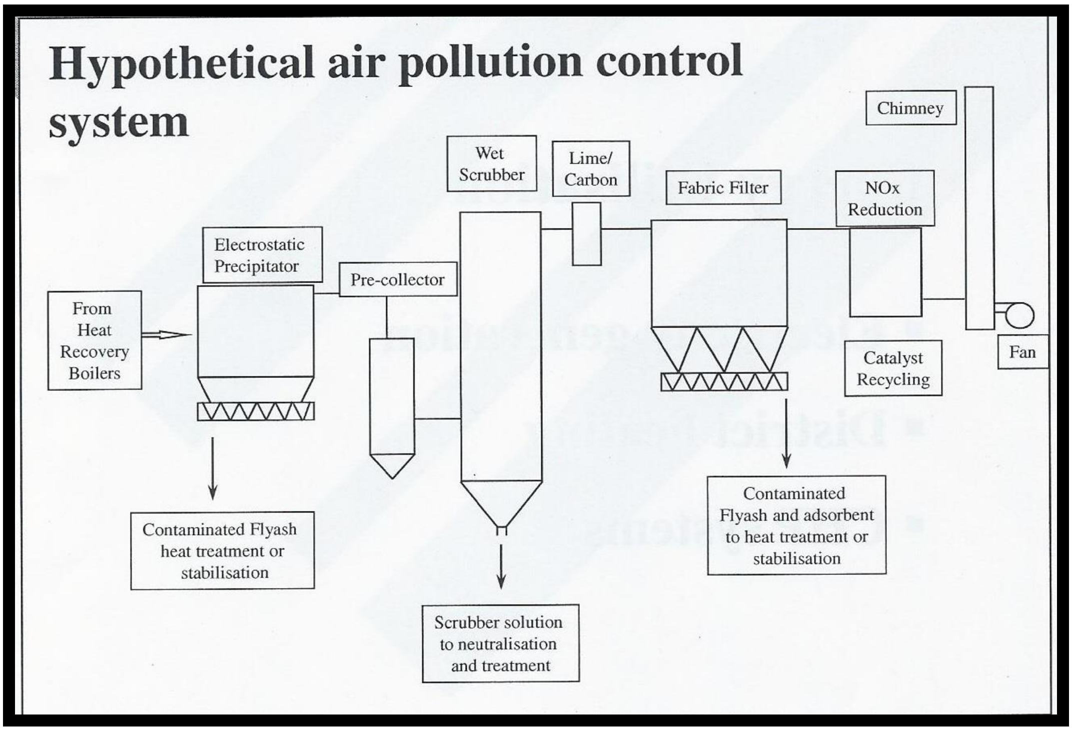


Figure 4. Air pollution technology (Lima et al, 2012)

2.3.2 Advanced thermal treatment

Broadly speaking, the two existing advanced thermal treatment (ATT) systems are pyrolysis and gasification. These systems differ in the amount of oxygen present in the process. In pyrolysis the reaction takes place in an oxygen starved environment and temperatures are set between 450°C and 850°C. In gasification there is only enough oxygen to oxidise the waste and reaction temperatures are usually above 650°C. The quantity of air required to complete combustion of fuel is calculated through the equation of stoichiometry of oxygen/fuel reaction. The equivalence ratios (stoichiometric ratios) for pyro-gasifiers as shown in figure 5 are as follows:

Gasification: 0.2 to 0.4

Pyrolysis: 0 to 0.1

Combustion: approximately 1.0

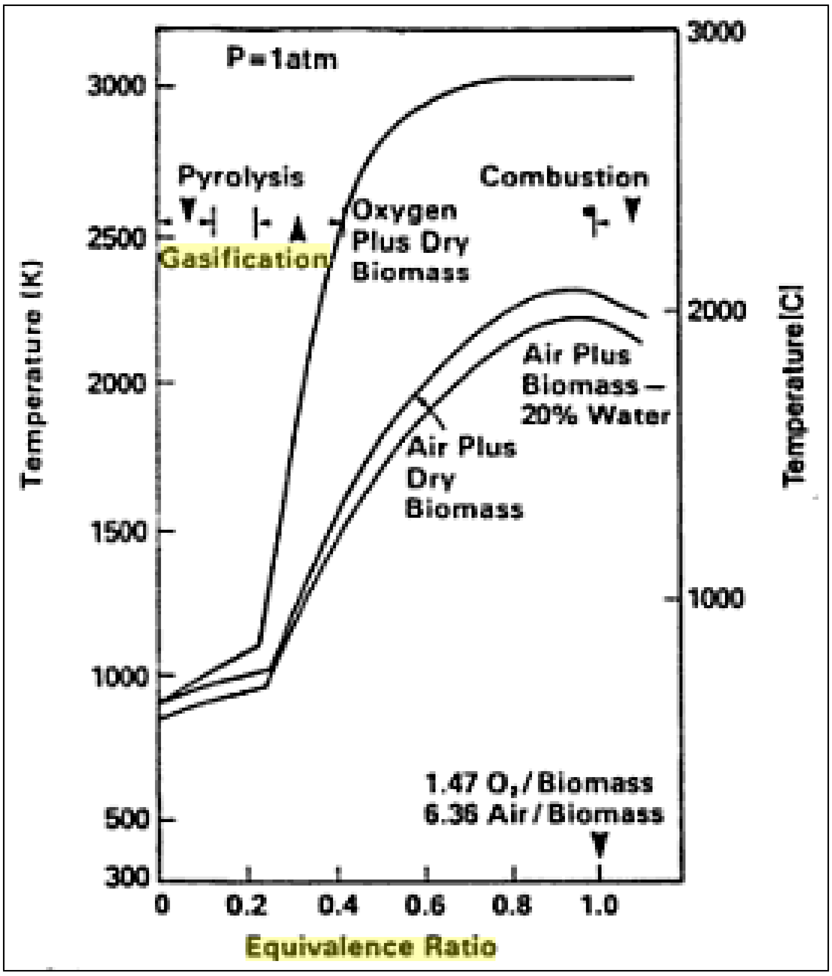


Figure 5. Equivalence ratios for gasification, pyrolysis and combustion. (Reed, T., 1998)

ATT systems require sorting of the waste prior to processing to remove glass and other inorganic materials. In some situations it is necessary to further treat the waste to meet specific requirements on moisture content and particle size. (Advanced Thermal Treatment of Municipal Solid Waste, 2013)

The resulting products from ATT processes include a solid residue (incineration bottom ash aggregate) and a product syngas containing mainly carbon monoxide, hydrogen and hydrocarbons. The resulting syngas from ATT processes varies in calorific value and composition depending on the technology. However, these systems have a tendency for issues associated to tar deposition which can lead to system failure.

The pre-treatment of waste and the technical difficulties associated to tar production and deposition make this a challenging system for processing municipal solid waste (DEFRA, Incineration of Municipal Solid Waste, February 2013).

2.4 Landfill

According to the EU official definition, landfill is a waste disposal site for the deposit of the waste onto or into land (i.e. underground), including internal waste disposal sites (i.e. landfill where a producer of waste is carrying out its own waste disposal at the place of production), and a permanent site (i.e. more than one year) which is used for temporary storage of waste, but excluding facilities where waste is unloaded in order to permit its preparation for further transport for recovery, treatment or disposal elsewhere, and storage of waste prior to recovery or treatment for a period less than three years as a general rule, or storage of waste prior to disposal for a period less than one year. This has been the preferred option for waste disposal in the UK (Towards zero waste, 2010).

However, this disposal method generates environmental issues. Landfill use produces a leachate which is associated to contamination of groundwater, thus potentially polluting water reservoirs; and air, through the emission of odours. Furthermore the use of landfill reduces the available space for construction resulting in the need of using the green belt for this type of activity. Moreover, from a waste management perspective landfill disposal prevents the re-use of materials. This has negative impact on recycling and ultimately will cause extra resources to be used.

These damaging consequences lead to the European Union adopting measures to restrict landfill use through the introduction of the Landfill Directive (1999). In the UK, these measures were initially transposed into the implementation of the Landfill Tax (LFT) in 1996 in order to enable the UK to meet EU targets. The LFT applies to all waste disposed of via landfill at a licensed site and it is charged by weight at two different rates which can be seen in figure 6 (Landfill Directive, 1999).

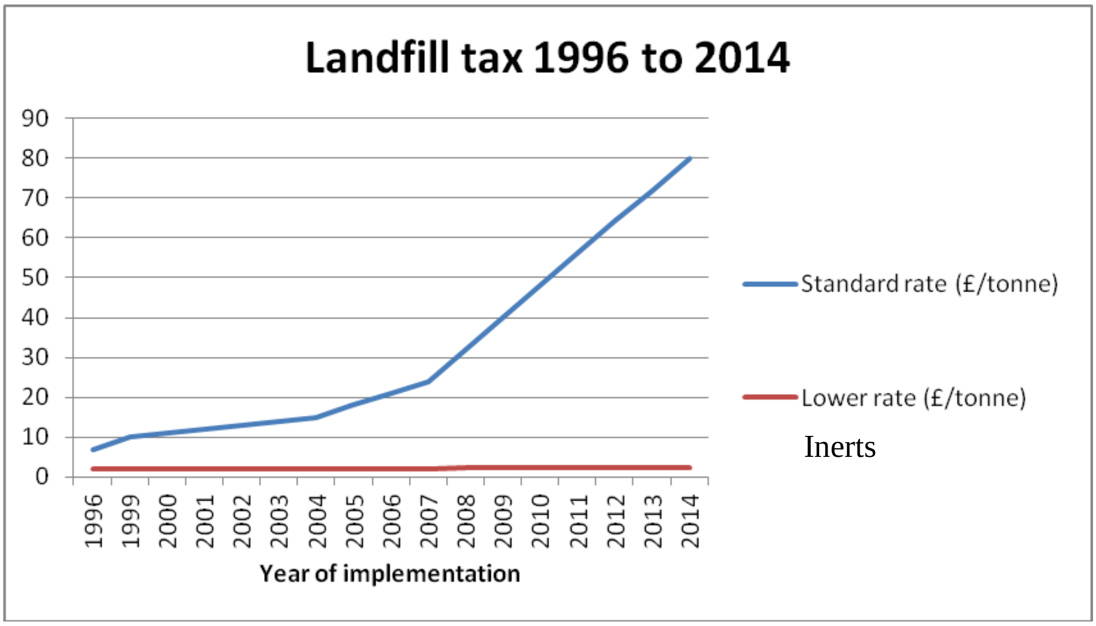


Figure 6. The evolution of landfill tax charge from 1996 to 2014 (HMRC, Landfill Tax 2014)

The lower rate is applied to inerts (inorganic compounds) such as those defined in Landfill Tax (qualifying material). The standard rate is applied to all other types of waste.

Exemptions to the landfill tax include dredgings (materials removed from the water), mining and quarrying waste, pet cemeteries, filing of quarries (under certain conditions) and waste from visiting forces (Defra, 2007).

The implementation of this legislation aims at reducing landfill use whilst making other disposal methods more attractive (Landfill Directive, 1999).

Landfill Directive targets are as follows:

- 50% by 2009 (compared to 1995 levels)
- 35% by 2016 (compared to 1995 levels)

The following section sets about to establish the research question investigated in this thesis and its adopted structure.

3. Aims and objectives of thesis

It was established, earlier in this chapter, that thermal treatment plays an essential role in the waste hierarchy. It stands in the last position before final disposal enabling organic waste mass reduction whilst providing energy recovery. However, evidence points to the fact that this method is more often used in a large-scale set (over 100 000 tonnes per annum). This is mainly because the variability of the material is more pronounced on a smaller scale. Hence, the aim of this study is to contribute to the understanding of the difficulties behind implementing small-scale thermal treatment in small communities.

The objectives of this thesis are:

- To establish the constraints behind setting up small-scale (under 100 000 tonnes per annum) thermal treatment facilities,
- To identify the feasibility parameters of these systems operation via techno-economic modelling

In order to analyse the feasibility of thermal treatment systems projected to smaller tonnages (less than 100 000 tonnes per annum), the following parameters were considered since these are mainly responsible for determining the performance of thermal treatment facilities (WRAP, A classification scheme to define the quality of waste derived fuels):

- Composition,
- Calorific value
- Moisture content
- Ash content

Thermal treatment benefits from waste-derived fuels which have a high calorific value and low moisture content. Calorific value can be defined as the energy contained in a material which is released during combustion (Lima et al. 2012). Moisture content is defined as the moisture present in waste and affects the calorific value as shown in figure 7.

Ash content is defined by the quantity of inerts present in the waste. Although these particles do not react during the thermal process they will deposit at the end of system and will, thus, require further disposal.

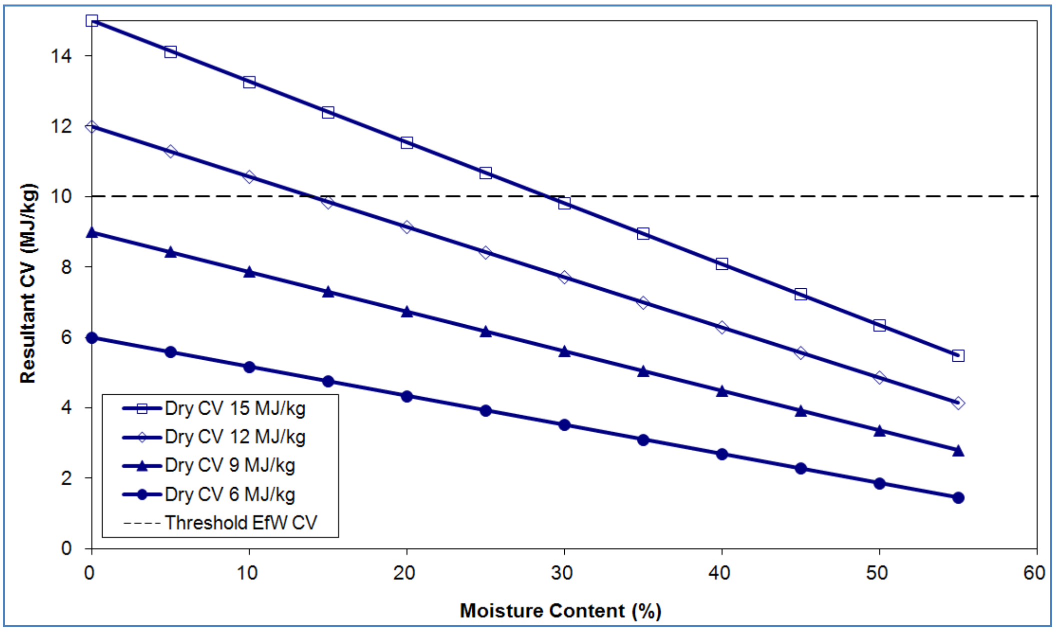


Figure 7. The relationship between calorific value and moisture content (Marsh et al. 2008)

Figure 7 shows that there is an inverse relationship between moisture content and calorific value therefore the greater the moisture content the lower the calorific value will be. Consequently the most appropriate waste materials for EfW systems will be those which have high calorific values and low moisture content (Arena U., 2011).

4. Structure of thesis

Chapter 2, which is divided in two sections, examines published literature on economic models applied to waste management and energy industries, such as coal fired and biomass powerstations.

Chapter 3 includes the description of the case-study area and fuel analysis.

Chapter 4 provides a methodology for the economic model used to analyse the feasibility of the use of small-scale thermal treatment technologies. Scenario analysis will be used to establish the sensitivity of the parameters investigated in the economic model.

Chapter 5 presents the results of the techno-economic model and sensitivity analysis.

Chapter 6 provides a summary of findings.

Literature review

1. Introduction

The aim of this chapter is to establish the key factors driving the analysis of EfW. In order to understand the principles affecting the implementation of EfW in the UK a review of existing literature is presented in this chapter.

Disposing safely of large volumes of municipal waste is a matter of increasing environmental concern, on a global scale. As a case in point, findings from the Environmental Research Foundation (ERF) demonstrate that waste disposal via landfill can result in serious leakage of toxics into groundwater, and hence to public drinking supplies. Other methods of dealing effectively with waste disposal are therefore a priority in terms of protecting the environment, and indeed public safety.

Climate change, which effect has been increased by human action as levels of carbon dioxide production grew with industrial development, has prompted governments world-wide to take action in order to minimise the impact. The Kyoto protocol was organised in order to provide a response to these effects on a global scale (Grubb, 2003).

The need to suppress waste production and control waste disposal resulted in the implementation of the EU Landfill Directive which states that the percentage of waste disposed of via landfill must be reduced by 75% of the 1995 targets by 2010; 50% of the 1995 level by 2013 and 35% of the 1995 level by 2020. However, as shown in Figure 8 the UK has taken longer than the rest of Europe to meet these targets. Traditionally, landfill disposal has been the preferred option in waste management in the UK however new technologies are slowly gaining more relevance and being implemented. Waste can be thermally processed in three different ways, as follows:

- Incineration which requires an excess amount of oxygen
- Gasification which requires a limited amount of oxygen resulting in gas, ash and tar.
- Pyrolysis which occurs in environments with no oxygen and results in gas, oil and tar being produced.

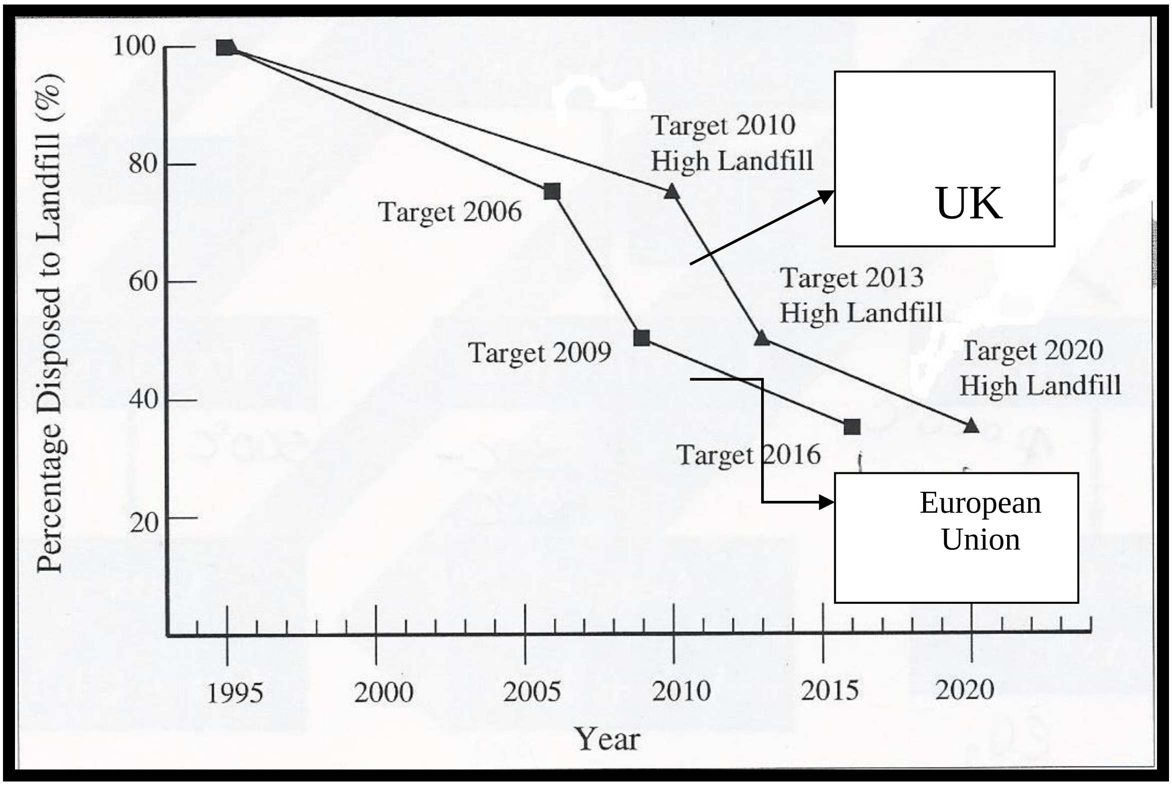


Figure 8. The diagram below shows the progression of the rest of Europe compared to the UK (Lima et al., 2012)

Thermal treatment in the UK is regulated by the EC Waste Incineration Directive. This piece of legislation sets the necessary requirements for the emissions to air, water streams and land; operational procedures; combustion conditions; monitoring requirements and public availability of data. The IPPC

(Integrate Pollution Prevention and Control) sets the best available techniques in the industry.

2. Incineration in the UK

As discussed in Chapter 1 incineration is the preferred method to final landfill disposal in the waste hierarchy. This section presents the aspects surrounding EfW implementation. When considering implementing an EfW system it is important to consider the following costs:

- Capital cost of purchase of the incinerator plant
- Planning and permitting costs
- Maintenance costs

An example cost of building for a thermal treatment facility available on the DEFRA report on thermal treatment systems is given below: (Defra, Advanced thermal treatment of Municipal solid waste). The same report also gives the indication that larger facilities (set to above 350 000 tonnes per annum) offer a lower gate fee.

- £145 - £200 m (for a moving grate incineration facility set to 150 000 tonnes per annum to 350 000 tonnes per annum)

The main sources revenue for this type of facility is the sale of energy in the form of electricity or heat. Occasionally it may be possible to find an outlet for incineration bottom ash (IBA) which can be used in construction as an aggregate (IBAA). EfW plants must obey to strict planning and permitting regulations. These are applied from the early stages of the process through to the running of the facility and finally to the decommissioning of the facility. (DEFRA, Incineration of municipal solid waste, February 2013)

In the planning process it is necessary to consult all the relevant parties including the Local Authority (LA) and the community. Having held discussions with the planning authority it is necessary then to submit a planning application to the LA, which will then issue a decision notice. Should this be favourable then pre-commencement conditions can be discharged. According to DEFRA the following must be considered when assessing the feasibility of an EfW plant: (WRAP, EfW development guidance)

- Location where the facility will be implemented
- The type of waste processed at the facility and to ensure this is available throughout the life of the EfW plant
- Energy production, requirements, end user and associated costs
- Running of the facility
- Available government incentives
- Gate fees and revenues
- Planning and permitting
- CAPEX and OPEX

An environmental permit is required to operate an EfW facility. These are issued by the Environment Agency (EA) which is also responsible for ensuring the facility runs within the legal limits. Table 2 lists the existing thermal treatment facilities in the UK.

Table 2. List of existing thermal treatment plants in the UK (Adapted from DEFRA report February 2013)

Incinerator plant	**Scale**	**Energy recovery**	**Established**
Edmonton, London	675000 tpa	55MWe	1975
SELCHP, London	420000 tpa	35MWe	1994
Tysesley, Birmingham	350000 tpa	25MWe	1996
Teesside	390000 tpa	30MWe	1998
Coventry	240000 tpa	17.7MWe 7.5MWth	1975
Stoke	200000 tpa	12.5MWe	1997
Marchwood, Southampton	165000 tpa	17MWe	2004
Portsmouth	165000 tpa	17MWe	2005
Nottingham	160000 tpa	14.4MWe 44.2MWth	1973
Sheffield	225000 tpa	17MWe 39MWth	2006
Wolverhampton	110000 tpa	7MWe	1998
Dudley	105000 tpa	7MWe	1998
Chineham	102000 tpa	7MWe	2003
Kirklees	136000 tpa	10MWe	2002
Grimsby	56000 tpa	3.2MWe 3.3MWth	2004

Isles of Scilly	3700 tpa	No energy recovered	1987
Allington	500000 tpa	43MWe	2008
Bolton	130000 tpa	7MWe	1971
Ardley, Oxfordshire	300000 tpa	24MWe	2014
Lakeside, Colnbrook	410000 tpa	37MWe	2010
Runcorn	850000 tpa	86MWe	2013/14
Devon	275000 tpa	20MWe	2014
Cornwall	240000 tpa	16MWe	2014
Crymlyn burrows	170000 tpa	5.7MWe	2002
Lerwick	22000 tpa	7MWe	1998
Dundee	120000 tpa	8.3MWe	1999
Dumfries	65000 tpa	5MWe	2009

It is possible to conclude from Table 2 that the majority of the existing facilities in the UK have been implemented in areas of large communities and have been projected to process more than 100 000 tpa. Only a small number of facilities have been implemented in rural areas where communities are spread through a large area and have been set to process less than 100 000 tpa.

3. Pyrolysis and Gasification

Pyrolysis and gasification are referred to as advanced thermal treatment. The difference between these methods and incineration is that a lower amount of oxygen is used in the thermal reaction. Figure 9 shows that processes associated to pyrolysis and gasification and resulting materials power generation process.

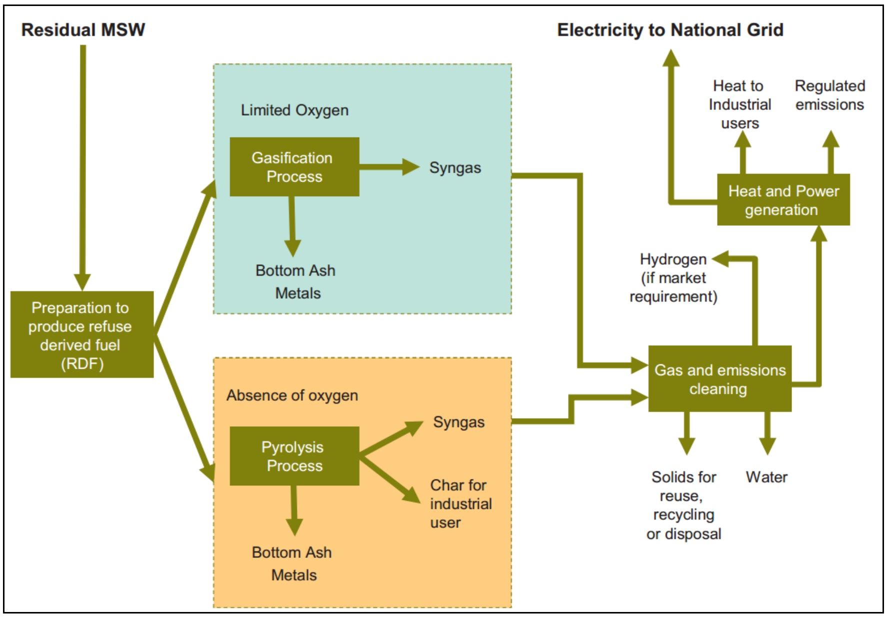


Figure 9. A representation of the gasification and pyrolysis processes (Defra, 2007)

Incineration is a method of disposal that can be located close to the point of waste collection thus reducing the costs of transportation and minimising the impact of waste disposal. Incineration reduces the volume of waste to 10% of its initial value and 33% of its original mass. A sterile ash is produced as a result of this process. The major point here is that, importantly, the process can be used as a source of energy which could feasibly be used to offset energy costs. An added advantage is that the bottom ash resulting from the process can be also sold to the aggregates industries for instance, generating another form of income. Overall this option is therefore more environmentally acceptable (RPS, 2008).

There is a high cost associated with initial investment in these systems. Operational and maintenance costs are also high. The generation of toxic pollutants must also be suppressed and controlled, also resulting in high costs. Plants operating prior to the implementation of the Waste Incineration Directive (WID) in the UK did not have efficient pollutants control systems which resulted in a very negative public opinion which persists years after the implementation of this regulation (RPS, 2008).

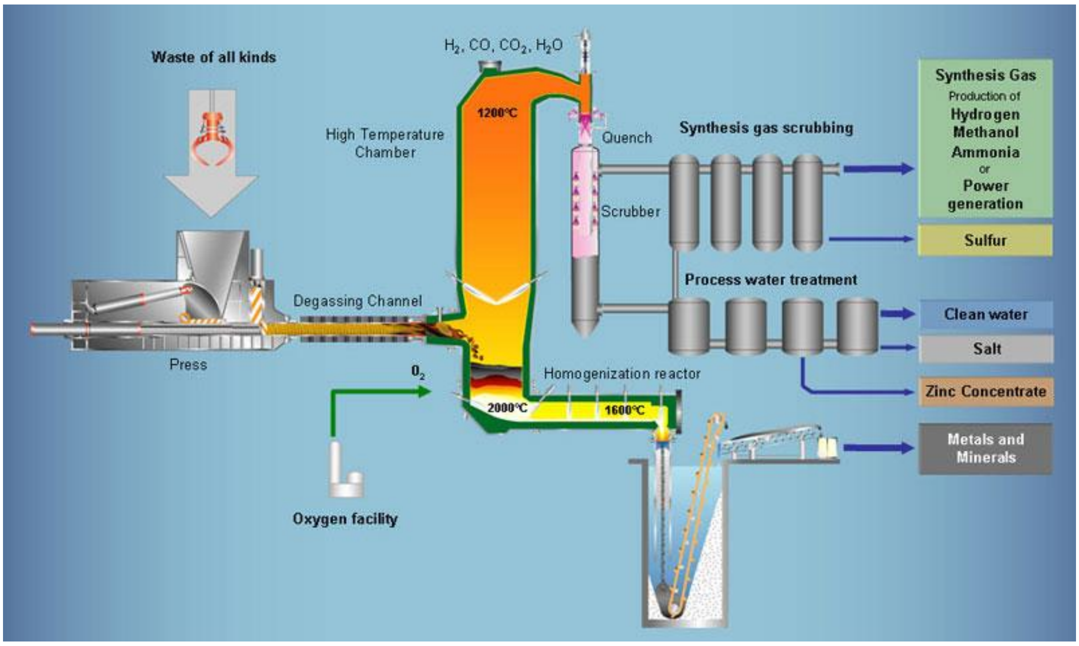


Figure 10 Thermoselect process diagram, an example of gasification system. Interstate Waste technologies available at http://www.interstatewastetechnologies.com/images/Process-Overview.jpg [accessed online 15th February 2014]

3.2.1 Operating costs

High costs are associated with most stages of Incineration operations. When projecting such a system it is necessary to consider:

- Sources of income

- Primary costs
- Availability of operation

The main potential sources of income are:

- Energy sales; originating from the direct sale of energy created in the process
- Gate fees; charged as materials arrive on site
- Recovery of recyclables; resulting from the sale of recyclables that can be recovered from the processed materials
- Recovery of Ferrous (magnetic) metal; resulting from the sale of materials arising from the recovery of metal in the ash
- Bulk residues (off-site); originating from the sale of residues

Primary costs originate from:

- Residues disposal; cost associated with bottom ash disposal
- Plant raw materials; cost of essential materials for operation (e.g. activated carbon used in cleaning systems)
- Maintenance; regular maintenance will result in a cost since when the plant is inoperative it is not producing the materials that will generate profit
- Labour; costs associated with labour such as
- Regulation and monitoring;

While the plant is not operating it is not producing recyclates, nor charging for gate fees, nor profiting from energy sales. This means that while plants are not available to operate they are incurring in major losses. Therefore it is of vital importance to ensure that plants are operating regularly (Boukis I. Et al., 2009).

3.2.2 Electricity and heat generation

The following data presents the income from energy sales and costs of ash disposal, based on a 24-hour operation over an operational period of 365 days. The feedstock material was based on the overall amount of waste presently produced by the MRF operation at the case-study area, LAS recycling (approximately 20 000 tonnes per annum at a net average CV of 12 MJ/kg) as identified in Lima (2012, a).

No fuel enhancers were considered in these calculations (although details of these can be found in Lima (2012, b). Government incentives such as the Renewable Heat Incentive or Renewable Obligation Certificates were not considered as these will be awarded depending on the quantity of biomass present in the waste. Hence the case for consideration is a nominal operating scenario without additional potential benefits.

Generally, advanced thermal treatment systems must operate continuously. This will ensure that production of electricity and/or heat is continuous and reliable. The production of electricity is in many cases a primary source of income in EfW plants consequently every day the plant is not operating will result in a loss of the plant operators. This matter should receive special attention when maintenance is required. Contingency plans must be in place to ensure that the economic feasibility of the plant is not compromised (Ilex Energy, 2005).

Villanueva Perales et al (2011) analyses the economical feasibility of ethanol production through the application of a techno-economic model. This model includes the design and modelling of the process and selection of catalysts. Results indicate that the high price of a crucial component in the operation – rhodium catalysts – leads to higher production costs. The relationship between high pressure and lower operating costs is also identified in Trippe (2011) where the impact of alternative gasification configuration on capital investment and production costs is analysed. This paper also concludes that the introduction of additional steam as a gasification agent results in increased production costs. Wood (2011) investigates the feasibility of biomass CHP systems and concludes that the optimum situation is achieved when electricity and heat are sold directly on-site and when the plant operates continually. In Wang et al (2011) the economic viability of hybrid heating CHP systems is explored. The paper concludes that fuel and heating costs are dominant contributors to operating costs.

The factors identified in these papers contribute to the understanding of the research developed in this thesis. It is particularly relevant the impact of higher pressure in production cost is a technical detail of great significance. The negative impact of transport on the model is also identified. The authors also suggest that ideally these systems should operate continually.

4.Political directives on waste management

In the UK incineration activities in Wales and England are regulated by the Environment Agency. The UK Government is the entity responsible for issuing the legislation in the UK.

The Waste Strategy 2007 stipulates that from the waste which cannot be recycled energy recovery must occur. The Government uses ROCS and enhanced capital allowances to encourage the use of the new technologies. The Waste Policy Review 2007 identifies key priorities for the government. These are:

- The diversion of waste sent to landfill by increase of the recycling and recovery rates;
- Focus on the carbon reduction benefits from the use of the waste hierarchy;

- Use of anaerobic digestion in the treatment of food waste;
- Use of methane originating from existing landfills

According to the government objective the aim of EfW is to recover the most energy possible from residual wastes not to process the most waste into energy.

The UK complies with EU legislation which has been transposed into domestic legislation: such as the IPPC Directive, Waste Framework Directive, Hazardous Waste Directive and Waste Incineration Directive (WID). The WID is the most relevant piece of legislation. Significantly, it does not cover:

- Vegetable waste
- Waste from virgin pulp and paper making
- Untreated wood waste
- Cork waste
- Radioactive waste
- Animal carcasses
- Experimental plants processing quantities under 50 000 tpa

Incineration activities are regulated in the UK by:

- Part A1: The Environment Agency
- Part A2: The local authority (LA)
- Part B: Strict monitoring of air pollution controlled by EA

A permit application must include:

- Description of the process (design, components, controls)
- BAT (Best Available Technique) assessment

- Emissions to the Environment including monitoring
- Dispersion modelling/environmental impact assessment
- Health risk assessment
- Efficient use of materials, water and energy
- Noise and odour
- Management

EPR Permit restraints:

- Plants must be compliant with permit conditions
- It is only possible to operate a plant to the extent authorised by a permit
- BAT must be in place, with no significant pollution being caused
- When plants cease to operate action must be taken to ensure pollutants are controlled

5. Resulting products

The parameters influencing the products of an EfW system such as electricity and heat are commented in this section.

Bridgwater et al (2002) compares different methods for power production in EfW systems. In this paper, conclusions suggest that the electricity production costs converge at the larger scale with the average electricity price paid in the EU. Therefore, there is potential for selling electricity directly to large consumers. Furthermore, this paper suggests the following situations in which profitability can be increased:

- Selection of areas where electricity local price is higher than average

- Selection of situations where waste feedstocks can attract a gate fee rather than a cost
- Selection of areas where there is a potential for co-production of speciality chemicals
- Sale of excess char

Previous experience resulting from the direct contact with this industry has shown that it is possible to locate areas where local price of electricity is higher than average but this will not necessarily drive the selection of a location to implement an EfW system. Furthermore, EfW systems fuelled by MSW derived fuels do not have the scope to attract significant gate fees instead this has fuel has been shown to operate with technical limitations. Vanreppelen et al (2011) investigates the feasibility of melamine formaldehyde resins (MF) and particle board (PB) in the production of activated carbon. Results show that the production of carbon at lower costs is associated to large manufacturers. By doubling the input rate by 2 tonnes per hour a significant reduction of 24% on selling price is achieved. This paper establishes a link between plant size and product cost.

In Wood (2011) a techno-economic model is employed and scenario analysis was performed to ascertain the feasibility of BCHP. Results show that there is little variation in electricity break even selling price. The study further concludes that generally smaller systems are less profitable than larger systems. These findings are relevant to the research developed because they describe feasibility parameters for small-scale systems. In particular, the fact that a continuous operation is more favourable reflects the negative impact of breakdown or maintenance time on the system's economic feasibility. As on-site direct sale of electricity and heat are feasible this shows that grid-connections scenarios affect economic feasibility.

In Mcllveen-Wright (2013) an assessment of electricity generation potential of MSW in Lagos, Nigeria is made. The model developed is based on the evaluation of BESP (break-even electricity selling price) and this variable is analysed against gate fee. The BESP for 50 MWe is £9.57 £/ MWh for a 15 years repayment period and gate fee set a £50/tonne. Results suggest that a decrease in load factor impacts on BESP (Best electricity selling price). If capital costs are higher than 50% of load factor than it would not be possible to generate electricity at £39.5/MWh (current market price in Nigeria). The technology is still viable at a maximum 25% above base case capital costs. The results show the parameters within which the technology operates.

6. Capital cost

Capital cost – or investment cost – is the amount invested at the start of a project to cover for the cost of the technology.

Wood (2011) investigates the feasibility of BCHP (Biomass fuelled CHP) systems. The paper identifies that small-scale BCHP systems can be economically viable when an attractive method of generating electricity and heat is applied. It also shows that these technologies can be viable without capital grant incentives when cost effective fuels are used.

Dael (2012) makes a comparison between biomass conversion systems. The systems evaluated are digestion of the organic fraction of municipal solid waste, co-digestion of manure and co-substrates and integration. This paper establishes a connection between pre-treatment and investment costs. According to this author the costs of pre-treatment have a greater impact on NPV (net present value).

Two key aspects are identifies in these papers. Firstly, the use of cost effective fuels and an attractive method for electricity generation contribute to a small scale system's feasibility. Secondly, the use of pre-treatment technologies has a negative impact on NPV which reflects the extra resources necessary to implement this technology in a system.

7. Techno-economic models

This chapter aimed at establishing key elements driving the analysis on EfW. In order to identify these factors a literature review including research papers developed in the area of waste management and economic analysis was performed. The information gathered from these papers shows that the preferred method to investigate economic feasibility is to create an economic model where information on chemical and physical properties on the type of waste investigated is included. Some economic model methods include Eclipse, Aspen Plus (Haro 2013), syncity (synthetic city) approach (Kostantinidis 2010) and the application of the Monte Carlo method through sensitivity and scenario analysis (Yassin, L. 2009). The main variables investigates in this model are electricity and heat selling price, capital cost, impact of legislation and running costs.

Further to the variables analysed in the material investigated it was found that calorific value, moisture content and tonnages also have an important role influencing the feasibility parameters of EfW technologies. Direct contact with this industry showed that these factors influence the technical performance of the technology and, therefore, have a serious impact on feasibility.

Over the next chapters a techno-economic model will be described and scenario analysis will be applied. The model will be based on the chemical and physical properties found in the waste streams investigated. Scenario analysis will include variation in chemical and physical content, changes to legislation impacting upon EfW operation and changes to operating periods in the facility.

8. Conclusions

In this chapter the factors driving EfW analysis were presented. Firstly, it has been shown that the negative impact of waste disposal methods such as landfill and growing carbon dioxide production prompted governments on a world scale to issue legislation that would prevent and control activities with an environmental impact. As a result of steps taken, thermal treatment became an important waste disposal method. This method can be divided into the following categories: incineration, gasification and pyrolysis. These waste disposal methods require strict planning procedures that involve the Environment Agency and Local authority. In the UK, the majority of these facilities tend to be scaled above 100 000 tonnes per year and is located around major urban areas. The main political directives affecting these technologies are the Waste Strategy 2007, the Waste Policy Review and the Waste Incineration Directive (WID). ROCs (renewable obligation certificate) were introduced in order to encourage investment in advanced thermal treatment.

In order to analyse EfW technologies it is necessary to investigate both technical aspects and economic aspects. Thus, techno-economic analysis is fundamental in this study.

Case study area (CSA) and fuel analysis description

3.1 Background

As described in the introductory chapter of this thesis, the aim of this study is to firstly establish the constraints behind the implementation of small-scale thermal treatment facilities and, secondly, to determine the parameters within which such an operation is economically feasible.

In order to understand the variables that affect a thermal treatment system, a techno-economic model was constructed. This method allows for an analysis of both the technological and economic factors impacting upon a system and the relationship between them. The techno-economic model was constructed through the use of an excel spreadsheet in which are included details of the EfW operation, electricity generation, waste composition and capital investment. In order to investigate the research question set in the introductory chapter of this thesis a case-study area (CSA) was selected. This will allow for the analysis of a real-life situation offering more accurate conclusions. A series of scenarios will be analysed in a techno-economic model in order to establish the sensitivity of the parameters analysed. These scenarios will cover a range of situations affecting waste composition, calorific value and moisture content of fuel and legislation changes.

The next section is dedicated to the description of the CSA, including characteristics of the environment where it is located and explanation of the activity that takes place in the business, including the waste streams processed onsite and its physical characteristics (moisture content and calorific value). The next chapter defines the techno-economic model which is constructed based on literature review and fed with CSA data to provide output based on small scale activities. Having established the methodology for the techno-economic model, a group of scenarios will be presented. The techno-economic model analyses these scenarios which incorporate real-life situations into this study given that the background data is from an operating recycling facility. The results of which are then discussed in chapter 5 of this thesis.

3.2 Case-study area

The case-study area (CSA) is the area of activity of LAS Recycling Ltd which encompasses a 30-mile radius from Lampeter. Figure 1 shows the location of Lampeter in mid-Wales. Within this area, household waste (HW) and co-mingled recycling waste (CRW) collections take place every week (Owen, 2008). Household waste is also referred to as general waste and it is composed by a mixture of materials such as plastic and paper but shows great levels of contamination from biodegradable sources. Co-mingled recycled waste is composed by recyclates namely plastic, paper and metals. This stream tends to present little contamination from biodegradable sources. Table 3 represents the residues resulting from these waste streams.

Although LAS Recycling Ltd operates with other types of waste streams, household and recycling wastes are the focus of this research. These ancillary activities, accounting for about 20% of the overall activity, will have a reduced impact upon a potential thermal treatment system because they account for a smaller quantity of the total waste processed onsite. The total area of activity includes part of the County of Ceredigion, Powys and Carmarthenshire. The main economic activities in the area are the production of meat and agricultural products. The industrial activity is concentrated in small industrial areas in the following locations: Felinfach, Lampeter and Aberaeron.

Figure 11. Map indicating the location of the case-study area. Ordnance survey, Getamap, 2014

The CSA includes a Materials recovery facility (MRF) that processes 20 000 tonnes per annum of co-mingled recycled waste and household waste. A MRF is a separation system that aims at segregating certain types of material from a waste stream. It is primarily used to separate recyclates from a waste stream. The MRF at the CSA will be described in greater detail over the next section.

3.2.1 Materials recovery facility (MRF)

Figure 2 represents the process that takes place at the MRF on the CSA. The two waste streams collected (HW and CRW) are processed separately in the MRF and, therefore, there are two sets of the residues identified in the diagram: trommel and ballistic separator residues and end-of-belt residue.

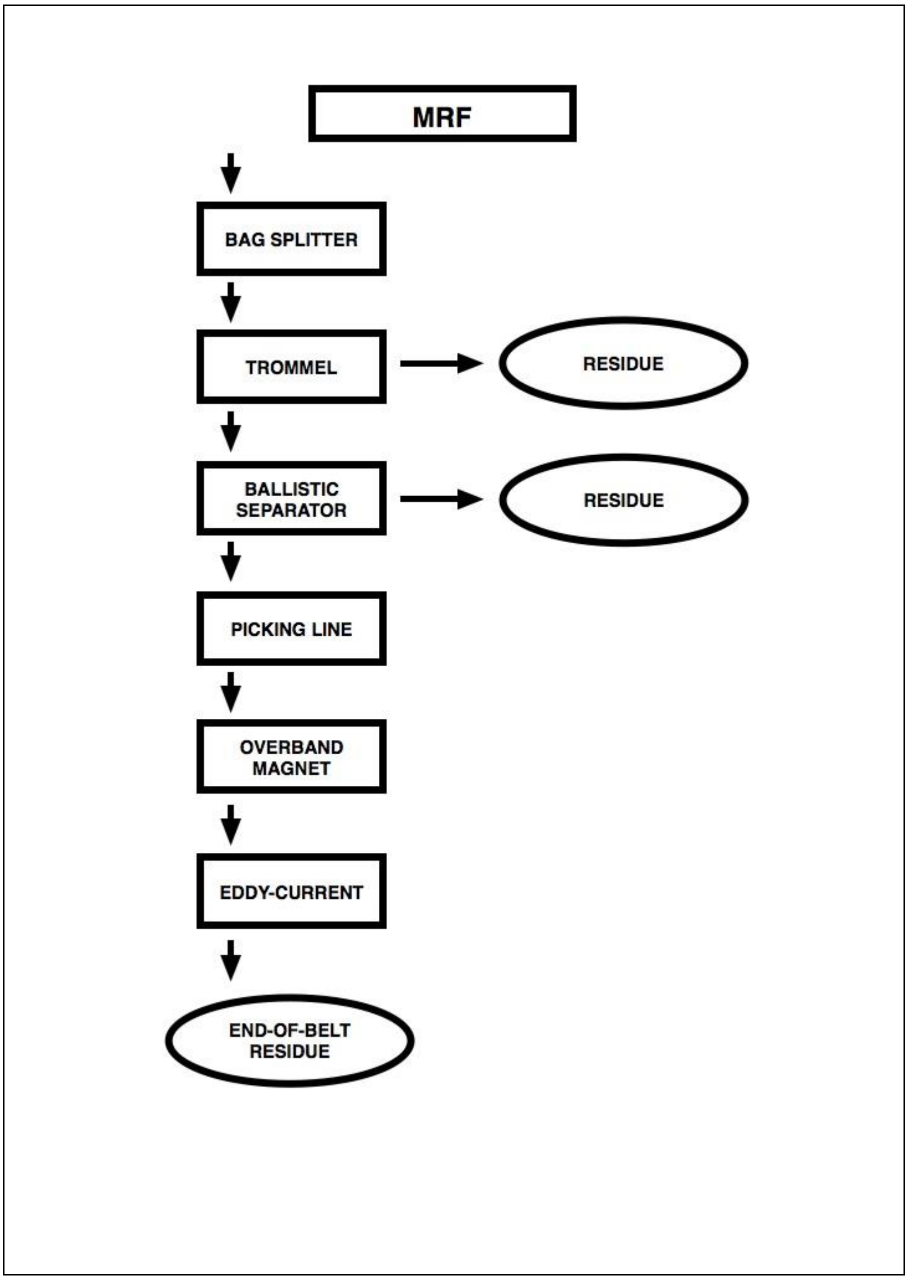


Figure 12. Diagramatic representation of the Materials recovery facility at the CSA

At the beginning of the process, the bags containing the waste go into a bag splitter allowing the waste to be processed in stream. After this stage an operator will manually remove bulky items or large pieces of fabric as these are likely to cause damage or prevent the mechanisms in the process to work normally.

After the initial stage, the waste passes through a trommel and a ballistic separator. In these components, small particles (under 5 cm) are removed from the waste stream. These systems operate by agitating the waste in a cylinder which allows particles of a certain size to fall through the sieves. The trommel removes three-dimensional particles, such as plastic bottle tops, whilst the ballistic separator removes two-dimensional particles from the waste stream such as paper and card. The materials removed fall through to a cage originating two of the three types of residue in the process.

In the next stage of the process the waste goes into a picking line where operators remove certain types of material from the waste stream. If household waste is being processed, the operators will select from the waste stream any materials that have recyclable value such paper or plastic. This type of selection is known as positive picking since the material selected is the one that has commercial value. On the contrary, if co-mingled recyclate waste is processed then negative picking will be used to remove materials that cannot be recycled from the waste stream.

Finally, the waste goes into an overband magnet and an eddy-current separator where metallic materials are removed from the waste stream. After this stage the waste reaches the end of the process and it is referred to as end-of-belt residue.

From the total amount of waste processed in the MRF the residue from the trommel account for 2.6% household unsorted waste and 2.2% co-mingled recycled waste, the residue resulting from the ballistic separator accounts for 2.8% household unsorted waste and 2.2% co-mingled recycled waste and the residue resulting from the end of the process – also known as end-of-belt residue – accounts for 4.4% household unsorted waste and 5.6% co-mingled recycled waste.

The end-of-belt residue resulting from the household waste process does not have any further recycling value, it is mainly composed of very fine particles, and it is disposed of via landfill. However, the same residue resulting from the process of the co-mingled recycled waste has a relatively greater quantity of plastic and paper than household waste. The MRF process delivers a greater quantity of household waste end-of-belt residue than of co-mingled recycled end-of-belt residue. If on the one hand the residue originating from the process of the co-mingled recycled waste is more adequate to thermal treatment, on the other hand a lot less of this material is processed which results in a lower overall calorific value. This will be further discussed over the next sections.

Figure 13. Image of a materials recovery facility. LAS Recycling Ltd. MRF facility [online] Available at [Accessed Accessed on 20th November 2013]

In the CSA, the residue resulting from the MRF process is aimed at being disposed of through thermal treatment processes. As described in chapter 1, in order to establish the feasibility of thermal treatment systems it is important to select a fuel with adequate moisture content and calorific value and composition. The next sections describe the methodology undertaken to establish waste composition, moisture content and calorific value.

3.2.2 Waste characterisation results

The following table represents the waste streams analysed in the waste characterisation and its relationship to the MRF components. As mentioned at the beginning of this chapter household unsorted waste presents great levels of contamination from biodegradable sources for example expired foods and nappies. As this stream is processed through the MRF the following three residues originate from the process: trommel fines, ballistic separator fines and end-of-belt residue. The trommel fines tend to be small particles of plastic, paper or metal for example bottle tops. The co-mingled recycled waste tends to be composed of materials that are destined for recycling.

Table 3. The resulting six residues from the MRF process

	Trommel	**Ballistic separator**	**End-of-belt**
Household unsorted waste	Household unsorted trommel residue	Household unsorted ballistic separator residue	Household unsorted end-of-belt residue
Co-mingled recycled waste	Co-mingled recycled trommel residue	Co-mingled recycled ballistic separator residue	Co-mingled recycled end-of-belt residue

Each of these residues was analysed to determine moisture content, calorific value and composition. The results of these tests will be presented below and discussed over the next section. Moisture content and calorific value were determined accordingly to BS EN 14774-3:2009 and BS EN 14918:2009 respectively.

The waste characterisation, which took place before calorific value and moisture content analysis, separated the waste into the following categories:

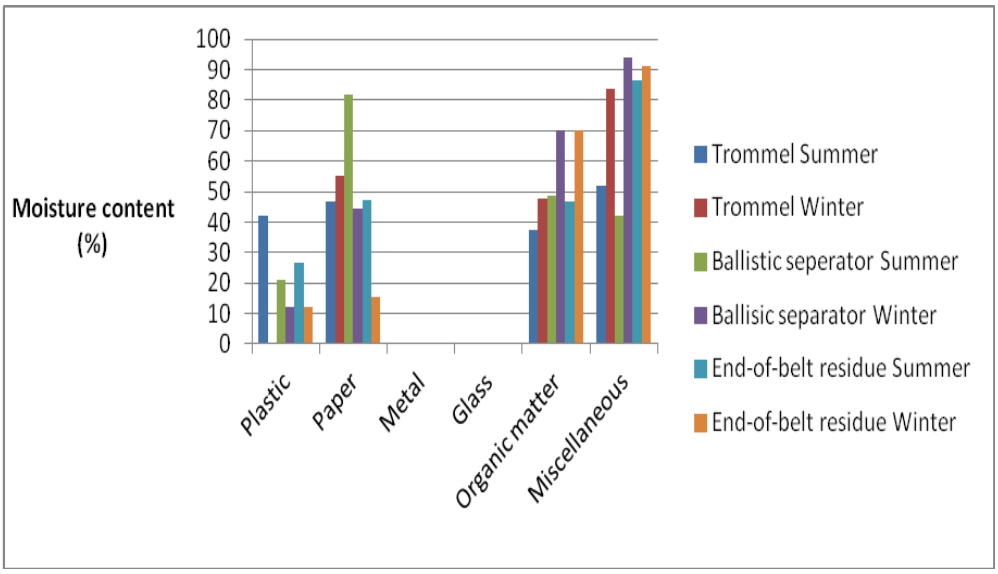
- Paper
- Plastic
- Metal
- Glass
- Organic matter
- Miscellaneous materials

The category above described as organic matter is composed mainly of food and vegetation. The miscellaneous category describes waste materials such as textiles and those that are contaminated such as nappies and cat litter.

Samples of each of these categories were analysed in order to establish moisture content and calorific value of the waste. Each of these tests were performed in the summer and repeated over winter to determine variance with seasonality (Feo and Malvana, 2012). Ash content analysis was excluded from these tests as this material is not reactive during thermal processing these materials are also referred to as inerts and are subject to a different tax rate as they are considered to have less of an effect environmentally.

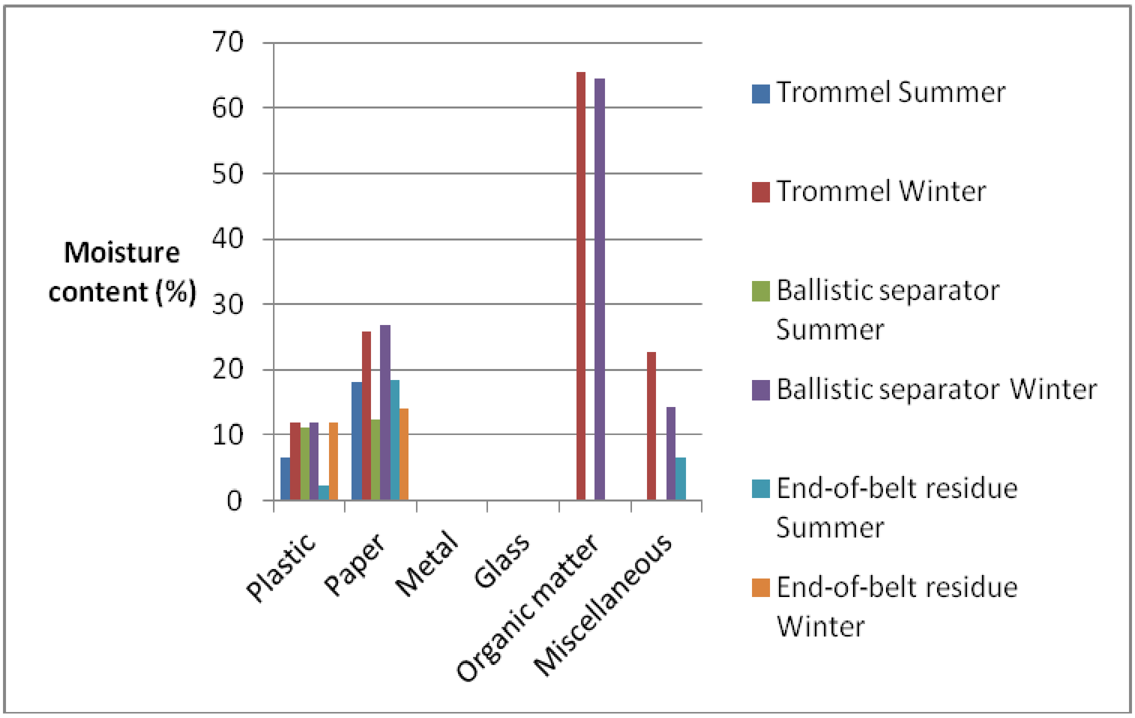
3.2.2.1 Moisture content results

Table 4: Household unsorted residue



Moisture content results are presented in tables 4 (Household unsorted residues) and 5 (co-mingled recycled residues). In each table a comparison between summer and winter results is presented in order to establish the effect of seasonality. In table 4 results show that there is an overall increase in moisture content in the winter. This results from the presence of organic matter and miscellaneous categories. Plastic and paper categories show little variance with seasonality. The co-mingled recycled stream reveals a greater increase in moisture content.

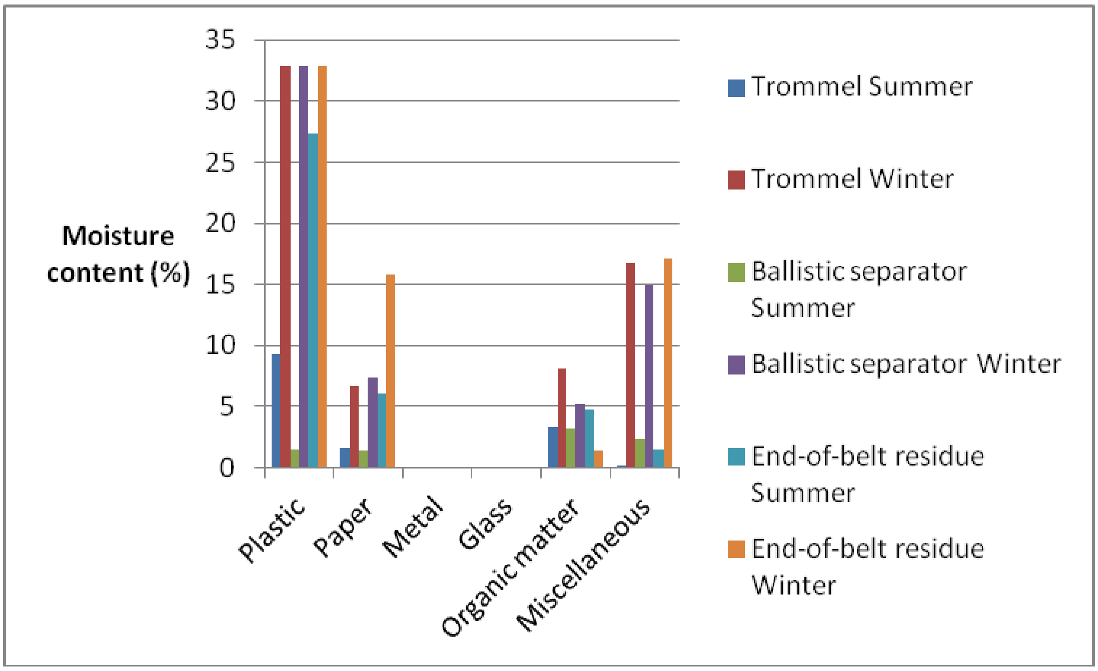
Table 5: Co-mingled recycled residue



Results show that household unsorted trommel residue there is an increase in moisture content in the winter except for a drop in the plastic stream. In the household unsorted ballistic separator stream there is a drop in moisture content in the plastic and paper categories but an increase in the organic matter and miscellaneous categories. In the household unsorted end-of-belt residue there is a drop in moisture content in plastic and paper categories and an increase in the organic matter and miscellaneous categories. In the co-mingled recycled residue stream, an increase is registered in the trommel and ballistic separator streams across all categories. in the end-of-belt stream there is an increase in the plastic category and a slight drop in the paper and miscellaneous categories.

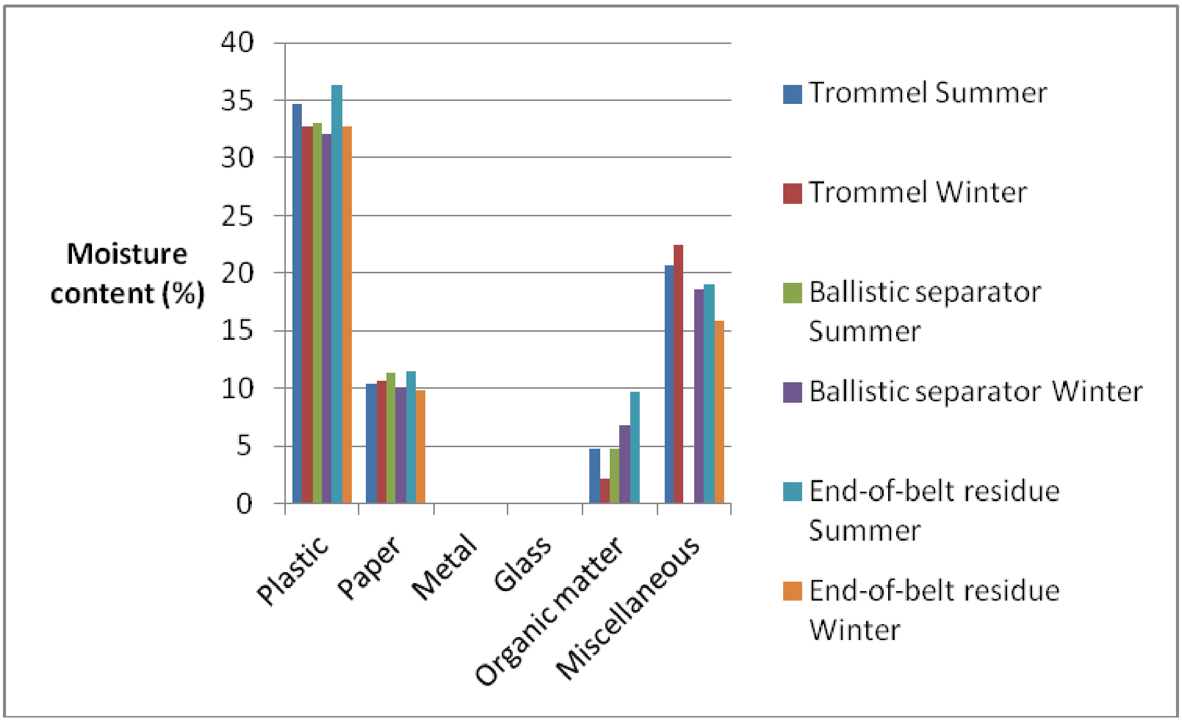
3.2.2.2 Calorific value as received (Ar) results

Table 6: Household unsorted residue



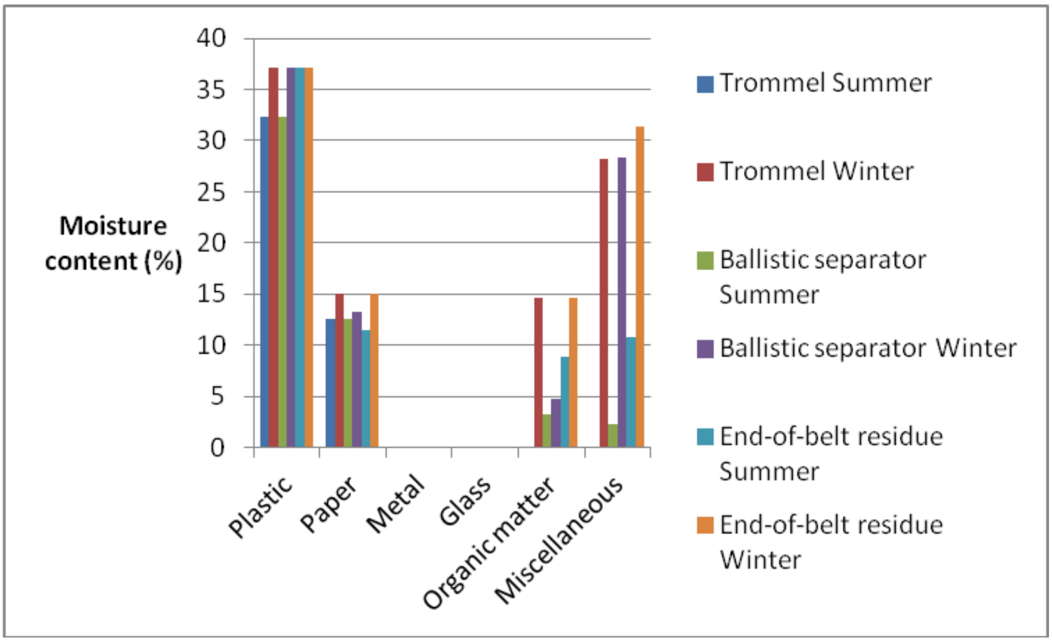
Results of calorific value as received (Ar) are presented in tables 6 (household unsorted residues) and 7 (co-mingled recycled residues). These tables establish a comparison between summer and winter results showing the impact of seasonality on calorific value. Summer values show that there is an increase in calorific value over the winter months in the household unsorted waste stream. In the co-mingled recycled waste there is a slight drop in calorific value. In the household unsorted residue an increase in calorific value (Ar) is registered in the winter across all streams and categories with the exception of the organic matter category in the trommel stream.

Table 7: Co-mingled recycled residue



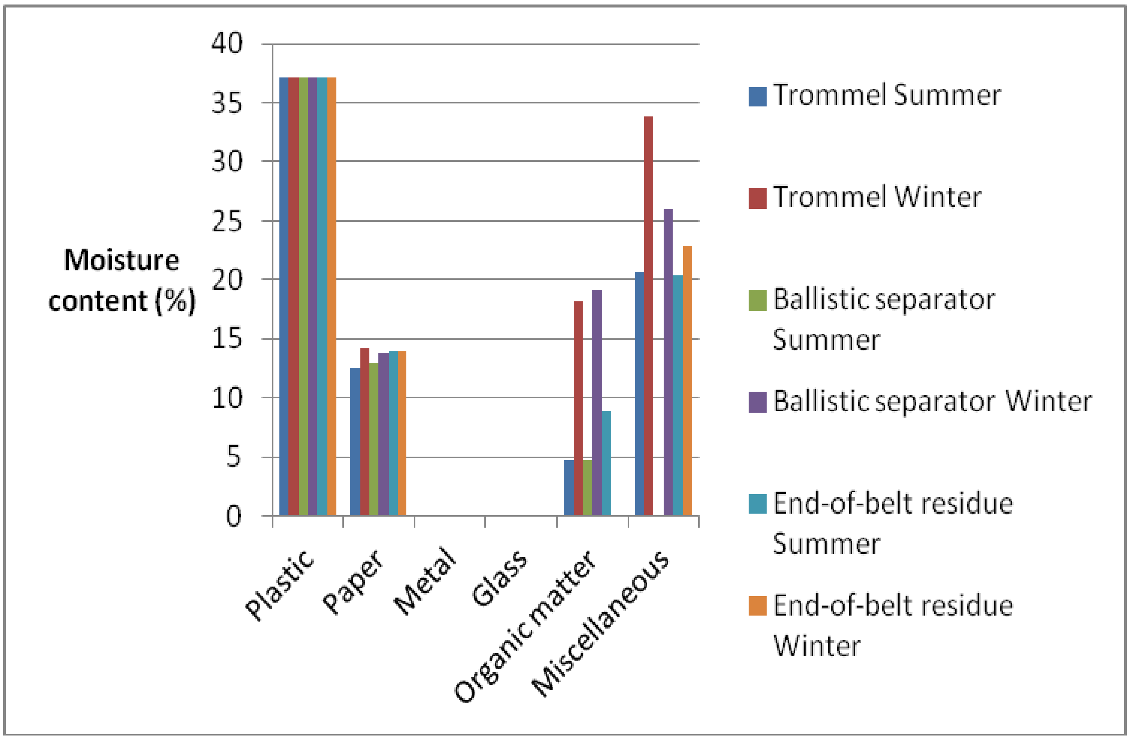
3.2.2.3 Calorific value dry-basis results

Table 8: Household unsorted residue



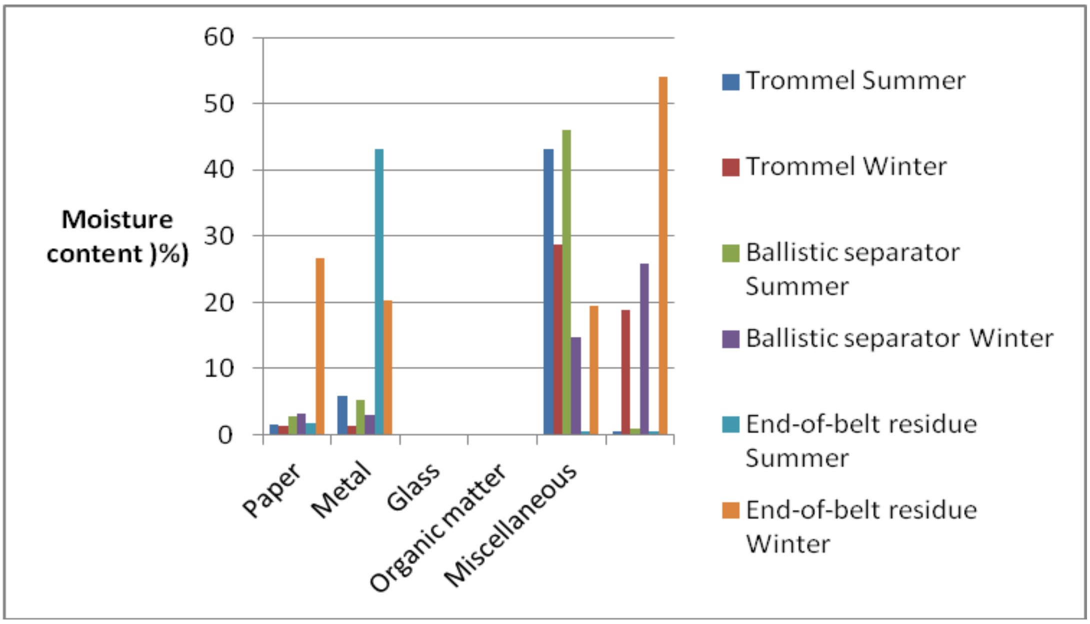
Results of calorific value on a dry-basis are presented in tables 8 (household unsorted residues) and 9 (co-mingled recycled residues). These tables show a comparison between summer and winter values. Results show that there is an increase in calorific value in the winter months. An increase in calorific value on a dry-basis is registered in the winter months on both household unsorted and co-mingled recycled residue.

Table 9: Co-mingled recycled residue



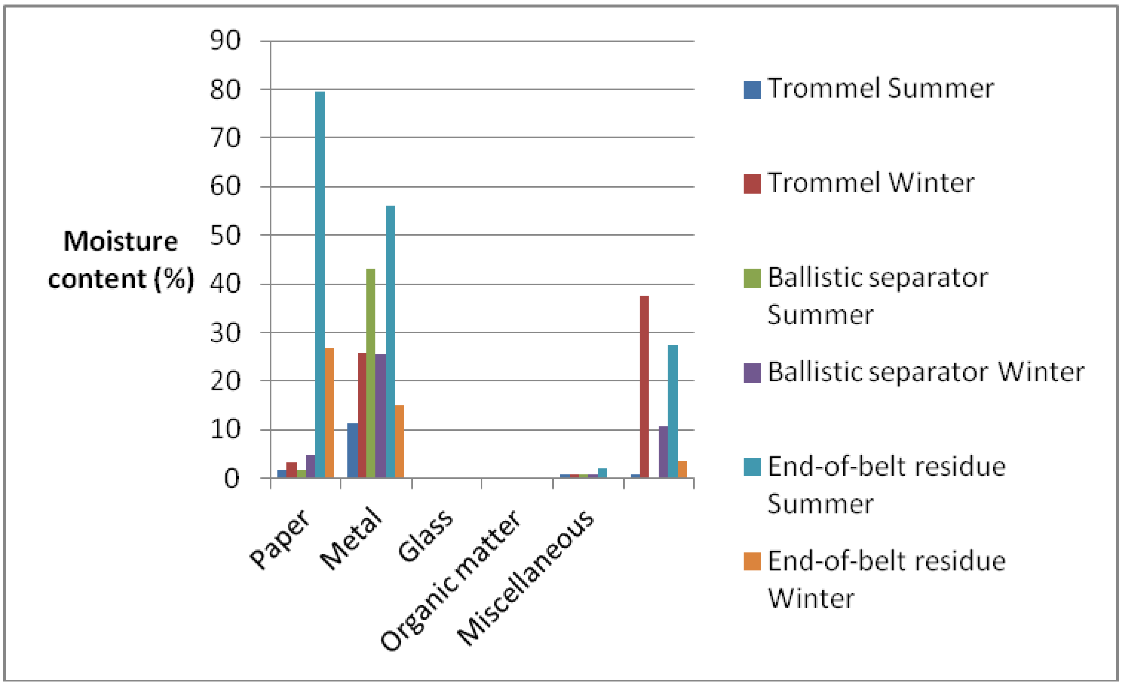
3.2.2.4 Waste composition

Table 10: Household unsorted residue



Results of variance in tonnages are shown in tables 10 (household unsorted residue) and 11 (co-mingled recycled residue). These results show an increase in tonnages in the winter. The greatest increase is associated with co-mingled recycled residue. Household unsorted trommel residue registers a drop in tonnages in the winter months in plastic, paper, metal and organic matter categories. The glass and miscellaneous categories register an increase in winter months. In the ballistic separator stream there is an increase in plastic, metal and miscellaneous categories whilst there is a drop in the paper, glass and organic matter categories. The end-of-belt residue shows an increase in tonnages in the winter months except for the paper category. The co-mingled recycled trommel category shows an increase compared to summer months. The same tendency appears in the ballistic separator stream. The end-of-belt residue shows a drop in tonnages across all categories except for metal and glass.

Table 11: Co-mingled recycled residue



4. Discussion

Although there is no real consensus in the industry as to what should constitute a waste derived fuel, it is generally accepted that the CV and moisture content will greatly influence the performance of EfW systems. Absolute minimum threshold CV values are available from EfW manufacturers, but these will differ based on the individual EfW system. Given the properties of the materials under consideration in tables 4 to 11 there are three potential options to raise the CV of the resulting EfW feedstock to above a typical threshold of 10 MJ/kg. These are:

- Option 1: To reduce the moisture content of the overall mix in order to increase the CV.
- Option 2: To add an external component with a higher CV to the mixture and hence raise the resultant average CV.
- Option 3: To remove some of the low CV components in the mixture, hence raising the concentration of high CV components.

Option 1 (partial drying) requires the use of an industrial dryer system to reduce the moisture content of the waste and promote CV to the threshold value. This will result in higher net project costs and a reduction in overall process energy efficiency, since thermal energy will most likely have to be purchased in order to dry the materials. The key advantage of this option is that the processed material will to some extent be homogenised (i.e. a high proportion of the EfW feedstock will be at the threshold CV), resulting in a more consistent operation of the EfW plant.

Option 2 (blending with a high CV component) requires the addition of a third-party waste stream with a higher CV. An example of this could be automobile tyres or low value and non-recyclable plastics. The main advantage to this approach would be the comparative simplicity of blending, compared to the expense of a drying process. This option does increase risk to the project, since the supply of the high CV component must be reliable and consistent, to ensure a constant, secure supply of EfW plant feed, above the threshold CV.

Option 3 (removal of low CV components) requires further sorting in a MRF-type operation. Whilst this option eliminates the risk of procuring either a dryer or high CV feedstocks, it poses a number of risks in terms of plant operation. It may (for example) be difficult training staff in the removal of low-CV components, ensuring the consistent operation of facility. There will also be a disposal problem for the rejected component, since this rejected material will not be suitable for EfW systems.

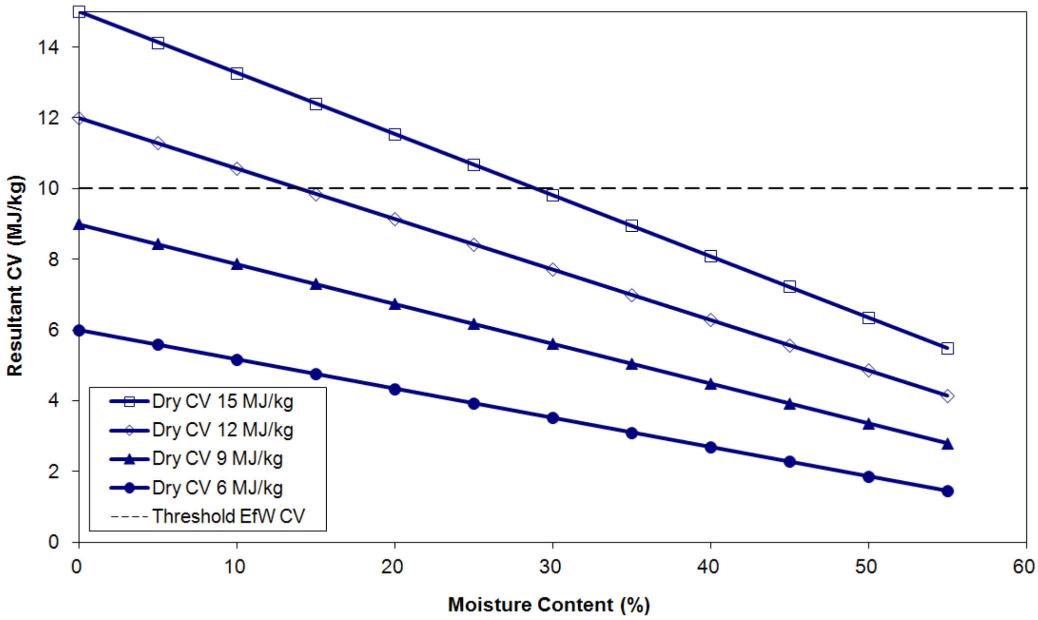


Figure 14: Graph of CV with moisture content for a variety of comparatively low CV fuels. Also included in the graph is the 10MJ/kg threshold suggested by the author's discussions with technology providers. (Marsh et al, 2008)

Table 12 shows the amount of additional dry material required per original kg of waste component (as received) in order to raise the original material CV to the 10MJ/kg threshold CV. Two materials were chosen as the fuel enhancer, based on experience and likely waste streams within the proximity of the test site; these were waste tyres and non-recyclable plastic. It was assumed that these materials would be available dry, and hence their dry CVs were used in the evaluation. CVs of 30 and 40 MJ/kg were used for tyres and plastic respectively.

Table 12: Mass of enhancement component to upgrade CV to 10MJ/kg required per kg of original component. [Based on CV of tyres 30MJ/kg; dry plastic 40MJ/kg; n/a indicates component is above 10MJ/kg as received and does not require additional material.]

Component		**Amount of tyres** **(kg per kg of component)**	**Amount of dry plastic** **(kg per kg of component)**
Co-mingled recycled waste	Residue	0.05	0.04
	Fines (Trommel)	n/a	n/a
	Fines (ballistic separator)	n/a	n/a
Household unsorted waste	Residue	0.27	0.18
	Fines (Trommel)	0.35	0.23
	Fines (Ballistic separator)	0.28	0.19

Table 13 shows the projected revenue obtained through the sale of electricity and heat based on typical generating efficiencies of 25% for heat and electricity. To improve clarity, Figure 15 provides a schematic representation of how the total potential energy from the approximately 20 000 tonnes of waste would be converted into saleable heat and electricity, with an estimation of the income from these streams. The sale price of electricity has been modelled at £0.10 £/kWh and heat at £0.2 £/kW. This information was obtained from representatives of the industry and are generic values for electricity and heat sale. For the purpose of this study it was assumed that a heat customer would be located in the vicinity of the EfW plant and therefore, there was no requirement for grid connection. The sale of electricity and heat resulting from an EfW plant is subject to demand of energy. Furthermore, it is important to consider the potential revenue from sale of energy versus the cost of implementing the necessary structures such as grid connection.

Table 13. Potential, electrical and heat energy available from the thermal treatment of waste for the operating scenario considered, with estimated income from the sale of electricity and heat. Values are calculated for 1 year of continuous operation.

Waste		**Mass of waste**	**Calorific Value**	**Potential Energy**	**Potential Energy**	**Electrical Energy**	**Electrical Energy**	**Thermal Energy**	**Thermal Energy**
		Tonnes	GJ/tonne	GJ	kWh	kWh	Income £	kWh	Income £
Household unsorted waste	Residue	14,751	12.5	184,535	5.13×10^7	1.28×10^7	3.20×10^6	1.28×10^7	2.56×10^5
	Trommel	2,921	7.9	23,047	6.40×10^6	1.60×10^6	4.00×10^5	1.60×10^6	3.20×10^4
	Ballistic separator	974	7.7	7,451	2.07×10^6	5.17×10^5	1.29×10^5	5.17×10^5	1.03×10^4
Co-mingled recycled waste	Residue	1,127	23.5	26,530	7.37×10^6	1.84×10^6	4.61×10^5	1.84×10^6	3.68×10^4
	Trommel	100	8.9	885	2.46×10^5	6.15×10^4	1.54×10^4	6.15×10^4	1.23×10^3
	Ballistic separator	33	10.4	343	9.53×10^4	2.38×10^4	5.96×10^3	2.38×10^4	4.77×10^2
Total		**19,906**		**242,791**			**4.22×10^6**		**0.34×10^6**

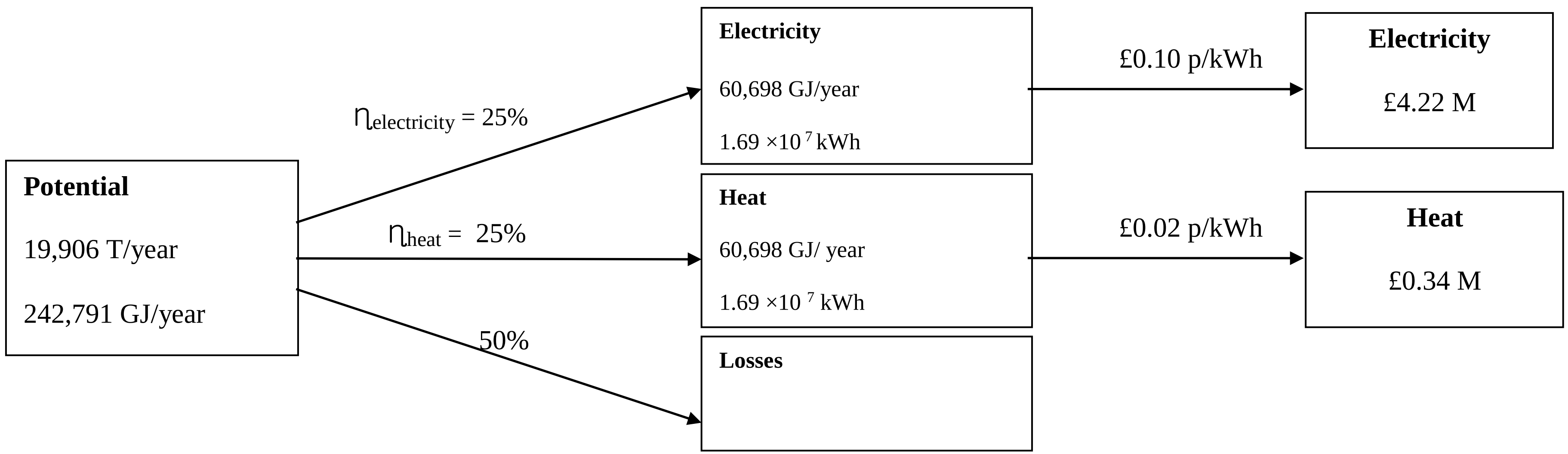


Figure 15. Schematic representation of the distribution of electricity and heat originated from a total of 19,906 tonnes of waste per year.

5. Conclusions

This chapter described the waste available at the case-study area providing information on moisture content, calorific value on a as received and dry basis and waste composition.

From the information in tables 4 to 11 it is possible to conclude that the higher calorific value waste is found in the co-mingled waste stream. However this type of waste is available in less quantity than household waste. This situation impacts on the performance of EfW systems and therefore options for calorific value manipulation were provided. The effects of varying the properties of the waste streams are further analysed in chapter 5.

Methodology of techno-economic model

4.1 Introduction

This chapter describes the methodology of the techno-economic model. The model is organised in different sections namely costs, operation, capital investment and energy production. The model is constructed on an excel spreadsheet and each section is represented by a table (Patel, 2011). There is a separate tab for waste composition and capital cost and then for each of the ten scenarios considered in the scenario analysis.

Capital cost tab includes repayment period calculations and it is linked to the waste composition tab. The capital cost tab also establishes the link between calorific value and moisture content of the waste and repayment period.

The waste composition values are fed into the running and operating costs table. The resulting value from this table is then fed into the energy production table. Finally, the results of these tabs are used in a separate sheet for capital investment cost calculations.

A base case scenario will be used to describe a nominal situation in the case-study area. In order to establish the feasibility of the variables involved, a scenario analysis approach was taken. This method is commonly used when it is important to establish the parameters within which these variables occur (Arena, 2010).

The model initially presents the base case scenario which includes the waste available and its potential for energy production (which is calculated from variables such as calorific value). Scenario analysis include an estimation of the potential energy from the waste available and the revenue it can generate through the sale of electricity and heat. Waste composition, capital investment and operation are also considered in the scenario analysis. In the model, a theoretical situation was evaluated in which the thermal treatment technology is incorporated in an existing MRF-type operation where EfW is being added as an enhancement to the current capability and thus it does not take into account transport costs from the point of origin of the waste to the point of energy production. In this particular situation the transport costs value would be null, since waste collection and delivery would be provided by the customer.

4.2 Overall structure

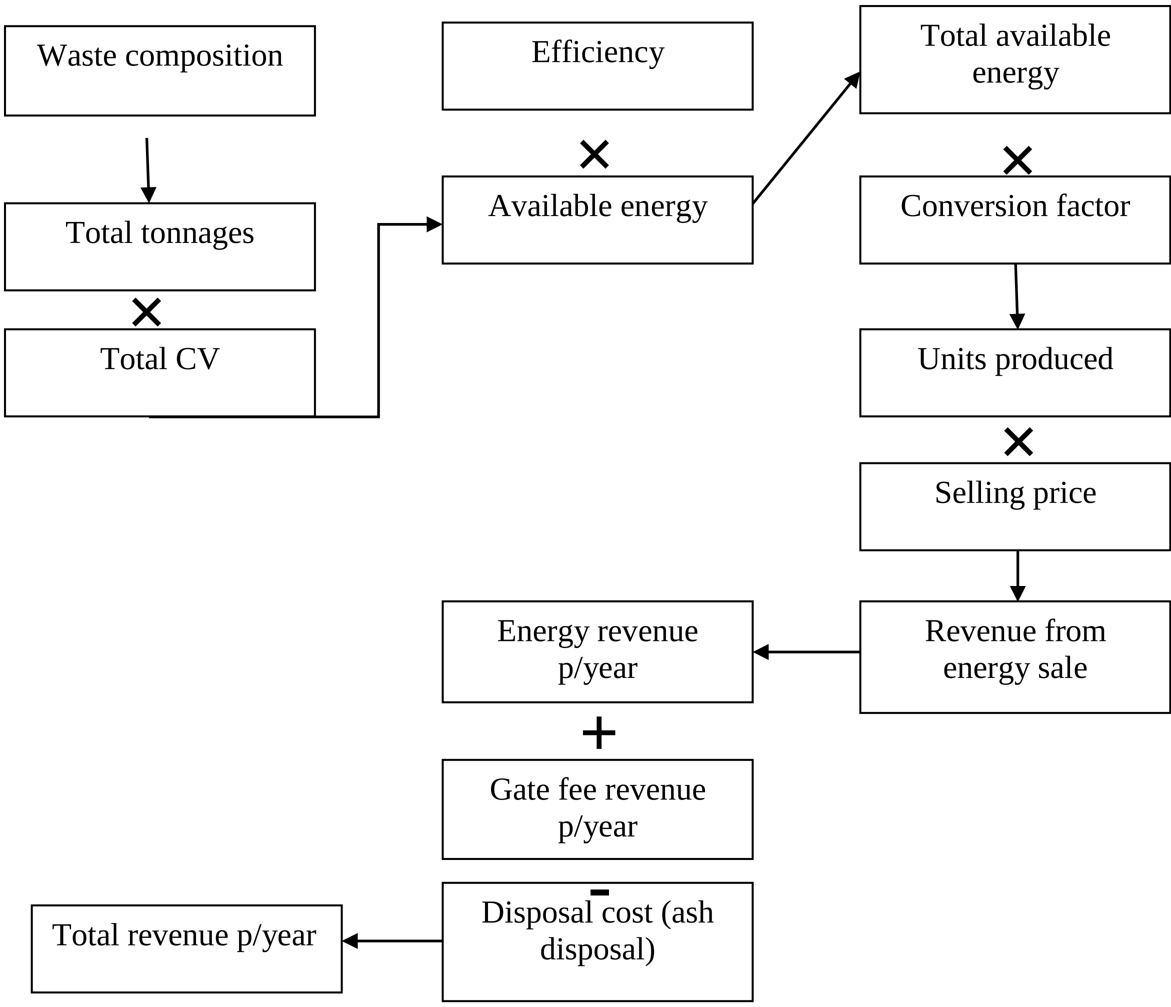


Figure 15. Structure of techno-economic model

The costs of setting up a network through which the electricity and heat could be transmitted onto to other areas were not considered because it was assumed that the end customer would be in the same area where energy production is taking place. To clarify it is assumed in the techno-economic model that the EfW facility would be integrated in the MRF and that the end customer, typically, a manufacturing process that would consume energy on a permanent basis.

Figure 1 reflects the calculations in the techno-economic model. These calculations are divided into three stages. Firstly, calorific value, moisture content and total tonnages are calculated in the waste composition table. This table includes a separate row for each household and recycling waste stream namely trommel fines, ballistic separator fines and end-of-belt residue totalling six waste streams (see Chapter 3 for more detail). The characteristics included in the table are moisture content, calorific value and tonnages. These are discriminated in its monthly and annual values and include totals for both variables considered. Secondly, these values are incorporated in the energy production table which includes total calorific value, total tonnages, efficiency factor, selling price per unit of heat and electricity, total available energy, units produced and revenue per year. These values include a separate row for electricity and heat calculations but the resulting values feed into a separate section on this tab that calculates energy revenue per year, gate fee revenue per year, disposal costs and total revenue per year. These values are then fed into the capital cost calculation tab and are crucial in determining economic feasibility. In more detail, this table's output is the total available energy which is result of the multiplication between the efficiency factor and the available energy. Revenue from energy sale is the result of the selling price multiplied by units produced.

Thirdly, the revenue from energy sale is fed into the capital cost calculations tab. This tab establishes a link between calorific value, moisture content and total repayment period, which is the number of years necessary to repay the investment.

4.3 Capital investment

Capital investment is the total amount of funds necessary to start an industrial project (DEFRA, 2012). This value accounts for the total amount borrowed plus interest rate. Interest rates vary with the type of loan available and the risk involved in the project. Traditionally EfW projects attract high risk, which is then reflected onto interest rates, because this is still considered an untested technology which is very sensitive to fluctuations in chemical and physical composition. Furthermore, there is a lack of pilot facilities that could assist by assessing technical performance.

In this section, the variables associated to capital investment, which are present in the economic model, are described.

The capital borrowed (A) is the total amount financed through a loan, including interest rates. The principal amount (P), also known as initial investment, is the actual amount available for developing a project. The nominal rate (r) is the interest rate applied to a loan. Compound interest means that each year the interest is added to the principal amount. The symbol t expresses the length of the loan in years.

In the economic model, the capital repayment section produces a calculation of profit after repayment. This is the result of the total revenue per year excluding the total repayment per year. This value is used to establish the relationship between waste calorific value and number of years necessary to repay the capital investment. These values will be varied in the scenario analysis and the results of this will be presented over the next chapter. Investment analysis will also be presented in the next chapter and will include net present value (NPV) and internal rate of return (IRR) analysis.

4.4 Cost

In order to construct the techno-economic model it was necessary to define some costs relating to human resources and production costs. These are shown in Table 14. The values used in this table were obtained from communications with EfW operators and based on an estimate from the expected waste tonnages. It is expected that the MRF will operate as an associated activity to the EfW operation and therefore it is necessary to maintain the same number of operators.

Table 14. Running costs of facility including labour and disposal costs.

Labour	
Operators	£49 £/day
Disposal	
Landfill costs	£70 £/tonne
Transport	£30 £/tonne
Gate fee	£73 £/tonne

For the purpose of building the techno-economic model it is assumed that the EfW facility would be included in the MRF process. This means that the MRF operators could be trained to operate the EfW facility and thus are included in the same process. Based on the estimation of waste tonnages processed on site it is expected that the EfW operation would require 7 operators totalling 14 operators over a two-period shift (Villanueva Perales, 2011). Landfill costs include gate fee and transport cost and are estimated to be about £70 per tonne. (Let's recycle).

4.5 Operation

In order to establish a techno-economic model it was necessary to fix factors such as days of operation per year, number of workers, tonnes processed in a day and cost of transportation. In this situation it was established that the thermal treatment facility would require two operators working full-time over 5 days a week for a period of 260 days per year taking into account periods of maintenance. The number of tonnes processed per year was considered to be about 20 000 tonnes.

Table 15. Operation period

Tonnes processed p/day	125 tonnes
MRF	
Workers	7
Period	
Days of operation p/week	5
Days of operation p/year	260
Transport p/tonne	£30 £/tonne

4.6 Energy production

In the energy production table (Table 16) the revenue per year is calculated through a series of fixed factors. This table translates the energy produced into an economic context providing a figure for revenue per year. This figure will then be used to calculate the feasibility of the scenarios analysed. This value was calculated in three steps:

Available energy calculation

$$\text{Available e} = \text{Total}_{\text{calorific value}} \times \text{Total}_{\text{tonnes}} \quad [J]$$

Total available energy calculation

$$\text{Total available energy} = (\text{Available e} \times \text{efficiency}) \times \text{conversion factor } [J]$$

Revenue p/year = total available energy × selling price per unit J [£ per year]

The energy production table reflects the energy that can be generated as electricity or heat from the thermal processing of the resulting residues of the MRF process. The figures for total calorific value and tonnages are taken from the waste composition table.

Efficiency was assumed to be 25% of all energy produced for each calculation (electricity and heat). The selling price per unit of energy was considered to be £0.03 for kWh electricity and £0.02 kWh heat. The total revenue per year is the sum of the revenue resulting from the sale of electricity and heat and the revenue resulting from gate fee charges excluding ash disposal costs. Ash disposal accounts for the disposal of the residue which results from thermal treatment processes. For ash content calculation see figure 16. The ash disposal value is calculated in the waste composition table. The values described in this section are nominal figures. These variables were varied in the scenario analysis in order to reflect sensitivity of the parameters described. Waste characterisation calculations provide a total for calorific value content and tonnages across all waste streams processed in the MRF.

These values were included in Table 16 and combined to calculate total available energy.

Table 16. Energy production of electricity and heat based on calorific value of waste available

ENERGY PRODUCTION	Electricity	Heat
Total CV	9.54 MJ/kg	9.54 MJ/kg
Total Tonnes	19824 T	19824 T
Efficiency	0.25	0.25
Conversion factor (to joules)	278	278
Selling price p/unit	£0.03	£0.02
Available energy	189127	189127
T available energy	47281	47281
Units produced	13144384	13144384
Revenue p/year	£394,331	£262,887
Energy revenue p/year	£657,219	
Gate fee revenue p/year	£1,447,204	
Disposal costs (ash disposal)	£44,566	
Total revenue p/year	£2,059,857	

As described in previous sections the values above are fed from the waste composition table (calorific value and total tonnages). The calculations in this table are shown in Figure 15. The output of this table is the total revenue per year and it results from gate fee revenue and disposal costs. The total revenue per year was then fed into the capital investment table.

Table 3 presents separate values for electricity and heat production although energy production is expected to be the same. Electricity and heat are charged at different rates and this is reflected in the table. Consequently the revenue resulting from electricity is higher than heat energy revenue.

4.7 Waste composition

Calorific value, moisture content and ash content tests were applied to the six resulting residues from the MRF process. The results were combined in order to produce a representative estimate of all the residues processed. This calculation was necessary to estimate the overall energy production. Calorific value, moisture content and ash content were calculated both in the summer and the winter to reflect the effect of seasonality. The data collected from the CSA reflected monthly values for disposal costs and tonnages received on site, therefore monthly values were estimated. These values contribute to calculate total energy produced on a monthly basis. Calorific value and moisture content were determined using the methods established in BS EN 14918: 2009 and BS EN 14774 – 3: 2009. The output of the waste composition table is the average calorific value of the six residues.

ENERGY PRODUCTION	Electricity	Heat
Total CV	9.74	9.74
Total Tonnes	19824.72	19824.72
Efficiency	0.25	0.25
Conversion factor	278	278
Selling price p/unit	0.03	0.02
Available energy	193092.7728	193092.7728
T available energy	48273.1932	48273.1932
Units produced	13419947.71	13419947.71
Revenue p/year	£402,598.43	£268,398.95
Energy revenue p/year	£670,997.39	
Gate fee revenue p/year	£1,447,204.56	
Disposal costs (ash disposal)	£44,566.20	
Total revenue p/year	£2,073,635.75	

WASTE COMPOSITION

Waste	Tonnes p/month	Disposal cost/month	Tonnes p/year	Disposal cost p/year	Ash (kg/month)	Ash (kg/month)	Ash (kg/year)	MC (kg)	MC (kg)	MC (kg/year)	Calorific val
Black bag					Winter	Summer	Total	Winter	Summer		Winter MJ/k
Residue	1229	£86,030.00	14748	£1,032,360.00	45.91	3.69	297.6	38.38	45.57	503.7	
Fines Trommel	240	£16,800.00	2880	£201,600.00	6.74	6.32	78.36	45.77	36.28	492.3	
Fines Ballistic sep.	80	£5,600.00	960	£67,200.00	9.59	9.11	112.2	44.36	45.54	539.4	
Total	1549	£108,430.00	18588	£1,301,160.00							
Clear bag											
Residue	95	£6,650.00	1140	£79,800.00	4.37	2.75	42.72	11.62	8.04	117.96	
Fines Trommel	8	£560.00	96	£6,720.00	6.82	3.4	61.32	24.29	12.88	223.02	
Fines Ballistic sep.	0.06	£4.20	0.72	£50.40	4.08	3.33	44.46	24.4	11.93	217.98	
Total	103.06	£7,214.20	1236.72	£86,570.40							
TOTAL	1652.06	£115,644.20	19824.72	£1,387,730.40	Annual Ash (%):	**3.21**	**636.66**	**Annual MC (%**	**10.56**	**2094.36**	

ECONOMIC MODEL / WASTE COMPOSITION / CAPITAL INVESTMENT / TABLE OF VARIABLES / Scenario 1 / Scenario 2 / Scenario 3 / Scenario 4 / Scenario 5 / Scenario 6 / Scenario 7 / Scenario 8

Figure 16. Screenshot of the techno-economic model (excel spreadsheet)

Economic model: sensitivity analysis results

5.1 Introduction

The results of the scenario analysis are presented and discussed in this chapter. The scenario analysis includes ten situations which will be used to establish feasibility parameters in the model. These scenarios reflect situations that are likely to occur in the economic and legislative context. The results of these situations were discussed based on its technical and economic effects on capital cost repayment period. This factor was used to measure the feasibility of the system. A maximum 10 year repayment period was selected as the point at which the facility was most likely to breakdown. Therefore, a scenario that would result in a repayment period longer than 10 years was deemed unfeasible. An investment analysis considering NPV and IRR is also included in this chapter. The conclusions of this exercise will establish the risk involved in EfW investments.

Scenario 1

In scenario 1 the impact of an increase in plastic and paper recycling is investigated. An increase in recycling in these particular waste streams results in an overall reduction of these materials in the waste streams resulting from the MRF operation, to be exact, end of belt residue and trommel and ballistic separator fines. In this scenario waste reduction is analysed in increments. The reduction in recycling results in an overall reduction in waste tonnages. Therefore, higher recycling reductions result in overall waste tonnage reduction. This scenario is justified by the rising tendency in recycling targets set by European legislation in recent years which is expected to continue over future years.

In order to investigate the impact of a potential increase in recycling plastic and paper a two-step approach was taken. Firstly, a reduction factor of 25% (equivalent to recycling waste reduction of 1000 kg), 50% (equivalent to recycling waste reduction of 1500 kg) and 75% (equivalent to recycling waste reduction of 2000 kg) was applied to plastic and paper across all waste streams. Secondly, the resulting CV was then applied to the total revenue calculation for each reduction factor. Results show that there is a pronounced drop in CV associated to a reduction factor of 75% in plastic and paper as shown in Figure 17.

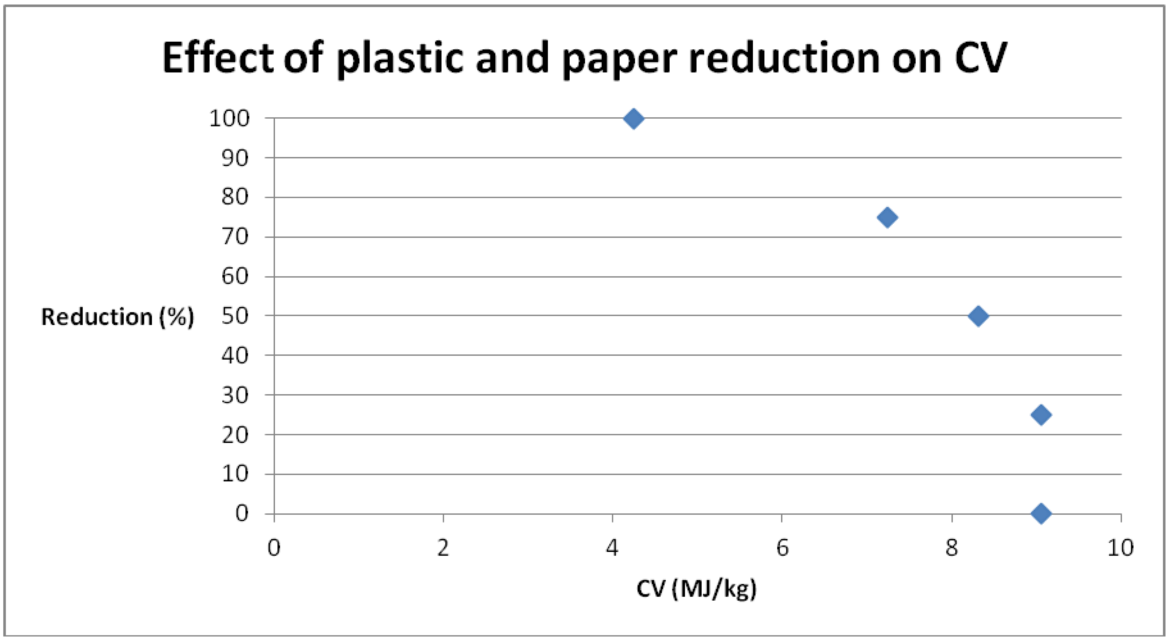


Figure 17. The effect of plastic and paper reduction on CV (MJ/kg)

These results were then applied to the repayment period calculation (see Table 18) which reveals that even with an abrupt drop in CV the EfW system is still economically feasible. This is evaluated through the capital cost repayment period. The project is still viable since its resulting values are still within a 10 year maximum period which is considered by industry experts as the maximum longevity period for an EfW facility.

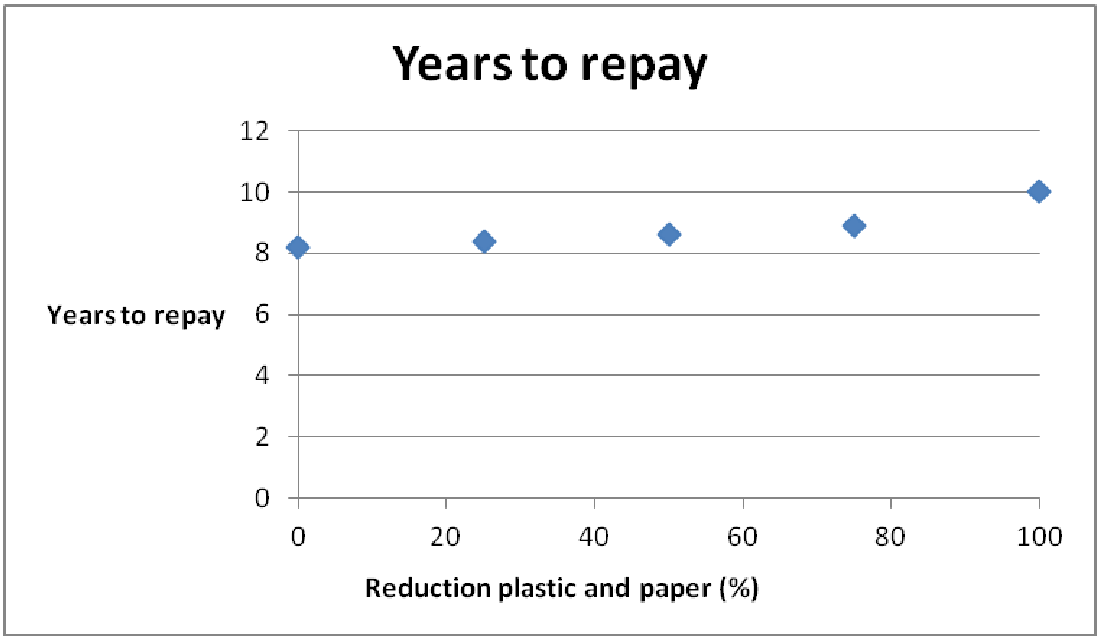


Figure 18. The effect of reducing plastic and paper on the repayment period

Figure 18 shows that the increase in plastic and paper reduction impacts on the repayment period. It is important to note that the tonnage reduction in the recyclates stream does not cause a serious impact on the feasibility of the project. These results show that at a small scale, the most important aspect in feasibility of EfW systems is waste reduction rather energy production.

A drop in CV seriously impacts upon technical performance but the overall effect on economic performance is minimal. However, the removal of plastic and paper would result in a potential delay of 2 years in capital cost repayment.

Scenario 2

In scenario 2 a reduction in overall waste tonnages is investigated. Effectively this scenario investigates the impact of running the facility at different waste tonnages. This scenario is likely to occur on a temporary basis when for instance technical maintenance is required.

In order to investigate the impact of this variation in operation an approach of reduction steps of 10% was taken. The initial step of 0% corresponds to the nominal situation and reflects a repayment period of 8.7 years. The next step of 10% reflects a situation at which the facility is operating 90% of the tonnages it was projected to process and so on.

A 100% reduction factor would correspond to no waste being processed in the facility which would result in the total operation shutting down and thus it is not considered in this study.

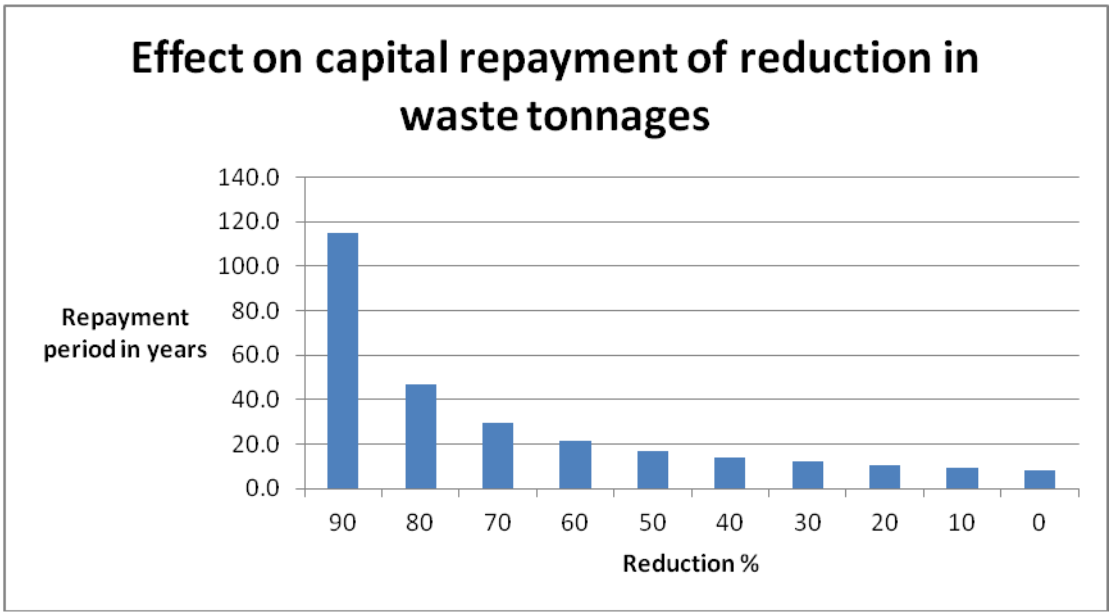


Figure 19. Effect of waste tonnages reduction on capital cost repayment period

Figure 19 shows that a reduction from about 20% on overall waste tonnages received on site the capital cost could not be repaid within the 10 year target. This conclusion reinforces the importance of the EfW system as a waste treatment process rather than an energy production system as discussed in chapter 1.

Scenario 3

Scenario 3 investigates the impact of increased moisture content on the calorific value of the overall waste stream. As discussed in Chapters 1 and 2 calorific value drops with increasing moisture content. This situation can be temporary when associated to seasonality. Waste characterisation exercises show that moisture content increases in the winter as it is associated to higher pluviosity. Figure 20 shows that higher moisture content is associated to lower calorific value. The impact of these results on capital cost repayment period is shown on Figure 21.

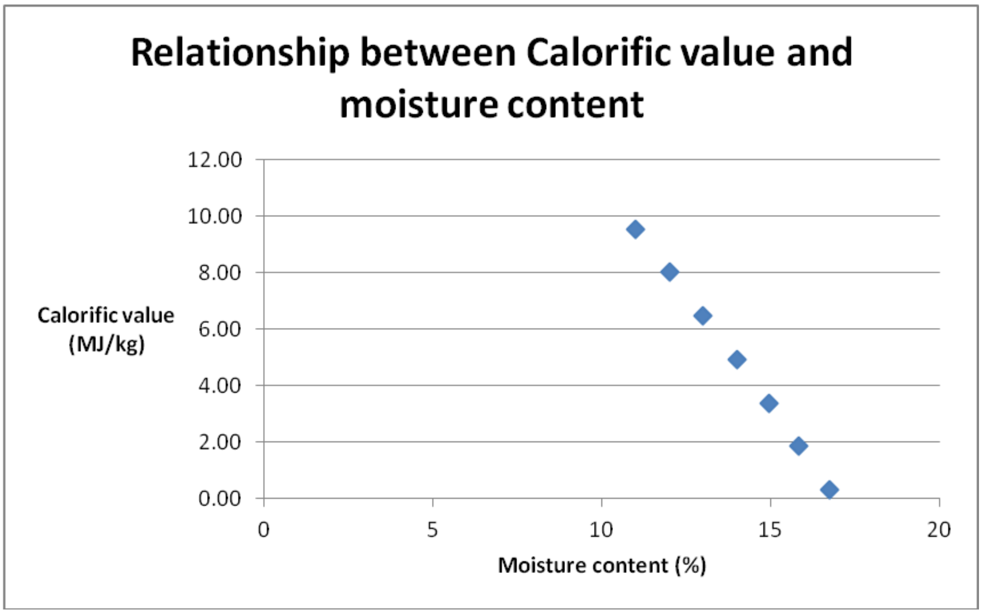


Figure 20. Relationship between increasing moisture content and calorific value in the waste streams at LAS recycling

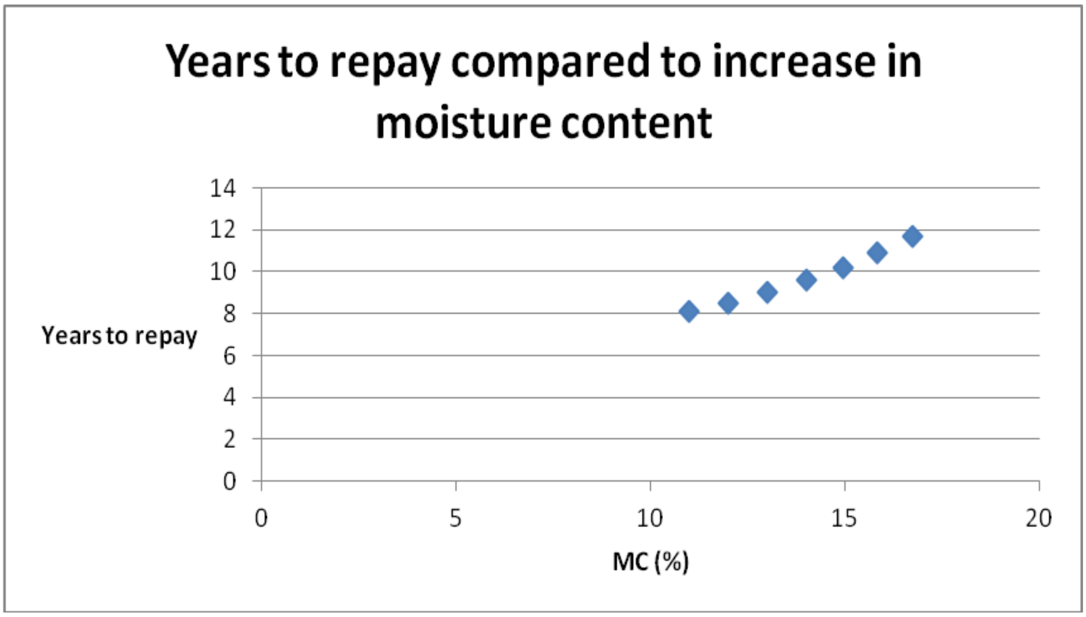


Figure 21. Effect of increased moisture content on capital cost repayment period (in years)

Figure 21 shows that higher moisture content is associated to a longer repayment period. In the case study area overall moisture content higher than 14% would result in a repayment period longer than 10 years.

Scenario 4

In scenario 4 an alteration to operation period is assessed. In the nominal situation the system operates 260 days per year allowing for maintenance and breakdown time.

This scenario evaluates the impact on the capital repayment period of reducing the operating period up to 150 days per year. This situation could result, as an example, from prolonged failure of the EfW system or unavailability of waste.

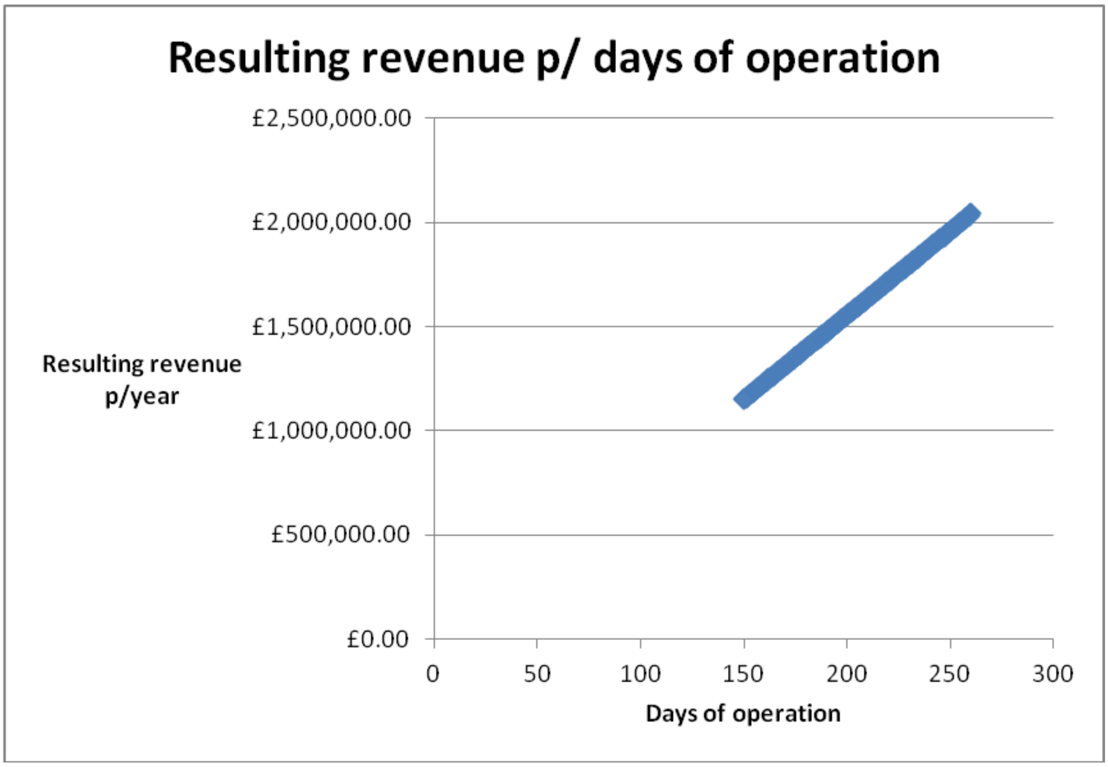


Figure 22 shows the relationship between days of operation per year and resulting revenue. Results show that the operation becomes unfeasible under 152 days of operation per year according to present values.

Figure 22 shows the relationship between days of operation and resulting revenue per year. These results were then applied to the capital cost repayment period calculations to establish the impact of the variation of the number of days. Figure 23 shows that the less the facility operates per year the less it produces and consequently the longer the repayment period becomes. Furthermore, results indicate that if the facility operates for less than 200 days per year it becomes unfeasible as the repayment period extends beyond 10 years.

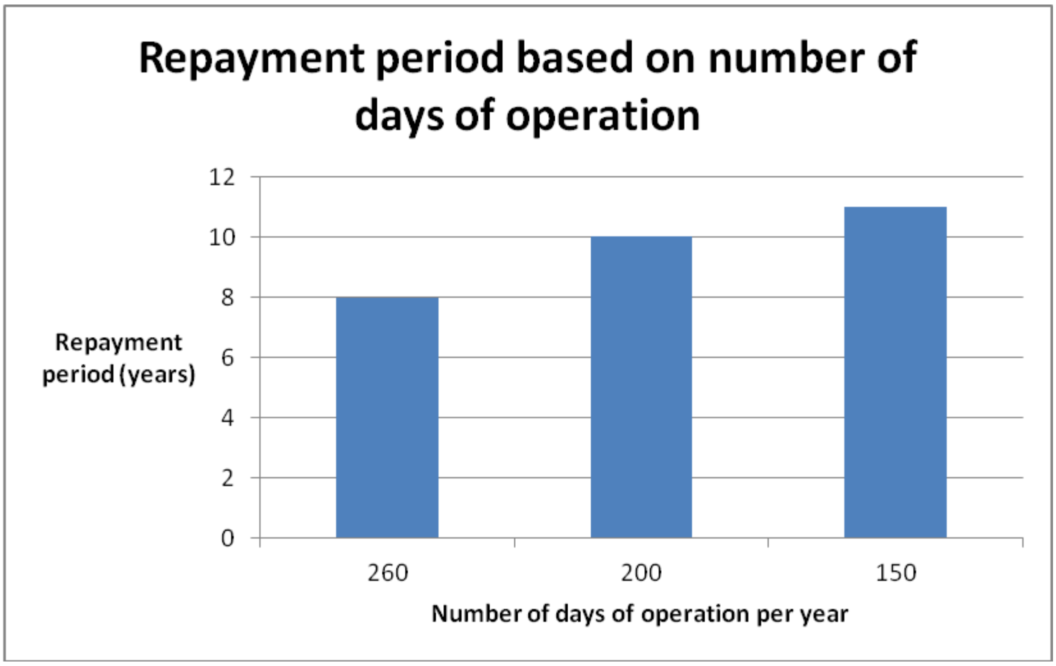


Figure 23. Repayment period based on days of operation

Scenario 5

Scenario 5 investigates the effects of the facility receiving more waste than what it was initially projected to. This situation could result from contractual issues or errors in the projection of the facility. An excess of waste tonnages at the facility would be reflected on an increase in landfill charges which would have an effect on revenue per year.

An increase in waste tonnages would also result in an increase in overall ash content. This material forms a type of end-of-process residue, known as IBAA (incineration bottom ash aggregate) which has economic value. Although the commercialisation of this product is not yet common practise there is a potential for this as a source of revenue alternative to energy sale.

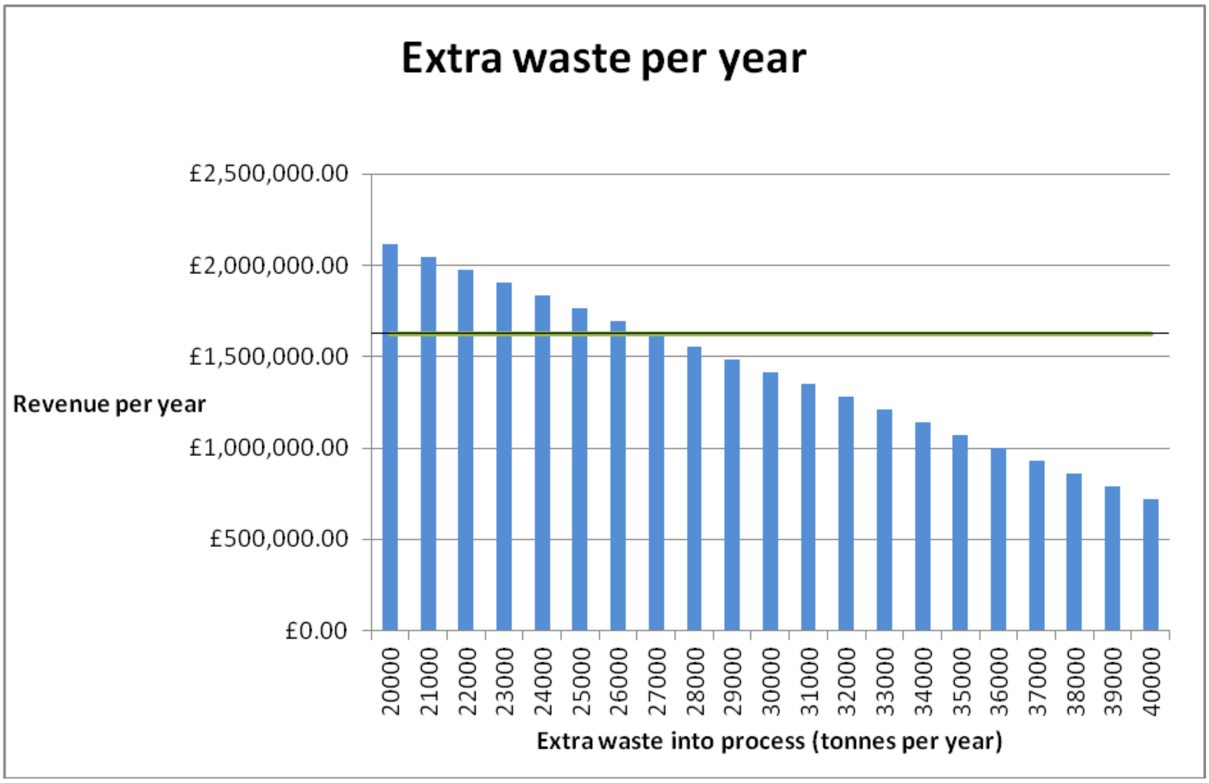


FIgure 24. shows the impact of receiving waste above the plant's maximum capacity. If the facility receives more than 27 000 tonnes per year the impact on revenue turns the facility unfeasible.

Figure 24 shows that if the facility receives more than 27 000 tonnes per year the revenue is not sufficient to repay the capital cost over 10 years. These results were obtained from the capital cost repayment period calculation.

Scenario 6

In this scenario the impact of variation in household waste tonnages is evaluated. Household waste accounts for the greatest part of all waste received on site (93%) at the case study area. However, this type of waste is the least calorific component across waste streams (average calorific value of household waste is 8.77 MJ/kg whereas unsorted recycling waste has a calorific value of 22.58 MJ/kg). As household unsorted waste is present in a greater quantity than unsorted recycling waste the resulting CV drops to just under 10 MJ/kg. In this situation it is beneficial to introduce a calorific value enhancement option to ensure values do not drop under 10 MJ/kg. A decrease in household waste tonnages is an option that would result in overall higher calorific value (since proportionally there would be a greater quantity of recycled waste).

This scenario aims at establishing the impact caused by reducing household waste tonnages which could result from the diversion of part of or the entire household component to another company due to contractual issues.

Figure 25 shows that the reduction of household waste tonnages is associated to higher revenue per year.

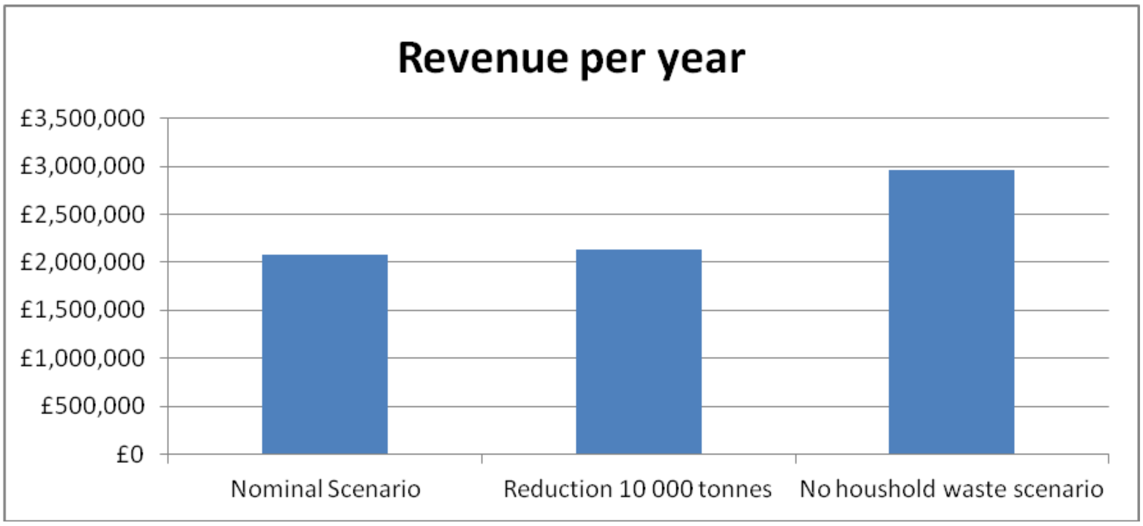


Figure 25. Effect of variation in household waste tonnages on revenue per year

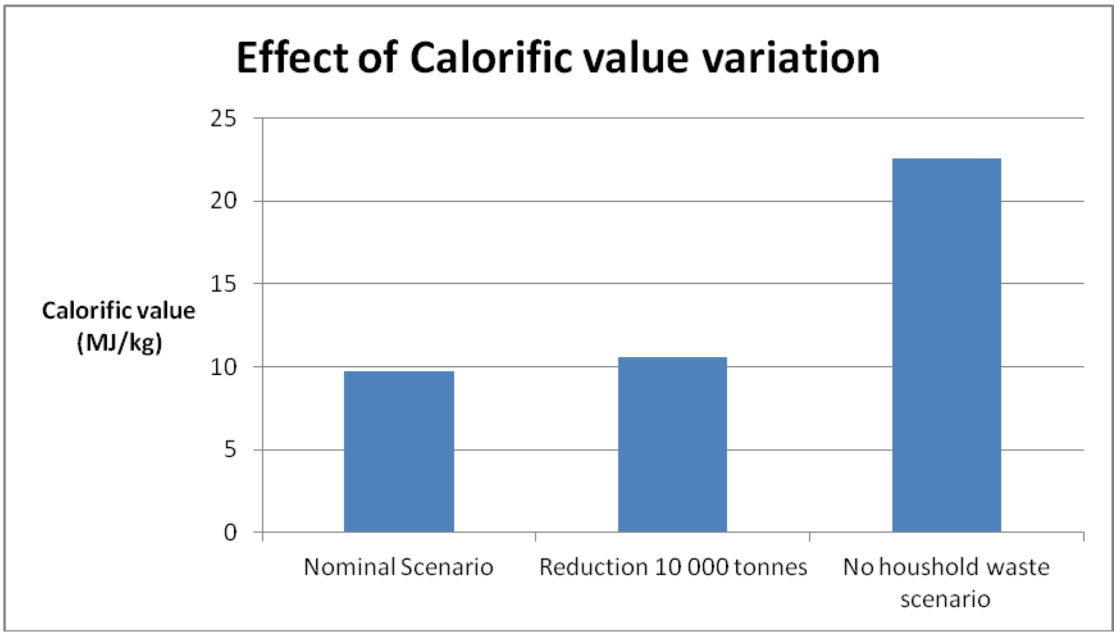


Figure 26. Effect of household waste variation on calorific value

Figure 26 shows that the reduction of household waste tonnages results in higher calorific value. In the "no household waste" scenario there is a great increase in calorific value. As discussed before this reflects that the composition of this type of waste has higher calorific value as it has a great quantity of plastic and paper. Figure 26 shows that the reduction of household waste tonnages is associated to a faster repayment period.

From a technical point of view the reduction of this type of waste is associated to higher calorific value which results in a better EfW performance. From an economic perspective this variation has a siginificant effect on reducing capital cost repayment period.

The effect of completely removing household waste results in a repayment period of about 5 years as shown in Table 27. This means that the removal of this waste stream would speed up the repayment period reflecting that this type of waste has the preferred composition for EfW facilities. This conclusion suggests that industrial or commercial wastes which tend to have higher composition of plastic and paper are a preferred option for EfW facilities.

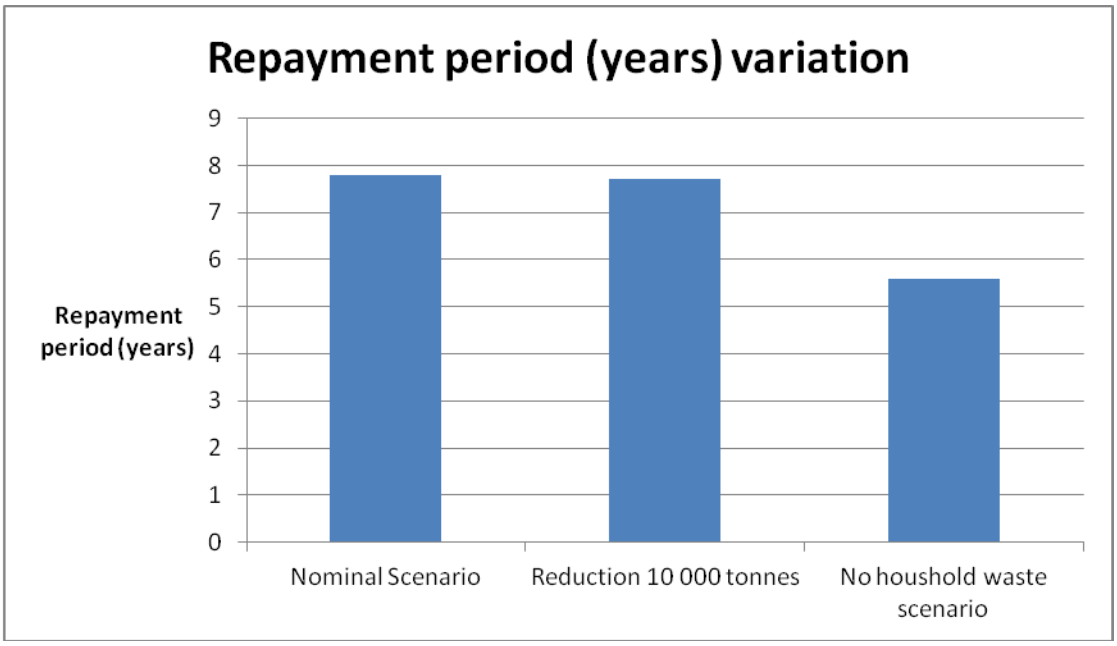


Figure 27. Effect of waste tonnages reduction on repayment period

Scenario 7

Scenario 7 investigates the impact of the reduction in calorific value of a specific category in the recyclates stream. For a better understanding of this scenario a specific case was investigated. In this example, the paper stream in the recyclates stream suffers a reduction. The impact of this alteration on overall calorific value and, consequently, repayment period, is investigated. This situation could originate from a change in the material caused by weather conditions, such as paper having higher moisture content during winter months, or by a permanent alteration such as the reduction of plastic carrier bags.

A reduction of 80% was applied to the paper category in the recyclates stream. The household waste stream was kept at previous levels resulting in a calorific value of 9.39 MJ/kg. This level of reduction resulted in a drop of 3 MJ/kg in the unsorted recycled stream. The effect of this reduction does not impact greatly on the overall calorific value of the waste.

Nominal situation

Winter	MJ/kg	Summer	MJ/kg
Household unsorted waste			
EOBR	12.71	EOBR	6.64
T	7.64	T	3.08
BS	7.4	BS	2.64
Unsorted Recycled waste			
EOBR	**23.55**	EOBR	**23.51**
T	**10.96**	T	**11.68**
BS	**12.13**	BS	**11.79**

Figure 28. Nominal situation (Excel exercise example)

Drop in CV (recyclates stream)

Winter	MJ/kg	Summer	MJ/kg
HUW		HUW	
EOBR	12.71	EOBR	6.64
T	7.64	T	3.08
BS	7.4	BS	2.64
RCW		RCW	
EOBR	**20.33**	EOBR	**19.81**
T	**1.55**	T	**4.76**
BS	**3.83**	BS	**1.32**

Figure 29. Drop in calorific value in the recyclates waste stream whilst unsorted household waste stream remains unaffected

The variation of calorific value in the recyclates stream has little effect on the overall calorific value as shown in Figures 28 and 29.

These results confirm the overriding effect of the unsorted household waste properties. From both a technical and economic perspective there is little impact from the variation of properties in the recyclates stream.

Scenario 8

In scenario 8 the impact of landfill cost variation is evaluated. In the nominal situation ash resulting from the EfW operation is disposed of via landfill. Alternatives to landfill disposal of incinerator ash such applications in construction are only available limitedly. Therefore, landfill costs still have a significant impact on an EfW facility economics. In the nominal situation, landfill costs were set to £100 per tonne. Alterations to this rate might result from legislative changes.

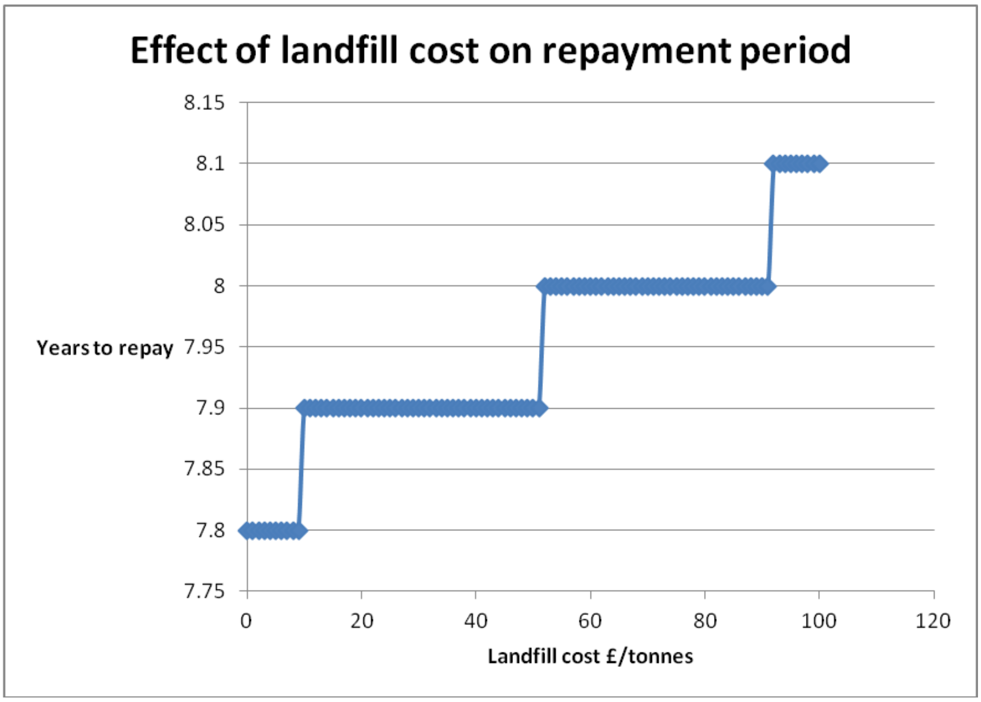


Figure 30. shows the relationship between landfill cost and repayment period

Figure 30 shows that a drop in landfill cost (£/tonne) is accompanied by a lower repayment period. Consequently it is possible to conclude that the higher the disposal cost the longer it takes to repay capital cost. Furthermore, the graph in figure 30 shows that the repayment period is affected by steps of about 20 £/tonne.

Scenario 9

The impact of the variation of the selling price of heat is evaluated in scenario 9. The revenue of the EfW facility originates from the sale of electricity and heat which vary in selling price. For the purpose of this investigation the selling price of electricity has been estimated in £0.03 per unit and heat selling price at a rate of £0.02 per unit. This scenario may occur as the result of market fluctuations. To calculate the impact of the oscillation of heat selling price on capital repayment five values were applied to the repayment period calculations. Results of this are shown in Figure 31 and reflect the increase in repayment period as heat selling price drops.

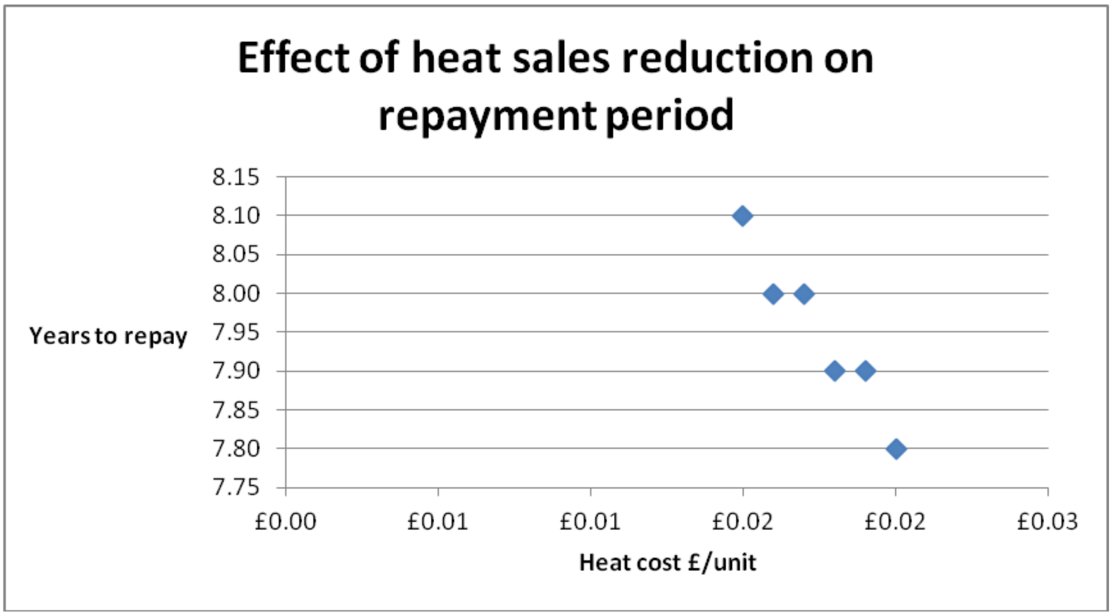


Figure31. The effect of heat sales on repayment period

A reduction in heat sales would originate a higher repayment period. In this scenario a drop in heat sales in the order of 25% of the original price was evaluated. Within the margins evaluated there is a relevant impact on process feasibility.

Scenario 10

Scenario 10 investigates the introduction of a drier as a calorific value enhancement technique. As discussed previously in chapter 1 and 2 the lower the moisture content the higher the calorific value of the waste (Marsh et al, 2008). When waste calorific value is found to be consistently low enhancement techniques are employed to minimise the impact of this on the EfW operation (Lima et al, 2012). The relationship between calorific value and moisture content suggests that there is a 1 to 2 MJ/kg increase in calorific value per each 5% drop in moisture content. Considering the resulting CV is 9.54 MJ/kg in the nominal scenario, an increase of 1 to 2 MJ/kg would enhance the calorific value to the region of 11 MJ/kg. The application of these values to capital investment calculations show that the introduction of a drier would result in a shorter repayment period, as indicated in Figure 32

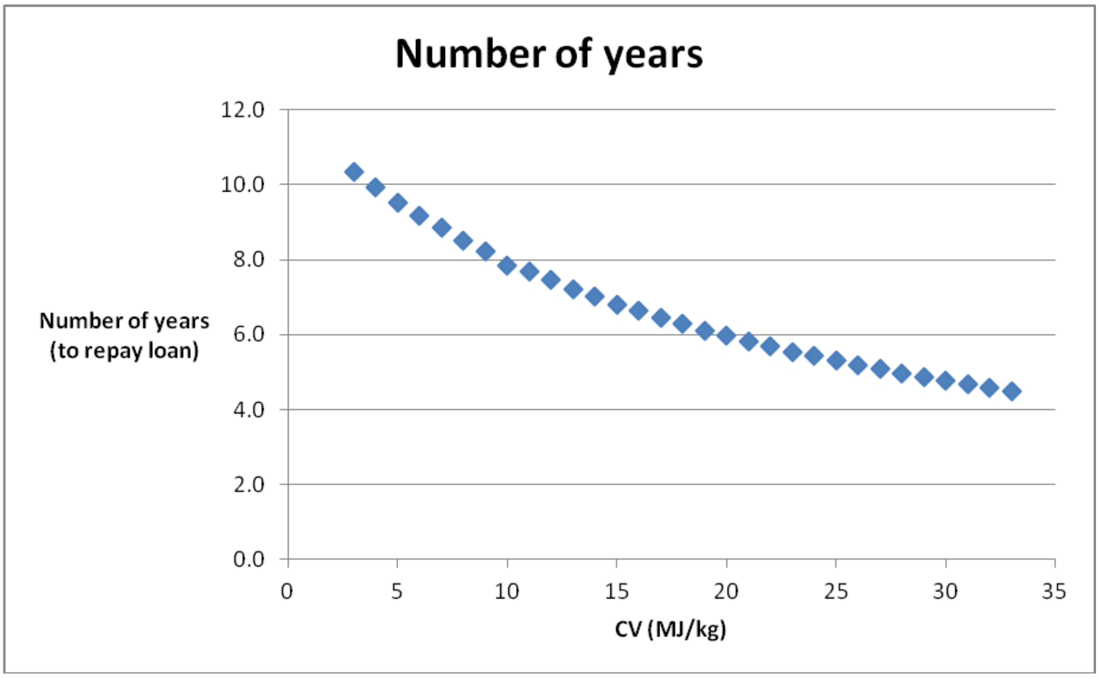


Figure 32. The relationship between repayment period in years and calorific value (MJ/kg)

Capital investment calculations, as shown in the graph in Table 32, show that in the nominal case scenario, for a calorific value of 9.54 MJ/kg a repayment period of 8.7 years is expected whilst for a 11 MJ/kg a shorter repayment period of 7.6 years can be expected. The introduction of this technology would result in a faster repayment period of between 10% to 15%.

From a technical point of view the performance of the facility would benefit greatly from the implementation of a drier as it would mantain calorific value above 10 MJ/kg. However, an assessment from an economic standpoint reveals that the cost of acquiring the equipment does not justify the investment in face of the reduced repayment period.

5.2 Discussion of results

Ten different scenarios were evaluated in order to establish sensitivity to variations in calorific value, moisture content, waste tonnages and operating procedures. The values applied to the scenario analysis reflect real life situations, knowledge of which was gained through working directly in this industry. Scenarios 1, 2, 3, 5, 6 and 7 reflect variations of waste composition and characteristics. Scenarios 4, 5, 8, 9 and 10 reflect changes to operating time and procedures.

5.2.1 Waste composition and characteristics

In Scenario 1, the reduction of plastic and paper in waste received on site is reflected on a decrease in calorific value. This has a serious impact on economic performance. However, the removal of plastic and paper would only result in a potential delay of 2 years in capital cost repayment but the repayment period would still be less than 10 years which means that the facility would still be economically feasible. Scenario 2 shows that a reduction in overall tonnages impacts greatly on economic feasibility. The graph in Figure 19 shows that from a 20% reduction on overall waste tonnages received on site the capital cost can no longer be repaid within the 10 year target. The results obtained from Scenario 1 and 2 show that the system is very sensitive to reduction in overall waste tonnages whilst variations in the plastic and paper stream produce little impact on repayment period. Scenario 3 evaluates the impact of increased moisture content in the system. Figure 19 shows that if moisture content increases above 15% than the impact on capital cost repayment make the investment unfeasible. Scenario 5 investigates the impact of the system receiving more waste than what it was projected to receive initially. In this situation results show that the repayment period extends over 10 years once the facility is receiving more than 27 000 tonnes of waste per year above a 20 000 tonnes per year limit. Scenario 6 shows that the impact of reducing waste tonnages on household waste has a positive effect in that it increases calorific value thus resulting in better EfW performance and also reduces the capital cost repayment period. In fact, if household waste is completely removed from the waste stream results show that the repayment period is reduced to 5 years as seen in Figure 26. Scenario 7 shows that the reduction of calorific value on recyclates stream has little impact on the overall performance of repayment period of the facility.

Results show that whilst recycled waste is a more appropriate fuel for EfW technologies than household waste, because it has a higher calorific value and lower moisture content, there is less of it available. This is confirmed by the scenarios where the household waste stream is reduced and yet the facility is capable of maintaining technical performance. In the event a of complete removal of household waste the facility is even capable of delivering higher revenue. However, as disucssed in previous chapters, recycling waste accounts for a small part of all waste received on site. This means that household waste would have a greater impact on overall economics. Consequently these results demonstrate that the facility has a more important role as a waste reduction system rather than an energy production system based on capacity and type of waste processed.

5.2.2 Operating time and procedures

In scenario 4, the impact of suspending the operation for 150 days was investigated. Results shown in Figure 24 reflect that the less the facility is operating the longer the repayment period becomes. Furthermore results indicate that if the facility operates less than 200 days per year it becomes unfeasible as the repayment period extends beyond 10 years.

Scenario 8 considers the effects of a decrease in landfill cost. Results shown in Figure 25 reflect that a drop in landfill cost (£/tonne) is accompanied by a lower repayment period. Furthermore, the graph in Figure 25 shows that the repayment period is affected by increments of about 20 £/tonne. Consequently it is possible to conclude that the higher the disposal cost the longer it takes to repay capital cost.

Scenario 9 shows that a reduction in heat sales would originate a longer repayment period. In this scenario a drop in heat sales in the order of 25% of the original price was evaluated. These results show that it is very important to source heat customers.

Scenario 10 investigates the effect the introduction of a drier would have on capital repayment period. Results show that a faster repayment period of between 10% to 15% would be achieved.

5.3 Investment analysis

Investment analysis is a tool used to establisht the riskiness of an investment and projects its potential return. This is very important because it aids decision makers identifying adequate businesses to invest in by providing a comparitive standard between different options. In EfW processes it is very important to identify the risk associsated to acquiring and installing these systems correctly . As discussed in Chapter 2, EfW technologies are associated to high risk investments because these are still considered to be an untested technology and, associated to this, there is a lack of pilot facilities where the technology can be tested prior to an investment.

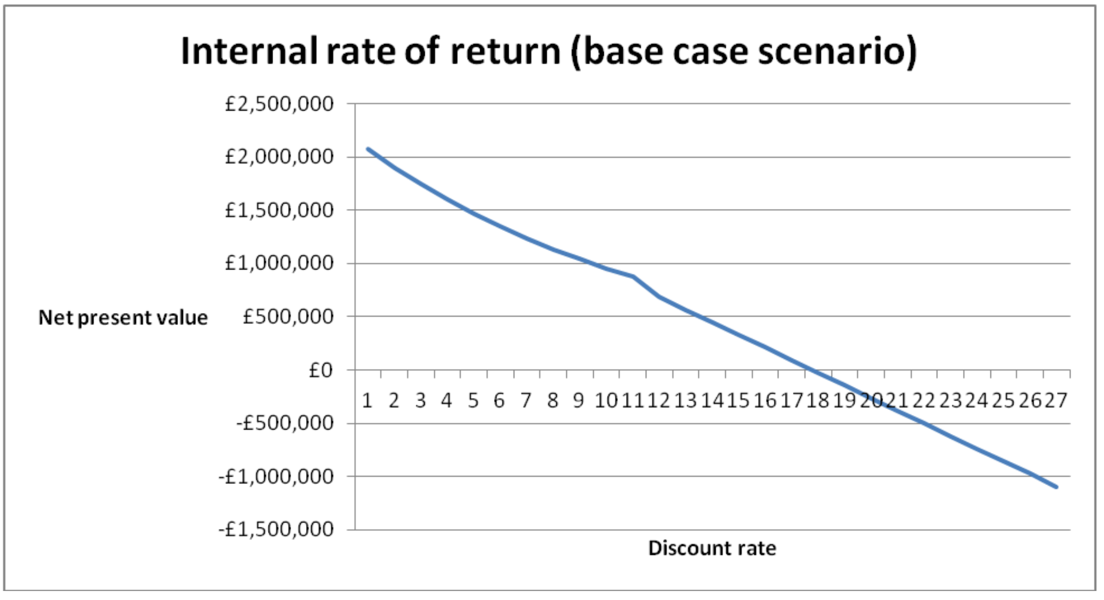


Figure 33. Internal rate of return (relationship between net present value and discount rate) applied to the base case scenario. IRR = 17%

NPV (net present value) is an indicator of the value an investment adds to a business. If it is a positive value it means that an investment would add value to the business. If it is a negative value then it means that the investment would subtract value from the business and if the value is null than there is no economic impact on the business and the decision of implementing the investment should be based on other factors.

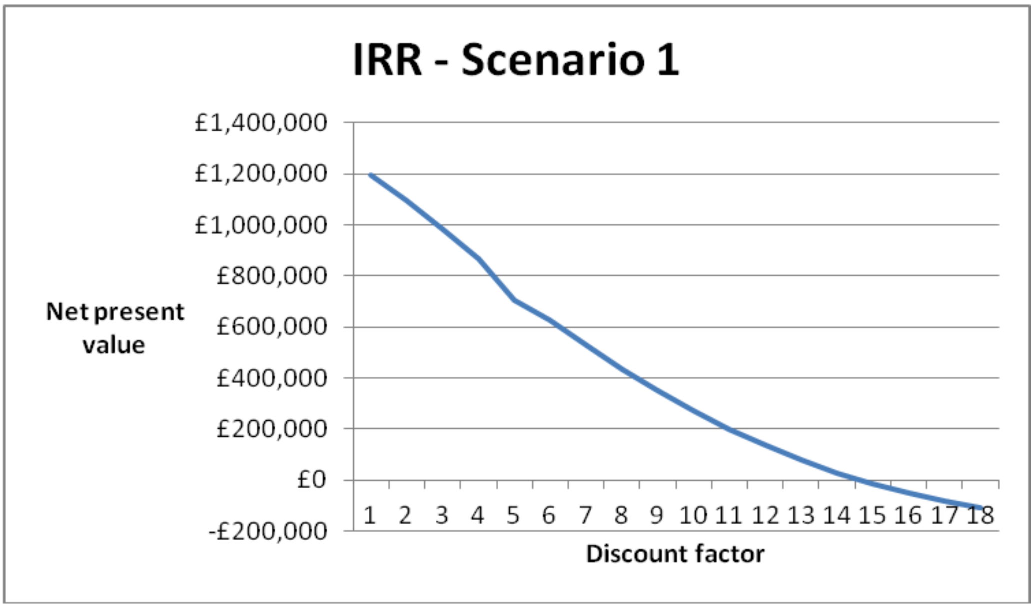


Figure 34. The graph shows the IRR for Scenario 1 is approximately 15%

In order to calculate the riskiness of an investment IRR is calculated. IRR is calculated by multiplying the return per year by the DCF (discount cash flow). The IRR is the point at which NPV is null. Figure 33 shows the IRR in the nominal situation. In this case IRR approximately 17%. IRR was applied to scenarios 1, 2, 3, 4 and 9 as these situations better reflect the impact of capital cost repayment. In the scenarios investigated IRR was always found to be lower than in the nominal situation and it oscilates between 6% and 15%.

Low IRR values reflect that an investment is very risky whereas high IRR values suggest a better internal return.

The results of IRR analysis show that the highest IRR is associated to the nominal situation. The IRR of Scenario 1, shown in Table 18, is approximately 15% which means that there is slightly more risk attached to this option than to the nominal situation. Scenario 1 investigates the impact of the reduction of plastic and paper so the results obtained from IRR show that the removal of these components causes a negative effect on the economic feasibility of the facility.

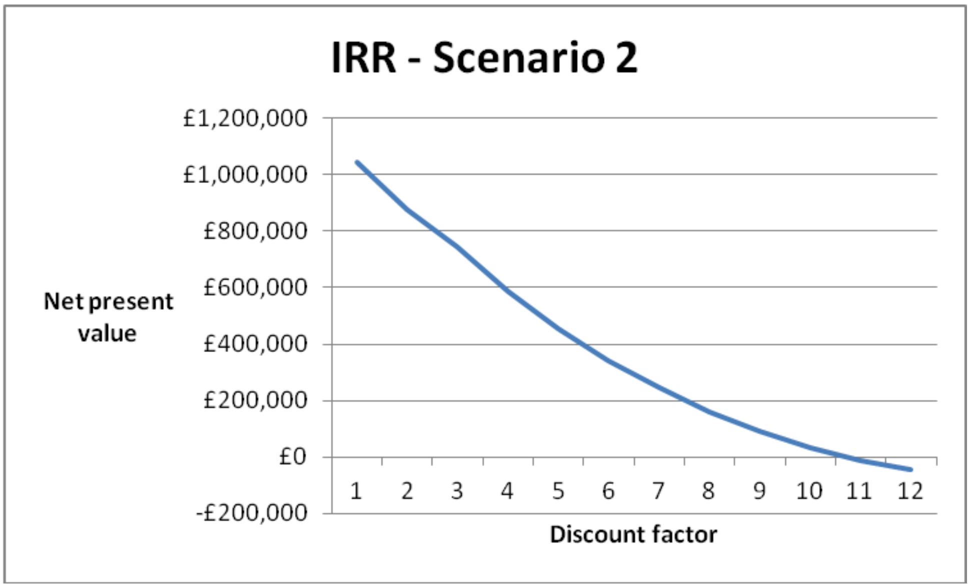


Figure 34. The graph shows the IRR for Scenario 2 is approximately 10%

In Scenario 2, the IRR is approximately 10%, as shown in Figure 34, thus reflecting that there is higher risk associated to reducing the overall tonnages present in the waste stream.

By comparison, IRR analysis shows that the reduction of waste tonnages is a higher risk business option than the removal of plastic and paper.

The IRR of Scenario 3 is shown in Figure 35, and it is approximately 9%. This scenario investigates the impact of an increase in moisture content across all waste streams. Results show that this option also poses higher risk than the nominal situation.

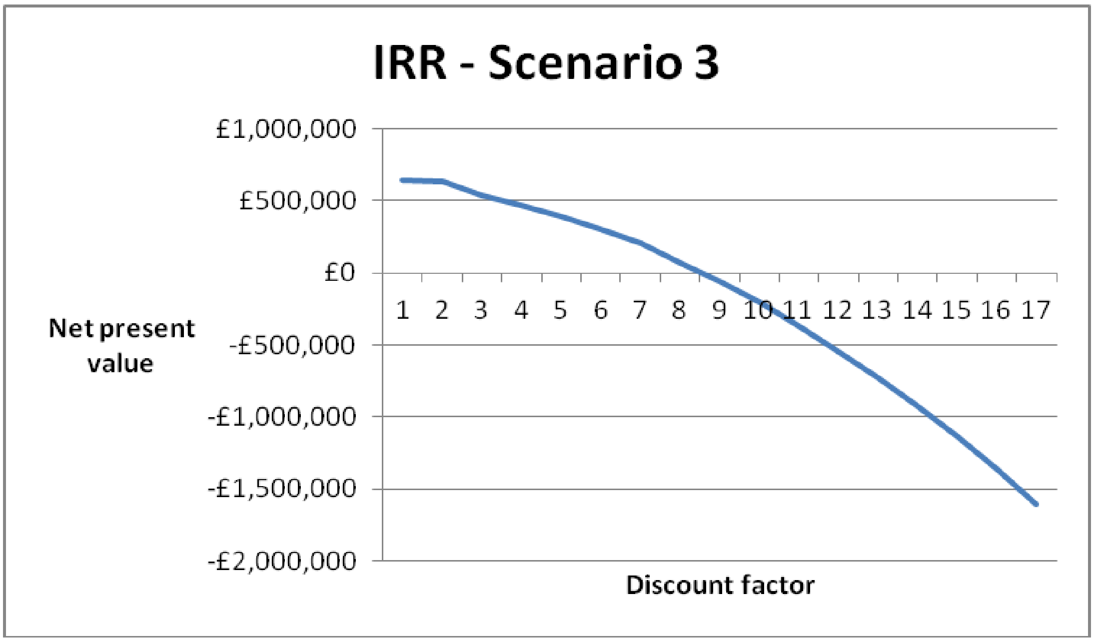


Figure 35. The graph shows the IRR for Scenario 3 is approximately 9%

The IRR of Scenario 4 is represented in Figure 36. In this scenario the IRR is 6% which is the lowest value calculated across all scenarios investigated.

Scenario 4 investigates the impact of the operation being suspended by 150 days and the results show that the impact of variations in operation is higher than the impact of variations in the chemical composition of the waste.

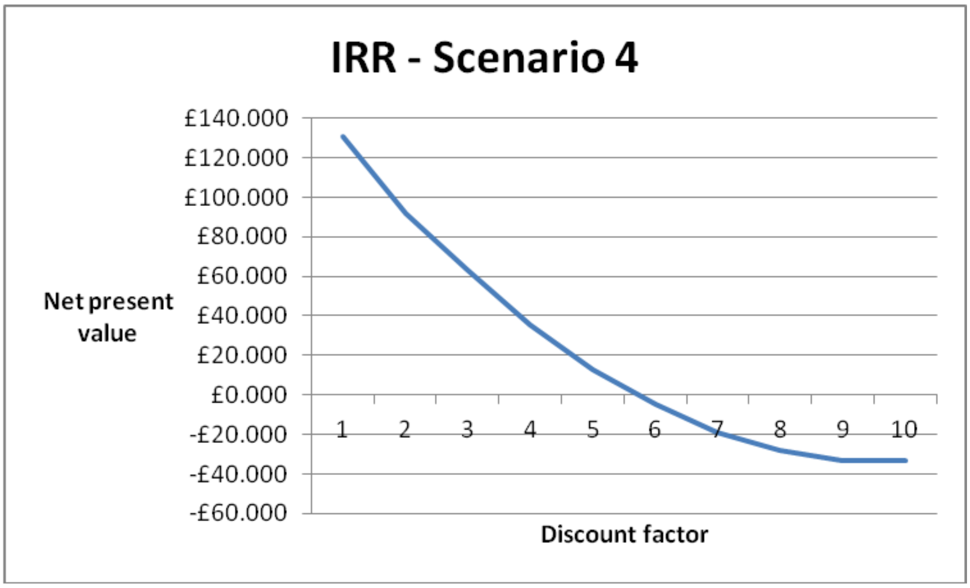


Figure 36. The graph shows the IRR for Scenario 4 is approximately 6%

IRR of Scenario 9 is described in Figure 37, in this situation there is a drop in heat selling price. The IRR for this case is approximately 14%. Comparatively this situation has a lower risk associated to scenario 1. Although these scenarios 1 and 4 reflect IRRs similar to the nominal situation the values achieved are lower and therefore these situations are considered to have higher risk associated to them.

From the IRR analysis it is possible to conclude that the impact of the variation of chemical properties in the waste such as moisture content and calorific value does not have such a great impact as the variation of waste tonnages. This fact had become apparent in the scenario analysis. Investment analysis contributes significantly to clarify the impact from an economic perspective.

These results show that EfW facilities at the scale investigated are more important as waste reduction processes rather than energy production systems.

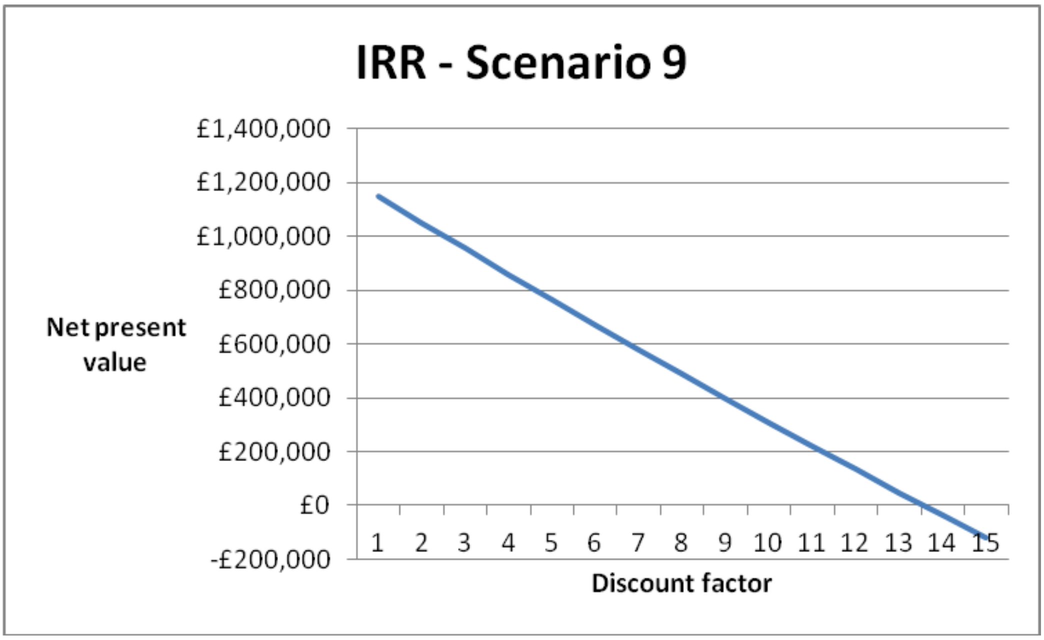


Figure 37. The graph shows the IRR for Scenario 9 is approximately 14%

5.4 Summary

- Scenario 1: the reduction of plastic and paper impacts greatly on calorific value but only represents a 2 year delay on repayment period
- Scenario 2: the reduction of overall tonnages results in the system breakdown when tonnages drop below 20%
- Scenario 3: If the moisture content in the waste increases more than 14% the system becomes infeasible
- Scenario 4: if the operation is suspended beyond 200 days the system is not viable economically
- Scenario 5: If the operation receives more than an extra 27 000 tonnes per year the system becomes infeasible
- Scenario 6: A drop of 10 000 tonnes per year in household waste has a positive impact on the system economic feasibility as the repayment period drops.
- Scenario 7: a drop in calorific value in the recyclates stream does not produce a significant impact in the process
- Scenario 8: a reduction in landfill costs has a positive impact in the system
- Scenario 9: A drop in heat selling price does not impact significantly on the process
- Scenario 10: if a drier is introduced in the process the repayment period drops 10 to 15%
- Investment analysis show that the IRR in the nominal situation is 17%
- IRR of scenario 1 is 15%

- IRR of Scenario 2 is 10%
- IRR of Scenario 3 is 9%
- IRR of Scenario 4 is 6%
- IRR of Scenario 9 is 14%

5.5 Recommendations for future work

It is recommended that future work in this area includes:

- Optimisation of routines in the techno-economic model which could advise the waste operators in selecting EfW systems
- Introduction of other variables in the model such as transport and variation of electricity selling price
- Real data from industry instead of the use of rough order magnitude costs

Conclusions

Waste production is a constant associated to human history. In modern times there has been an increase in waste produced which is associated to the industrial revolution. It is in this period that the first relevant pieces of legislation controlling waste disposal were produced. Landfill and incineration became the primary waste disposal techniques and these are still in use today.

Waste disposal is now governed by European Union legislation which establishes an order of waste disposal methods. Waste arisings in the UK show that there is still too much waste being disposed of via landfill. Not only does this impact environmentally but there is also an economic impact associated to it since government measures imposed higher landfill costs to prevent its use.

The aim of this thesis was, therefore, to contribute to the understanding of the difficulties surrounding the implementation of energy-from-waste particularly in smaller communities. The objectives were to establish the constraints behind setting up small-scale (under 100 000 tonnes per annum) facilities and to understand the feasibility parameters of this type of operation through the use of a techno-economic model. It should be noted that such a model has not previously been published in academic or professional literature and hence there was a definite need for this analysis to be undertaken.

Previous literature shows that research undertaken in this area made use of techno-economic models based on the chemical and physical properties of the waste. At a second stage sensitivity and scenario analysis were used to establish feasibility parameters.

A description of the case-study area (CSA) and the fuel was provided. The information gathered shows that the waste received on the CSA has a high quantity of moisture content and low calorific value. This is the result of the composition of the waste streams which reflect a greater quantity of household waste whilst there is less recycling waste. As these characteristics are not ideal for EfW systems three options in calorific value manipulation were provided. These suggest that varying calorific value and moisture content in the waste produce an effect on the fuel.

A description of the techno-economic model is provided to show how this was constructed and which variables were used. Sensitivity analysis results demonstrated that a successful operation of a small scale facility is more reliant on gate income than energy sales, and fluctuations in input tonnage are a greater concern economically than changes in calorific value.

The results of the sensitivity analysis show that whilst the project is feasible at a nominal basis it attracts high risk which reflects that this technology is unproven and subject to variations in calorific value and moisture content. Furthermore, the results point to the fact that small-scale EfW systems are primarily relevant as a waste disposal method rather than an energy production system. This is shown through the impact that the variation of waste tonnages has on overall economics and in particular on the household waste stream.

Results show that the variation of calorific value and moisture content on the recycling waste stream produces little impact on overall performance. This confirms that although this waste stream is more adequate to EfW systems the fact that there is less of it results in a low impact. The results obtained from the techno-economic model show that the feasibility factors can be listed as follows:

- High calorific value fuel
- Low moisture content fuel
- Facility must operate over 200 days per year
- Low disposal cost favours the system feasibility
- A facility projected to small scale cannot process more 27 000 tonnes per annum.

These feasibility parameters establish operational and fuel conditions within which the system operates. Further to these technical aspects investment in EfW is discouraged by the lack of operating facilities where the process can be tested. Furthermore, these systems have traditionally been poorly received by the general public which has an impact on the planning process.

It is recommended that future work in techno-economic models applied to EfW systems include the optimisation of routines in the techno-economic model and the introduction of other variables in the model such as transport and electricity selling price. Furthermore, the use of data obtained directly from EfW operators would be of great benefit to the research in this area allowing for more accurate results.

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Appendix A

Waste characterisation tables

A1. Moisture content during winter (%)

Summer						
Category	HTR	HBSR	HEOFR	CRTR	CRBSR	CREOBR
Plastic	42.11	21.05	26.67	6.67	11.11	2.31
Paper	46.53	82.05	47.05	18.18	12.50	18.30
Glass	0	0	0	0	0	0
Metal	0	0	0	0	0	0
Organic matter	37.50	48.78	46.94	0	0	0
Miscellaneous	52.00	42.11	86.67	0	0	6.64

A2. Moisture content during summer (%)

Winter						
Category	HTR	HBSR	HEOFR	CRTR	CRBSR	CREOBR
Plastic	0	12	12	12	12	12
Paper	55.2	44.3	15.51	25.8	26.7	14.1
Glass	0	0	0	0	0	0
Metal	0	0	0	0	0	0
Organic matter	47.5	70	70	65.5	64.4	0
Miscellaneous	83.85	93.8	91.3	22.8	14.2	0

A3. Calorific value Ar (MJ/kg) during summer

Summer						
Category	HTR	HBSR	HEOFR	CRTR	CRBSR	CREOBR
Plastic	9.34	1.51	27.28	34.72	33.07	36.34
Paper	1.68	1.37	6.06	10.31	11.37	11.42
Glass	0.14	0.14	0.14	0	0	0
Metal	0.7	0.7	0.7	0	0	0
Organic matter	3.32	3.17	4.73	4.7	4.7	9.7
Miscellaneous	0.15	2.33	1.45	20.6	0	19.07

A4. Calorific value Ar (MJ/kg) during winter

Winter						
Category	HTR	HBSR	HEOFR	CRTR	CRBSR	CREOBR
Plastic	32.8	32.8	32.8	32.8	32.8	32.8
Paper	6.73	7.39	15.8	10.58	10.14	9.8
Glass	0.14	0.14	0.14	0	0	0
Metal	0.7	0.7	0.7	0	0	0
Organic matter	8.13	5.17	1.41	2.15	6.79	0
Miscellaneous	16.71	14.99	17.11	22.38	18.59	15.8

A5. Calorific value on a dry-basis (MJ/kg) during summer

Summer						
Category	HTR	HBSR	HEOFR	CRTR	CRBSR	CREOBR
Plastic	32.3	32.3	37.2	37.2	37.2	37.2
Paper	12.60	12.6	11.45	12.6	13.0	13.98
Glass	0.14	0.14	0.14	0	0	0
Metal	0.70	0.70	0.70	0	0	0
Organic matter	0	3.17	8.91	4.7	4.7	8.91
Miscellaneous	0	2.33	10.81	20.6	0	20.43

A6. Calorific value on a dry-basis (MJ/kg) during winter

Winter						
Category	HTR	HBSR	HEOFR	CRTR	CRBSR	CREOBR
Plastic	37.2	37.2	37.2	37.2	37.2	37.2
Paper	15.02	13.27	15.02	14.26	13.83	13.89
Glass	0.14	0.14	0.14	0.14	0.14	0.14
Metal	0.70	0.70	0.70	0.7	0.7	0.7
Organic matter	14.64	4.7	14.64	18.16	19.10	0
Miscellaneous	28.26	28.38	31.34	33.85	26.06	22.8