# Appropriate scales and technologies for energy recovery by thermal processing of waste in the urban environment

**Liban Yassin**

Centre for CO2 Technology

Department of Chemical Engineering

University College London

A thesis submitted for the degree of

Doctor of Philosophy in the University of London

February 2008

ProQuest LLC
789 East Eisenhower Parkway
P.O. Box 1346
Ann Arbor, MI 48106-1346

*I, Liban Yassin, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.*

"The future of life on our planet is a matter of increasing concern, as we are being confronted with several warnings about growing fragility of the Earth's life support system. Expanding our understanding of the life support system and sustainable development are, doubtless, two of the most important issues mankind is presently facing"

Göran Wall

I would like to dedicate this thesis to my loving parents...

# Abstract

In the developed world, 75% of the population live in urban areas, a figure projected to rise to nearly 83% by 2030, while in the developing world, the rate of urbanisation is even faster. One of the most important environmental problems associated with urbanisation is the amount of waste that is generated at a rate that outstrips the ability of the natural environment to assimilate it and authorities to manage it. Therefore, if we are to deliver a more sustainable economy, we must do more with less by making better use of resources. The recovery of energy from waste or EfW is an important component of an integrated waste management strategy, as it reduces our reliance on landfill. It is also a low carbon, low cost fuel, which by displacing fossil fuels can help the UK Government in meeting its energy policy and emission targets. Furthermore, EfW can contribute to energy security through diversification of supply; it is projected that EfW may supply up 17% of the total UK electricity consumption by 2020.

The main objectives of this work are to investigate the appropriate scales and technologies for the production of energy from waste in the urban environment. The suitability and effectiveness of fluidized bed combustion and gasification processes have been studied, together with gas clean-up systems. The most appropriate scales for each of these approaches in relation to system efficiencies and costs were evaluated, so that a sound judgement can be made as to which processes should be used in the urban context.

Within this framework, a comprehensive assessment of fluidized bed reactor types and operational process conditions has been presented. Current and future status of these technologies was discussed, as well as the non-technical barriers hampering their development. The assessment concluded with a review of the different emissions and residues generated from the thermal treatment processes, their management, practices and costs.

Mass and energy balances of traditional moving-grate combustion plants and key issues regarding the treatment of the output gas stream have been investigated during a five-month placement programme at Germanà & Partners Consulting Engineers in Rome (Italy). The aim of the study was to gain an in-depth understanding of design methodologies and engineering principles applied in the detailed design of real industrial energy recovery plants.

The study led to the development of a consistent approach for the technical and economic evaluation of more advanced technologies, namely fluidized bed combustion and gasification systems. Two different scale scenarios of 50,000 tpa and 100,000 tpa plant capacities were considered for the generation of electric power using a steam turbine for the combustion process and gas engine & combined cycle gas turbine (CCGT) for the gasification process. Mass and energy balances of the processes were performed and the cost effectiveness of the different waste treatment options was assessed using a discounted cash flow (DCF) analysis, which includes current market-based mechanisms, such as eligibility for Renewables Obligation Certificates (ROCs).

A sensitivity analysis was carried out to evaluate the effects of changing system variables on the economic performances of the different waste treatment options. Seventeen system variables have been chosen and the effects of a ±10% change in these variables on the levelised costs and gate fees were examined. These variables include waste calorific value, gasifier efficiency, prime mover electrical generation efficiency, as well as electricity and ROC prices and biodegradable fraction of the waste. As part of this study, the techno-economic performances of traditional moving-grate combustions systems was reported and compared against the different fluidized bed systems co-located with Mechanical Biological Treatment (MBT) facilities.

The work was subsequently extended to analyse the technical and cost effectiveness of the simultaneous generation of heat and power from EfW fluidized bed combustion and gasification systems, using the same scale scenarios of 50,000 tpa and 100,000 tpa. The study focused on the additional capital and operating costs involved in incorporating combined heat and power (CHP) into EfW facilities. The projected revenues from heat sales and eligibility for ROCs were also evaluated for a range of market penetration levels. Furthermore, the environmental benefits associated with EfW with CHP facilities were assessed and the $CO_2$ savings achieved from displacing fossil fuels in the separate generation of heat and power were also determined.

# Acknowledgements

This research project would not have been possible without the valuable support and time of many people. First and foremost, I would like to thank Dr Paola Lettieri and Professor Stefaan Simons for their support and guidance throughout my PhD. I would like to give my warmest and heartfelt thanks to Paola whose advice, dedication and constant encouragement has been instrumental in the completion of this work.

I am greatly indebted to Professor Antonino Germanà and Engineer Pasquale Criscuoli for their technical expertise and kind hospitality during my work placement at Germanà & Partners Consulting Engineers in Rome (Italy). The placement has provided me with an invaluable experience and my stay in Rome remains one of the fondest memories of my PhD. I also would like to thank Dr Tim Elson for his assistance with ChemCAD and the staff of the Computing and Electronic Systems office; Martyn, Mark & David. A sincere thank you to the administrative staff of the Chemical Engineering Department. I am particularly indebted to Pattie and Nely for allowing me to have access to their facilities in the office.

To Dr Olumuyiwa Owoyemi "*Oli*", thank you for your great friendship and support. Many thanks to my dear colleagues and friends; Luca, Sarah, Giovanna (x2), Panos, Namso, Baodong, John, Deji, Maxwell and Chandni. (*I can only mention a few!*). Finally, I would like to thank my parents for their constant encouragement and to Clare Foster for simply being there for me.

I acknowledge the financial support from the Engineering and Physical Science Research Council (EPSRC) and thank Professor Chris Coggins and the Waste Consortium members for their advice.

# Contents

# List of Tables

# List of Figures

# 1 General Introduction

## Summary

In this chapter, an overview of the link between human activities and climate change is given and the need for a radical change in the way we obtain and use energy is discussed. The goal of this project is presented thereafter and the chapter concludes with an outline of the thesis.

## 1.1 Human activities and climate change

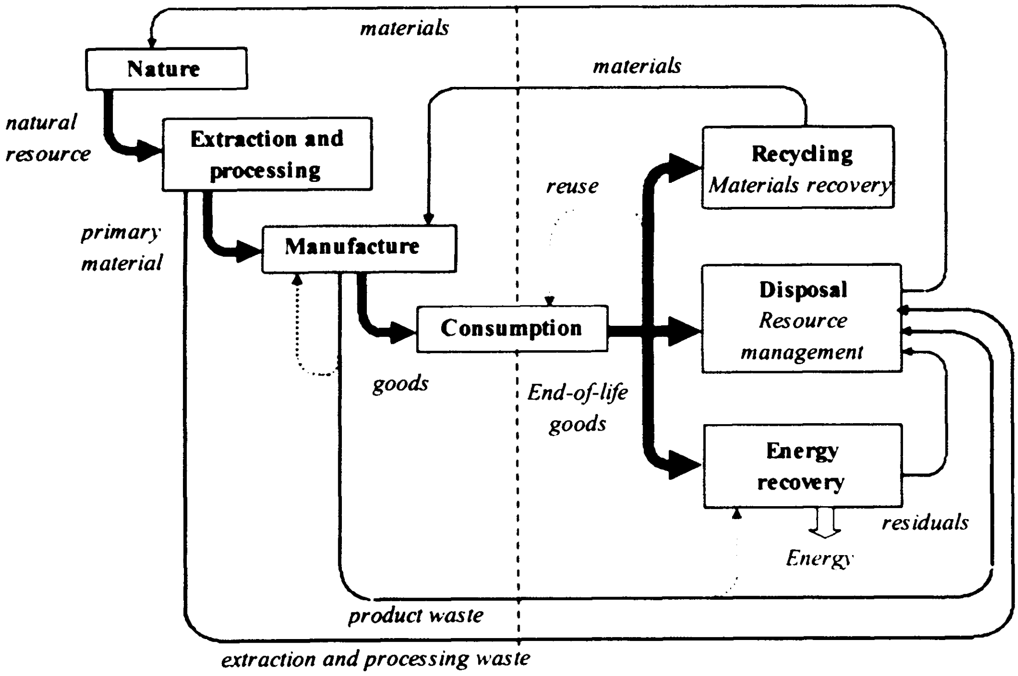
From 1995-2000, the world's urban population grew at a rate of 2.2% per year and in 2000, 75% of the population in the developed world lived in urban areas. This figure is projected to rise to nearly 83% by 2030, while in the developing world, the rate of urbanisation is even faster (United Nations, 2002). Along with this, came increased demands for energy and natural resources, fuelled by increasing consumption levels per capita in rich countries and rapid rise in consumption in developing countries, namely China and India. As a consequence, urbanisation and the increased demands for energy have provided the setting for increased human activities, which have major economic and environmental impacts.

As we burn fossil fuels and change land use, we are changing the nature of the earth surface and contributing to climate change. These activities led to an increase in the concentrations of a number of greenhouse gases (GHG), such as carbon dioxide, methane, chlorofluorocarbons and ozone in the atmosphere. In fact, deforestation alone is reported to account for 20% of global carbon dioxide emissions (Defra, 2006a). Greenhouse gases trap heat in the Earth atmosphere through the greenhouse effect, which is the primary cause of global warming. Although there are many processes that can change the Earth's global climate, such as ocean processes and solar variations, global warming is 'very likely' to have been caused by human activities according to the recent 2007 Intergovernmental Panel on Climate Change (IPCC) report (2007).

The outlook of the report is quite stark. Hotter temperatures and rises in sea level "would continue for centuries". Erratic weather patterns including heat waves and heavy rainfalls "will continue to become more frequent" and sea ice in the Artic may disappear "entirely" towards the end of the century. Other effects of global warming include loss of habitats, increased desertification and water stress, with consequences for agricultural production.

Climate Change also poses a major risk to the global economy. The Stern Review by the former Chief Economist and Senior Vice-President of the World Bank, Nicholas Stern, reported that climate change, if unabated, will have a serious impact on global economic growth. Greenhouse gases need to be stabilised in the next 20 years then fall 1-3% afterwards. This will cost the global economy 1% of its GDP. Otherwise, we will risk a global recession worth up to 20% of global GDP (Stern, 2007). Although Stern's approach was criticised by some economists, his final message was loud and clear, "if we act now, we can avoid the very worst".

Therefore, if we are to satisfy our basic needs and "enjoy a better quality of life without compromising the quality of life of future generations" (Defra, 2005a), we must improve our resource efficiency and reduce climate impact. This involves getting the most out of our finite resources and minimise waste. Ultimately, we need to shift processes from linear and 'open loop' systems, where natural resources and capital investments move through the system to become waste, to 'closed loop' systems, as shown by the resource cycle in Figure 1.1. The figure depicts the industrial ecology through which natural resources undergo different processes, where each process has its own inputs and outputs (Lettieri, 2007). Waste outputs from one process may be used as resource inputs to another and the return of waste to the environment, in a way that enables them to be extracted and used again, can only be achieved through complex interactions of technological, economic and societal factors.



Adapted from Lettieri (2007)

Figure 1.1 The Resource Cycle

## 1.2 Energy, the changing climate

In 2000, the Twenty-Second Report by the Royal Commission on Environmental Pollution (RCEP), titled "Energy- The Changing Climate", presented preventative measures and a completely different approach in the way we obtain and use energy to the UK and wider communities (Clift, 2007). The RCEP recommended ensuring that concentration of carbon dioxide in the atmosphere does not exceed 550 ppmv (parts per million by volume). The UK, as a contribution to the global efforts, must reduce carbon dioxide emissions by almost 60% from their current level by 2050. The RCEP also recommended changes that would reduce carbon emissions and enable the UK to reach its target, while protecting its environment and quality of life (RCEP, 2000).

These changes include the reduction of energy use through smarter application of technology, especially in the heating and cooling of buildings, which accounts for over 50% of residential carbon dioxide emissions (Clift, 2007). Other changes include using fossil fuels more efficiently and large deployment of alternative energy sources. The efficient use of fossil fuels entails the transition to a new energy economy by switching to gas, which has lower carbon content in relation to its energy content compared to oil and coal.

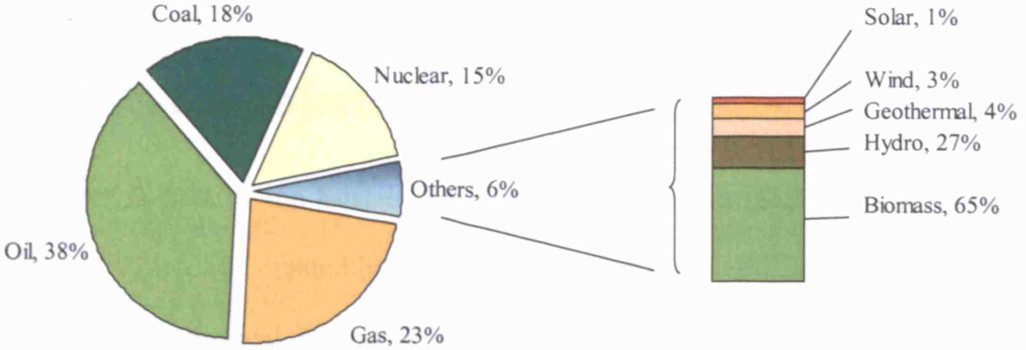
Combined heat and power (CHP) plants supplying heat to district heating systems are also encouraged, as they can provide a growing market for renewable fuels such as biomass. The deployment of alternative energy sources that are renewable and sustainable are needed as substitutes for fossil fuels. The potential for growth and expansion of renewables sources, such as solar, hydro power, wind, biomass and geothermal is great, especially after the oil crisis in 1970s, which led many countries into diversifying their energy sources.

However, to fully realise the potential of these sources, one has to address their numerous challenges, such as the 'technological gap' that needs to be overcome for the transition from fossil fuels to renewable energy sources, while at the same time, keeping pace with an increasing global demand for energy. Therefore, a significant financial and technical assistance is required to provide and develop alternative energy systems in "ways that will cause least damage to the environment" (RCEP, 2000).

## 1.3 Which renewable energy?

The UK Government has committed itself to reducing carbon dioxide emissions by 60% by 2050, as recommended by RCEP's Twenty-Second Report (see previous section). However, in order for the Government to reach its target, it has to find alternatives to fossil fuels and bring them into use as sources of heat and power at the earliest possible opportunity. Renewable energy sources reduce greenhouse gas emissions, improve security of supply by diversification of energy production and encourage creation of new jobs. In 2002, renewables accounted for 6% of the total energy demand in Europe.

Figure 1.2 shows that almost two third of the renewable energy came from biomass and hence, contributing to around 4% of the total EU energy supply. This figure is expected to double up to 8% of the total EU energy supply by 2010 (European Commission, 2005). Therefore, biomass has a critical role to play in the EU's long-term sustainable energy strategy.



Adapted from European Commission (2005)

**Figure 1.2 Breakdown of energy consumption in the EU in 2002**

There are now many dedicated and established biomass energy systems that produce heat and/or power, gaseous fuels and other valuable materials. These systems are able to use a large variety of feedstock, including municipal solid waste (MSW), which has contributed to 13% of the primary bio-energy production in the EU in 2002, while the rest came from wood residues and energy crops combined (81%) and biogas (4%).

Biomass, beside its environmental, social and economic benefits, is currently the only available renewable energy source that can produce competitively priced fuels for transport in larger quantities and the only widespread source of high-grade renewable heat. However, it is "far from being fully deployed in the UK and a considerable biomass feedstock resource is not being utilised" according to the Biomass Task Force (2005), who also urged the UK Government to treat waste "as a secure and sustainable source of biomass energy". As a consequence of the 2005 Biomass Task Force report, the Government's UK Biomass Strategy was published in May 2007, in which it defines the Government's aspirations for the sustainable development of biomass for heat and power, transport fuels and industrial products (Defra, 2007a).

## 1.4 Research objectives

This project is part of the Sustainable Urban Environment (SUE) waste management consortium, which was created by several UK university groups and is sponsored by the Engineering and Physical Science Research Council (EPSRC). These university groups include:

- Goldsmith College (Department of Anthropology);
- Imperial College London (Department of Environmental Science & Technology);
- University College London (Centre for CO2 Technology);
- University of Sheffield (Department of Chemical and Process Engineering);
- University of Southampton (School of Civil Engineering & the Environment);
- University of Surrey (Centre for Environmental Strategy).

The Consortium addresses the problems of waste resource management in urban environments, with emphasis on the technical, social and economic constraints. It is specifically concerned with wastes arising from the manufacture and consumption processes shown in the resource cycle in Figure 1.1, which are to the right of the vertical dashed line. The overall aim of the Consortium is to build on the underpinning scientific expertise of individual partners to carry out research that will:

- In the short to medium term, contribute towards meeting impending legislative requirements without making an inappropriate and irrevocable commitment to any particular type of treatment technology;

- In the medium to long term, contribute to the development of waste management strategies that are optimal in environmental, societal, technological and economic terms.

The main objectives of the UCL project, and thereby of this research, are to investigate the appropriate scales and technologies for the production of energy from waste in the urban environment. The suitability and effectiveness of fluidized bed combustion and gasification processes have been studied, together with gas clean-up systems. The most appropriate scales for each of these approaches in relation to system efficiencies and economics were evaluated, so that a sound judgement can be made as to which processes should be used in the urban context. Therefore, the main deliverables of this work can be summarised as follows:

- A comprehensive assessment of fluidized bed reactor types and operational process conditions focusing on advanced thermal treatment processes, namely gasification. Report of the present and future status of these technologies, as well as the non-technical drivers affecting their commercial development. Review of the different emissions & residues generated from the thermal treatment processes, their management, practices and costs.

- Investigate the process design of energy-from-waste (EfW) industrial plants and clean biomass systems, through a collaboration study with Germanà & Partners Consulting Engineers in Rome (Italy). The aim of this aspect of the PhD was to develop the mass and energy balance of a more traditional and commercial-scale moving-grate combustion plant and investigate the efficiency of alternative reagents for the treatment of flue gases.

- Analyse the technical performances of advanced technologies, namely fluidized bed combustion and gasification systems. Demonstrate the importance of choosing appropriate energy conversion systems, such as steam turbines, gas engines, fuel cells and CCGT, to determine the applicability of EfW processes at different scales, ranging from 2,000 tpa to 260,000 tpa of waste input.

- Evaluate the technical and economic analysis of small-to-medium scale EfW fluidized bed combustion and gasification systems at two different scale scenarios of 50,000 and 100,000 tpa. The aim was to highlight the implications of different scales and technologies on system efficiencies and waste treatment costs. Perform mass and energy balances of the different waste treatment options for electricity-only generation and assess their cost effectiveness using a discounted cash flow (DCF) analysis.

- Examine the technical and economic performances of EfW systems with combined heat and power. The study focused on the additional capital and operating costs involved in incorporating CHP into these facilities, as well as the projected revenues from heat sales and eligibility for ROCs.

- Assess the environmental benefits associated with EfW with CHP facilities and the $CO_2$ savings achieved from displacing fossil fuels in the separate generation of heat and power.

## 1.5 Thesis outline

In Chapter 2, a literature review of the waste management practices, policies and strategies are presented, together with a comprehensive review of thermal treatment processes of waste. Chapter 3 reports the work that has been carried out during a five-month placement programme as part of this research project at Germanà & Partners Consulting Engineers in Rome (Italy), which investigated the scales and technologies of EfW and clean biomass processes. The chapter also outlines the application of a kinetic model that was used to compare the performance of two reagents utilised in the gas treatment process for the removal of gaseous acids in terms of cost and efficiency. In Chapter 4, the techno-economic performances of small-to-medium scale EfW fluidized bed combustion and gasification processes are reported. A sensitivity analysis is also performed to take account of uncertainties in the economic model input parameters. The first part of Chapter 5 highlights the potential for combined heat and power in the UK, while the technical and cost effectiveness of EfW with CHP are presented in the second part. In Chapter 6, the main conclusions are summarised and suggestions for future work are reported.

# 2 Introduction to waste management

## Summary

In this chapter, the literature review begins with an introduction to waste management practices, policies and strategies. Thermal treatment processes of waste are outlined, with a comprehensive review of the current and future status of these processes. The chapter concludes with a review of the different emissions and residues generated from these processes, their management, practices and costs.

*Parts of this chapter have been published in:*

Yassin, L., Lettieri, P., Simons, S., Germanà, A. (2005). Energy Recovery from Thermal processing of Waste: A Review. In: Institution of Civil Engineers, (ed.). *Engineering Sustainability*. Proceedings of The Institution of Civil Engineers, **158**, Issue ES2, 97-103.

## 2.1 Waste, the burning issue

"Until the last ten or twenty years sustainable energy was thought of simply in terms of availability relative to the rate of use. Today, in the context of the ethical framework of sustainable development, other aspects are equally important. These include environmental effects and the question of wastes" (Energylinx, 2007).

The issue of waste is not new to anyone and in recent years, one cannot argue that the total quantity of waste has increased significantly in the EU countries and the rest of the world, raising the critical question of its safe treatment and disposal. In addition to this, the way we manage and dispose of waste has a direct influence on greenhouse gas emissions. Therefore, it is no surprise that sustainable waste practices are moving up the political agenda. Beside the Biomass Task Force's vision for waste as a sustainable source of energy, the Stern Review explicitly highlighted the role of waste management, and in particular energy recovery systems, in helping to reduce greenhouse gas emissions (Stern, 2007).

Waste is generated as a by-product in all human activities and according to White et al. (1995), it refers to anything that lacks '*use*' or '*value*'. Waste became a major issue in the UK during the industrial revolution between 1750 and 1850, when many people moved from rural areas to the cities. This led to the growth of urban population and the consequent increase in domestic waste, which was matched proportionally by an increase in industrial waste.

The Public Health Act of 1875 placed a duty on local authorities to arrange for the removal and disposal of waste. A series of toxic chemical waste dumping incidents in late 1960s and 1970s highlighted waste as a major source of environmental pollution and led to the introduction of the Deposit of Poisonous Waste Act of 1972. This was followed by the Control of Pollution Act in 1974, which controlled waste disposal on land through a new licensing and monitoring system for waste disposal facilities. Therefore, waste management was '*born out of social necessity*' as the link between public health and the environment was identified (Williams, 2005).

Thirty incinerators were constructed between 1969 and 1981 in recognition of the need for environmentally acceptable means of waste disposal. However, this was less than 10% of the total municipal waste generated in the UK every year and the rest of the waste was landfilled. The majority of the plants did not have energy recovery systems to offset disposal costs and with new legislations to limit emissions resulted in the closure of many of these incinerators (Williams, 2005). Further development of waste management legislations in the UK and Europe saw the introduction of the 1990 Environmental Protection Act, the 2000 Pollution Prevention and Control Regulations and the Landfill Regulations 2002.

Waste management was also addressed in the Sixth Environmental Action Programme in 2002, which called for a number of inter-related measures designed to reduce the environmental impacts of resource use in line with "Community Strategy for a Sustainable Development". The proposed strategy included a hierarchy of options, in which primary emphasis is on the waste prevention, followed by promotion of recovery (through re-use, recycling and energy recovery) and by the optimisation of final disposal methods (Eurostat, 2003).

Waste prevention requires the design of materials, goods and services in such a way that their manufacture, use, reuse, recycling and end-of-life disposal results in the least possible generation of waste. This has been promoted by the United Nations Environment Programme (UNEP) for some 15 years under the broader concept of cleaner production (UNEP, 2002). However, according to the European Environmental Agency (EEA), progress in this field is proving to be a very difficult challenge (EEA, 2003). This is mainly because, from a thermodynamic point of view, zero-waste processes cannot exist as the efficiency of processes used in all types of human activities is always less than

100%. Decoupling of waste generation from economic growth is also another barrier, especially in growing economies. Therefore, while waste prevention is proving very difficult to legislate, the attention is now focusing on waste treatment and disposal to ensure *'the sustainable management of natural resources and wastes'* (UNEP, 2002).

## 2.1.1 The UK national waste strategy

"If every country consumed natural resources at the rate the UK does, we would need three planets to live on" (Defra, 2007b). As a nation, we consume natural resources and produce waste at an unsustainable rate. In 2005/06, the UK produced 35.1 million tonnes of municipal solid waste. Sixty four percent was landfilled, while 27% was recycled/ composted and only 8% was incinerated with energy recovery, as shown in Figure 2.1 (Defra, 2007c).

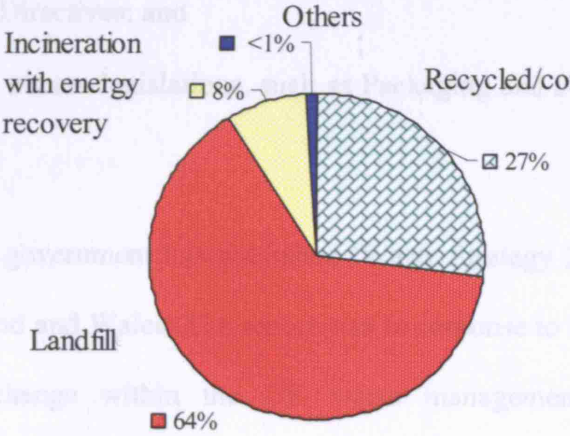


**Figure 2.1 Municipal waste management in England in 2005/6**

Although recycling and composting of waste has nearly quadrupled since 1996/97, about two third of the waste is still landfilled. Clearly, this is not acceptable as landfilling is a missed and 'wasted' opportunity. Landfilling is also a major source of methane, a greenhouse gas 23 times more potent than $CO_2$. Other components, such as leachate, can cause significant environmental pollution in air and ground water and give rise to odour. Therefore, if we are to deliver a more sustainable economy, we must do more with less. This can be achieved by optimising the recovery of resources from waste, whether as materials through recycling and composting or as energy or fuel through efficient biological and thermal processes (Yassin et al., 2005).

The UK waste management policy is largely derived from EU legislations, which fall into three categories (Waste Watch, 2007):

- Horizontal legislations that set the overall framework for the management of waste, including definitions, such as the EC Framework Directive on Waste (75/442/EEC);
- Legislations on treatment operations, which set technical standards for the operation of waste facilities, such as the Landfill (1999/31/EC) and Waste Incineration (2000/76/EC) Directives; and
- Specific waste stream legislations, such as Packaging and Packaging Waste Directive (94/62/EC).

In May 2000, the government has published 'Waste Strategy 2000' as a national waste strategy for England and Wales. The report was in response to the EU Landfill Directive and to deliver change within the UK waste management practices (Sustainable Development, 2000a). The Waste Strategy 2000 included the establishment of national targets for recovery of municipal waste and recycling/composting of household waste.

This was followed up by the publication in 2007 of a new strategy for cutting waste in England, with an emphasis on its role in tackling climate change and resource efficiency. The Waste Strategy for England 2007 is expected to have an annual net reduction in global greenhouse gas emissions from waste management of at least 9.3 million tonnes (mt) of carbon dioxide equivalent per year compared to 2006 (Defra, 2007b). The main objectives and targets of the strategy include:

- Decouple waste growth (in all sectors) from economic growth and put more emphasis on waste prevention and re-use;
- Meet and exceed the landfill directive diversion targets for biodegradable municipal waste in 2010, 2013 and 2020;
- Increase diversion from landfill of non-municipal waste and secure better integration of treatment for municipal and non-municipal waste;
- Secure the investment in infrastructure needed to divert waste from landfill and for the management of hazardous waste;
- Get the most environmental benefit from that investment, through increased recycling of resources and recovery of energy from residual waste using a mix of technologies.

Table 2.1 summarises the new increased recycling and recovery targets for household and municipal waste in England.

**Table 2.1 Recycling & recovery targets for household and municipal waste in England**

| Category | 2010 | 2015 | 2020 |
|---|---|---|---|
| Reduction in residual household waste from 2000 levels of 2.2 million tonnes | 29% | 35% | 45% |
| Recycling and composting of household waste | 40% | 45% | 50% |
| Municipal waste recovery | 53% | 67% | 75% |

The Government's overall objective for waste policy is to break the link between economic growth and the environmental impact of waste, which is set out in its 2005 sustainable development strategy and is based upon a hierarchy of preferred options (Defra, 2005a). The hierarchy represents a chain of priority for waste management, extending from the ideal of prevention and minimisation to the last resort of disposal. This is shown in Figure 2.2. Minimisation of waste is the uppermost in the hierarchy and it involves reduction of waste at source by developing clean technologies and processes that require less material in the end product and produce less waste during manufacture. This has the incentive of making significant savings in raw materials, energy use and production and waste disposal costs (Williams, 2005).

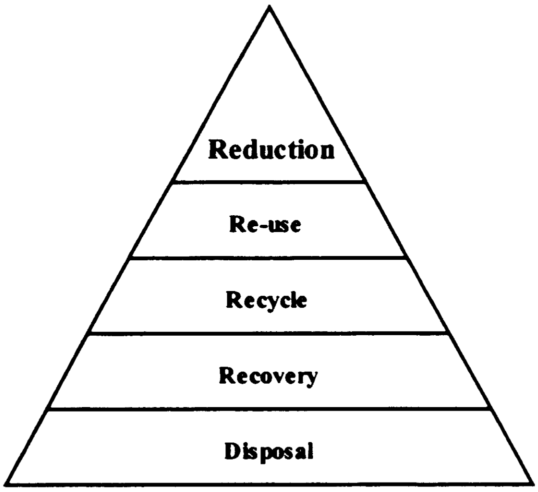


**Figure 2.2 The Waste Hierarchy**

Recycling is preferable to energy recovery where it is economically viable and environmentally acceptable. However, even in countries with highly developed recycling infrastructure, significant amount of MSW will remain after recycling to make energy recovery an environmentally justified and economically viable option ahead of final disposal to landfill (IEA, 2003).

In the 2007 waste strategy, the Government has introduced greater financial incentives to reflect the waste hierarchy and create opportunities for the reduction, re-use, recycling and recovery of energy from waste. This includes increasing the landfill tax escalator to £8 per year and introducing enhanced capital allowances for investment involving the use of solid recovered fuel for combined heat and power facilities (Defra, 2007b). The Government introduced the Landfill Allowances Trading Scheme (LATS) in April 2005 to help the UK meet the demands of the EU Landfill Directive. The LATS system is intended to provide a cost effective way of enabling England to meet its targets for reducing the amount of biodegradable municipal waste that is landfilled. Each waste disposal authority (WDA) is set allowances on the amount of biodegradable waste they can send to landfill, which reduces year on year. Failure to meet these targets incurs financial penalties of £150 for every tonne of waste exceeded for local authorities, while the UK as a whole could face significant fines from the EU. However, these allowances are tradable between the WDAs, so that authorities can sell their surplus allowances or purchase more if they expect to exceed their allocations. They can also save them for own use in subsequent years or borrow from their own future allowances for use in the current year. In 2005/6, the average trade price was £16.79 per allowance. Seven local authorities bought extra allowances and three borrowed in order to meet their allocations (Environment Agency, 2006a).

Ultimately, the 'best' disposal option will inevitably depend on the environmental and economic circumstances of each situation. In the past, local authorities used the principle of Best Practicable Environmental Option (BPEO) in producing their municipal waste management strategies. This identified waste management options that provide the most environmental benefits, as well as meeting legislative and practicability constraints, such as costs.

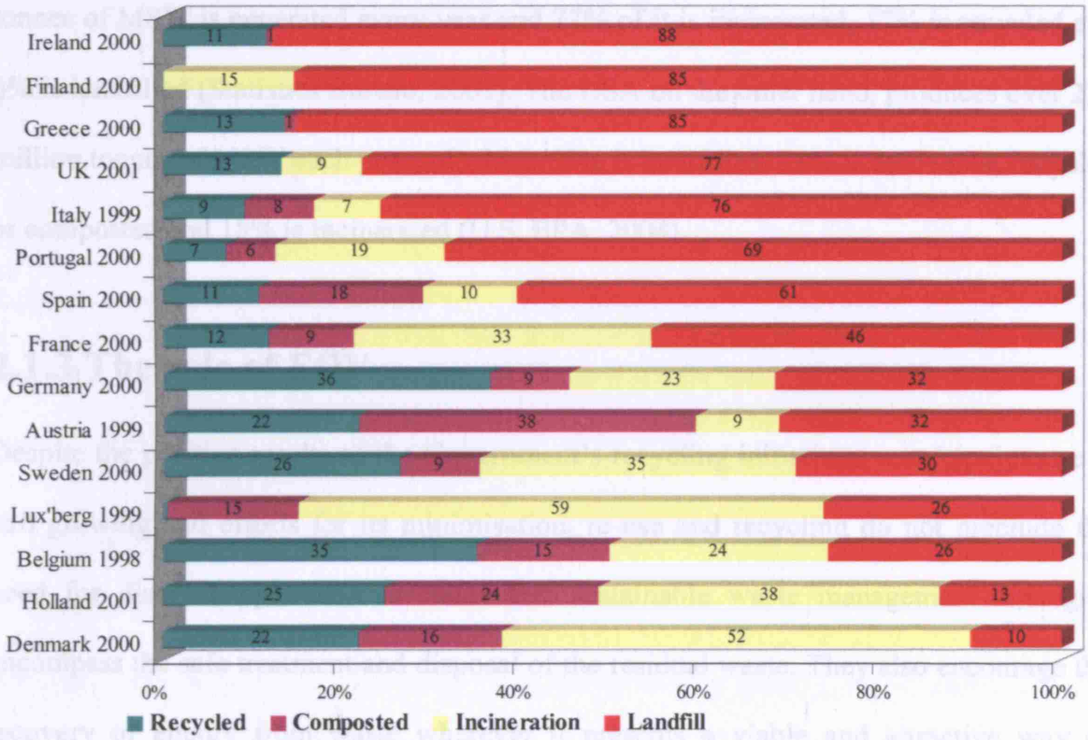
It is important to note here that the best practicable option may not be necessarily the cheapest. However, the process was criticised to be restricted to the disposal of a particular waste stream without examining the production process to determine whether the waste can be minimised, recovered or recycled (RCEP, 1988). In 2005, the Planning and Policy Statement 10 (PPS 10) was introduced, in which Sustainability Appraisals replaced the BPEO (ODPM, 2005). Despite the replacement, driving waste management practices up the waste hierarchy is still to remain a key planning objective. The application of WISARD, which was often used to assess and compare the environmental impacts of different waste management scenarios, is also being replaced with WRATE life-cycle assessment software (Environment Agency, 2007a).

As apposed to WISARD, the new life-cycle assessment software includes new technologies, such as gasification and anaerobic digestion, as alternative routes for the diversion of waste from landfill. Life-cycle assessment (LCA) techniques calculate emissions and residue releases to air, water and land. It is a 'cradle-to-grave' approach as it follows the consumption of primary resources involved in all stages of the municipal waste cycle, from the extraction of raw materials, through operation of waste collection and treatment processes, to final disposal. LCA also takes account of the resources saved and environmental burdens avoided if secondary materials recovered from waste are used as substitutes for primary raw materials (Scottish Executive & SEPA, 2003).

Although the UK's waste performance still lags far behind much of Europe, since the waste strategy in 2000 and the introduction of several Government initiatives, such as the landfill tax and LATS, the UK has made a significant progress. Recycling and composting figures are up, less waste is being sent to landfills and most importantly, municipal waste is growing much less quickly than the economy at 0.5% per year (Defra, 2007b). This is encouraging results for the Government and its quest for a sustainable economy.

## 2.1.2 Waste management outside the UK

Over 3000 million tonnes of waste is generated in Europe every year according to the European Environment Agency (EEA, 2003). Municipal waste arisings in Europe are large and continue to increase. More than 306 million tonnes are estimated to be collected each year. The treatment and disposal of municipal waste vary considerably from one EU country to another, as shown in Figure 2.3.



Data from Eurostat (2003)

**Figure 2.3 MSW management in Europe**

Landfilling is the predominant treatment option in most of these countries. This is mainly because of its low cost. However, according to Eurostat (2003), there has been a recent decline in waste disposal to landfill in Western Europe and increased recycling. In Germany, approximately 45% of the waste generated is recycled and composted and similar trends are seen in Belgium, Netherlands and Norway. Incineration is also largely used, particularly in Denmark and Luxembourg, where it represents 52% and 59% of total municipal waste managed, respectively.

In Japan, which is part of the International Solid Waste Association (ISWA), the shortage of land in accessible areas limits the availability of suitable landfill sites and is the driving force behind Japan's waste management policy. Waste policies are based on waste reduction and recycling to minimise the amount of material sent to landfills. The main disposal method is incineration with or without energy recovery. More than 52 million tonnes of MSW is generated every year and 77% of it is incinerated, 17% is recycled and 6% is landfilled (Statistics Bureau, 2003). The USA on the other hand, produces over 230 million tonnes of MSW each year, of which 57% is landfilled, 28% is recovered, recycled or composted and 15% is incinerated (U.S. EPA, 2004).

### 2.1.3 The role of EfW

Despite the positive results of the Government's recycling initiatives, municipal waste is still growing and efforts for its minimisation, re-use and recycling do not preclude the need for disposal options. Successful and sustainable waste management strategies encompass the safe treatment and disposal of the residual waste. They also encourage the recovery of energy from waste wherever it presents a viable and attractive way of integrating with recycling and re-use activities.

A major environmental benefit gained from MSW energy recovery is the reduction in greenhouse gas emissions. A study by the International Energy Agency (IEA) has reported that, for conventional incinerators with EfW, the total emission of carbon dioxide is about 367 grams of $CO_2$ per kWh (IEA, 2003). This is compared to 446 and 987 grams of $CO_2$ per kWh for gas and coal fuel boilers, respectively. Furthermore, around 50-100 kg of methane per tonne of waste could be released if the MSW is sent to landfill. This is equivalent to 1610 kg of $CO_2$ per tonne of waste, as methane has a higher global warming potential.

Regarding this, EfW is an important component of an integrated waste management strategy as it reduces our reliance on landfill. It is also an alternative source of energy, which by displacing fossil fuels can help achieve the UK's targets of 60% reduction in carbon emissions by 2050 and 10% of UK electricity generation from renewable sources by 2010. Furthermore, EfW is expected to account for 25% of municipal waste by 2020, with the potential of generating 17% of all electricity used in the UK (Lee et al., 2005). For this reason, in the 2007 Energy White Paper, the Government placed EfW in a wider energy policy context, underlying its importance as a low carbon, low cost fuel. This is in light of our increased dependence on foreign imports of oil and gas at a time of sharp increases in energy prices, as well as concerns over the future security and diversity of supply (DTI, 2007a).

Therefore, it is very significant that energy is recovered from waste effectively through the use of the most efficient, clean technologies. These technologies include anaerobic digestion, mechanical and biological treatment processes (MBT), direct combustion or incineration and advanced thermal treatment (ATT) processes including gasification and pyrolysis. Although there is no obvious 'best' technology as this would depend on local circumstances, the Government particularly supports the recovery of heat as well as power or CHP in its recent waste strategy for England (Defra, 2007b). Hence, the focus of this research project is on the recovery of energy by the thermal treatment of waste.

## 2.2 Thermal treatment of waste

Energy is recovered from waste via biological, physical and thermal processes, all which employ various reactor types and configurations. In an integrated waste management system, MSW is prepared and sorted by a series of mechanical separation techniques to give further options for recycling and recovery. The waste can be sorted into different fractions constituting of:

- Recyclable materials such as glass and metals;
- A combustible fraction, which may be utilised as a refuse derived fuel (RDF);
- An organic rich fraction such as garden waste, which may be biologically treated.

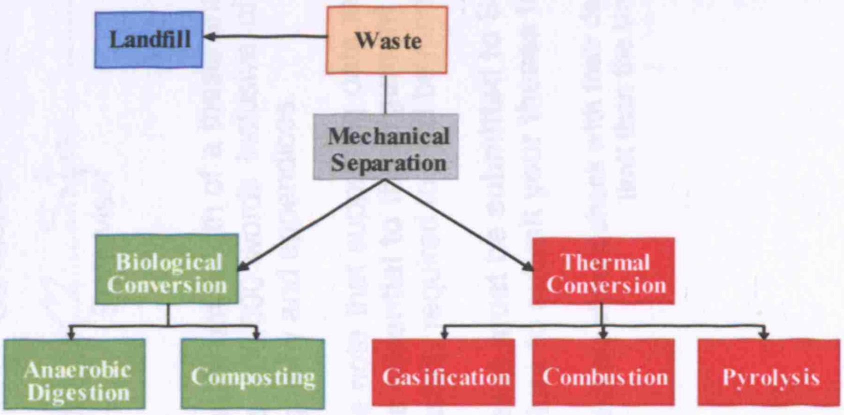


**Figure 2.4 MSW treatment for energy recovery processes**

Figure 2.4 illustrates the options for energy recovery from MSW treatment. It is important to note here that RDF is the common term used for a fuel produced from waste. The European Commission has issued a mandate (TC 343) for the standardisation of fuel prepared from waste and calling it solid recovered fuel (SRF) (Defra, 2007d). SRF, once standardised, will be traded as a fuel in the energy market guaranteeing the quality of the fuel for energy producers. Another term used in the industry is refined renewable biomass fuel (RRBF), which is highly refined and sorted to have a consistent composition of over 90% biomass (Coggins, 2006).

MSW can be sent directly or as RDF to dedicated facilities, such as incinerators, or other EfW plants incorporating advanced thermal treatment processes (ATT), such gasification and pyrolysis. It can also be co-combusted with other fuels, such as coal, in power generation, cement productions or other large thermal processes. Energy is then recovered as heat, which can be used for district and industrial heating and/or power. The latter is the most common form of energy recovery, as power can be easily distributed and sold via the national grid. For heat, consistent and local demands as well as heat networks and consumer connections are required.

Ultimately, the generation of combined heat and power should be pursued, as this helps to increase the overall energy efficiency and carbon savings of the EfW facility. Gasification and pyrolysis have the advantage of producing a gaseous product known as syngas, which can be burned in conventional steam turbines or used in dedicated gas engines and turbines. The latter have higher conversion efficiencies for electricity generation and are usually used in Combined Cycle Gas Turbine (CCGT) and CHP plants. The syngas can be also further processed via gas synthesis to produce speciality chemicals, such as dyes and food flavourings, and liquid fuels, such as hydrogen and gasoline.

Figure 2.5 illustrates the main energy recovery options from waste using different conversion systems or prime movers. For combustion processes, steam turbines are widely used in heat and power applications, as they can operate across a large range of capacity from 500 kWe to more than 500 MWe. The heat from the combustion process can also be used as a hot source in an Organic Rankine Cycle (ORC) turbo generator for the production of power.

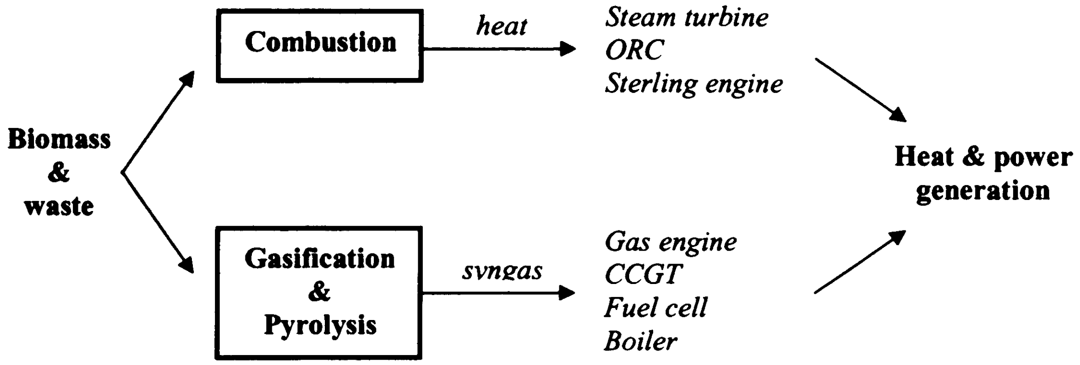


**Figure 2.5 Energy recovery options from waste using thermal treatment processes**

ORC processes have reached market introduction for small-scale decentralised biomass CHP systems. Unlike steam turbines, which are economically feasible only for capacities more than 1.5 MWe, ORC units can effectively utilise low temperature heat sources to produce electricity in a wide range of power outputs, ranging from few kW to 3 MW. A total annual efficiency of 88%, comprising of an electric efficiency of 14.5% and a thermal efficiency of 73.5%, is reported in the literature for a decentralised biomass CHP plant with an ORC unit. The ORC unit has an electric capacity of 1.1 MW and a thermal capacity of 5.0 MW (Obernberger et al., 2002).

Another emerging technology for decentralised biomass CHP plants includes the Sterling engine, which is receiving special interest in micro-scale applications (<150 kWe). However, the technology has only been operated with biomass fuels that have low ash and chlorine contents (Obernberger & Thek, 2004a).

In a combined cycle configuration or a CCGT unit, the syngas from gasification and pyrolysis processes is combusted in a gas turbine to produce electricity. The resulting hot exit gas from the turbine has significant amounts of energy, which can be used to produce steam in a heat exchanger or a heat recovery steam generator (HRSG). The steam is then fed into a steam turbine to generate more electricity. If the steam is used for heating purposes then the plant would operate in a CHP mode. The syngas can also be cleaned further for the production of a hydrogen-rich gas, which can be utilised in a fuel cell.

A comparison between the different conversion technologies used for generating heat and power is presented in Table 2.2. The table summarises the thermal and electric efficiencies of these technologies, as well as their durability and average investment costs. The investment costs of the technologies are indicative values and vary from one plant to another, depending on the size of the plant; bigger plants benefit from economies of scale and are cheaper per kWe of installed capacity (Jörß et al., 2002).

**Table 2.2 Comparison of conversion technologies for heat and power applications**

| | **Steam turbine** | **ORC** | **Gas engine** | **Gas turbine** | **CCGT** | **Fuel cell** |
|---|---|---|---|---|---|---|
| Power (MWe) | 0.5->100 | 0.2-1.5 | 0.015-20 | 0.2->50 | 3->300 | 0.01-0.25 |
| Power/Heat ratio | 0.1-0.5 | 0.1-0.5 | 0.5-2.4 | 0.2-0.8 | 0.6-2.0 | 0.8-1.0 |
| Electrical efficiency (%) | 10-40 | 14-20 | 25-45 | 15-35 | 30-40 | 35-40 |
| Thermal efficiency (%) | 40-60 | 79-80 | 50-60 | 40-60 | 40-60 | 20-50 |
| Lifetime (yrs) | 30 | 20 | 10 | 20 | 20 | > 5 |
| Investment cost (€/kWe) | 1000-2000 | 1600-3000* | 340-1600 | 450-950 | 450-950 | > 2500 |

* based on biomass cogeneration with nominal rating between 400-1500 kWe per unit (Duvia & Gaia, 2002)

## 2.2.1 EfW in the UK

In the UK, EfW technologies are predominately direct combustion or incineration processes. However, public perception of incineration is not great and has to some extent hindered the development of EfW technologies. This is largely because of the NIMBY (Not In My Back Yard) effect and concerns about emissions and waste being diverted from minimisation and recycling initiatives (DTI, 2006a). Nonetheless, these concerns are exaggerated. Firstly, the UK county of Hampshire, for example, now has three EfW plants proving that the NIMBY effect can be overcome through public dialogue and education.

Regarding the emissions, the UK Health Protection Agency (HPA), also supported by several studies (Enviros, 2004), have concluded that emissions from municipal waste treatment that comply with modern regulatory requirements, such as the Waste Incineration Directive, pose very little health risk (HPA, 2005). Finally, EfW diverts waste from landfill and not from recycling and composting. Experiences from other European countries that are more advanced in recycling policy implementation than the UK, such as Austria, Belgium, Denmark, Germany and Sweden, indicate that high recycling rates can co-exist with high EfW rates (Eurostat, 2003). Therefore, EfW should be considered as an integral part of an "environmentally responsible and sustainable waste management strategy" (Porteous, 2005).

The main success of those advanced European countries in developing infrastructure for recycling, as well as diversion of waste from landfill is because they have had relevant policy, planning and financial mechanisms in place for a relatively long time. This is compared to the UK, who only recently has acknowledged the role that EfW can play as part of an integrated waste management solution. In Denmark, for example, EfW facilities are built near communities who welcome the cheap energy and heat they provide. Whereas, a landfill ban in Austria has increased landfill cost to over €280/tonne, thus forcing local authorities and industry to look for alternative routes to deal with waste, such as EfW and MBT (SLR Consulting, 2005).

Advanced thermal treatment processes and, in particular gasification processes, are seen as alternatives to the traditional combustion processes and provide additional routes for the diversion of waste from landfill. Gasification processes offer increased possibilities for recovering value from waste by being compatible with front-end processes and producing solid residues that are more suitable for re-use than from combustion. Gasification processes can be configured to employ more efficient energy conversion systems, such as gas engines and turbines, and therefore, they have better electrical generation efficiencies. They also benefit from flexibility of scale, as they can be built in a modular manner, as opposed to combustion processes, which are typically centralised operations (Juniper, 2003).

This difference in scale and size can make it easier for gasification processes to treat waste near its source of origin (The Proximity Principle) and find local markets for heat and power. The Proximity Principle has been described in the UK Waste Strategy 2000, as a tool for planning authorities and businesses when considering the requirements for, and location of waste management facilities and regional self-sufficiency (Sustainable Development, 2000b). Treating waste near its source also reduces transport impacts and raises awareness in local communities that the waste they produce is a problem, which they must deal with. Heat and power generated from EfW facilities can be utilised locally, relieving some of the increased energy demands on larger power stations and gas networks.

Although gasification is not a new concept, it is only in recent years that it has been commercially used to treat MSW or refuse derived fuels (RDF). Most of the successful commercial operations have been in Europe, Japan and North America (Defra, 2007e). In the UK, there is no commercial plant for MSW gasification, and it is this unavailability of proved track record that is rendering the technology not 'bankable' in the current market state. Nevertheless, as the Government pursues its mandates to the diversion of biodegradable waste from landfill and recognises that greenhouse gas emissions should be an important criterion for stakeholders developing EfW plants (Defra, 2007f), gasification is becoming an important part of regional and national waste policies, which favour it as a clean energy recovery technology ahead of landfilling and combustion.

Alongside the wide range of measures set out in the 2007 Energy White Paper for meeting our long-term energy challenges, the UK Government has proposed greater levels of support for gasification under a banded Renewable Obligation (DTI, 2007b). If accepted after consultation, this distinction or banding would come into force in April 2009. The Renewable Obligation Certificates (ROCs) provide financial support for electricity generated from the biomass fraction of MSW using advanced conversion technologies, such as gasification, pyrolysis or anaerobic digestion. Conventional EfW technologies with good quality CHP were recently made eligible for ROCs, subject to compliance with the Combined Heat and Power Quality Assurance (CHPQA, 2007).

In addition to ROCs, Defra signed contracts with Novera and ENER-G in late 2006 to build waste gasification plants in East London and the Isle of Wight, respectively, as part of its New Technologies Demonstrator Programme. Compact Power was also awarded the funding by Defra to build a new gasification/pyrolysis plant at Avonmouth.

The programme is an incentive intended to overcome the possible perceived risks related to the introduction of alternative technologies in England. This will be achieved through the provision of accurate and impartial technical, environmental and economic information to key decision makers in both local authorities and the waste industry in general.

Although Novera Energy was given the planning permission for its East London gasification plant, it has withdrawn from the programme in August 2007 due to the lengthy planning application and was going to miss the tight deadlines imposed by the programme. However, the company is intending to complete the project and is very optimistic that the greater support proposed for gasification processes will be more than enough to cover the lost grant, which was about £6-7 million (letsrecycle.com, 2007a).

In the following sections, a comprehensive review of traditional combustion and more advanced waste thermal treatment processes, including gasification and pyrolysis, is presented. The review will focus on gasification processes, which is part of the main deliverables of this research project, thus the status and marketed gasification technologies for MSW treatment in the UK will be presented in more detail in section 2.2.3.

## 2.2.2 Combustion or is it incineration?

Combustion is the total oxidation of the organic matter in waste at temperatures in excess of 850°C to produce heat, water vapour, carbon dioxide and non-combustible material or bottom ash. The emissions and residues from the combustion processes are described in more details in section 2.3. Combustion reduces the volume of waste by approximately 90% and the remaining inert bottom ash residue can be used as secondary aggregate, and hence, reducing the need to quarry for new materials. Although the actual process design and plant layout may differ from one facility to another, a schematic diagram of a typical EfW combustion process is illustrated in Figure 2.6.

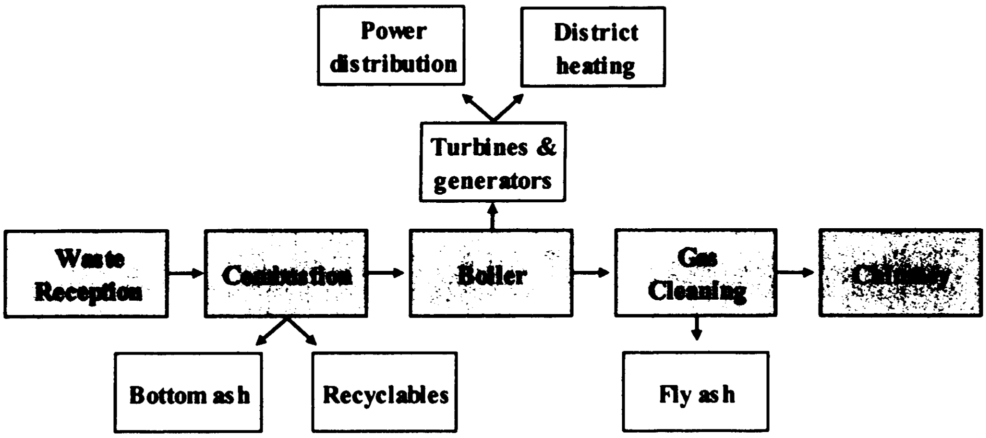


**Figure 2.6 Schematic diagram of a typical EfW combustion process**

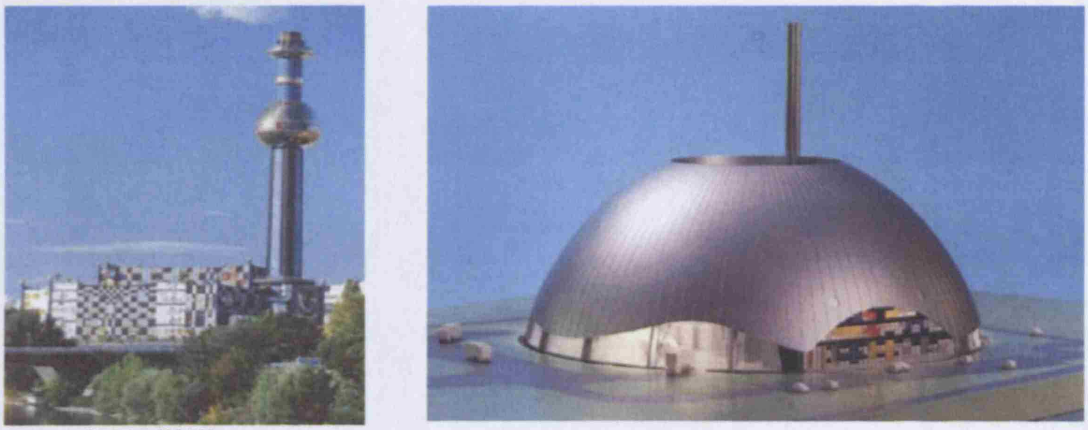
The process consists of waste reception, combustion chamber, energy recovery and emissions and residues handling. The combustion process converts the heat energy in the MSW or RDF into steam, which can be used to generate power via a steam turbine and/or used for heating. MSW typically has an energy content of 9-11MJ/kg, while RDF can have energy content of up to 17MJ/kg (Defra, 2007d). If a combustion plant was to generate only heat, it can achieve a thermal generating efficiency of 80-90%; on the other hand, an electricity-only plant can achieve an electrical generating efficiency between 20-27% (ERM & Golders Associates, 2006).

### 2.2.2.1 Status of combustion technology

Waste combustion is a mature industry and the second major option for waste treatment and disposal in many countries across the world, as shown previously in Figure 2.3. However, as highlighted in the previous section, the public perception of waste combustion is bad, even though there are stringent emissions legislations in place (see section 2.3 for further details). Modern combustion plants have efficient energy recovery systems with sophisticated gas clean-up processes, produce energy and reduce waste to inert residues.

There are also many examples of good practices in the UK and overseas regarding the integration of EfW plant into the community. Plants can be designed and built to handle the waste of a particular town or community and, at the same time, provide low cost district heating and electricity. Paris, for example, has three large EfW facilities integrated into the city's district heating infrastructure and supply around one third of central Paris heat requirement (CIWM, 2003).

In addition to this, facilities are now being designed in a variety of imaginative ways to make a positive contribution to the environment. In Vienna (Austria), one of the city's EfW plants is an architectural feature of the city and is shown in Figure 2.7, which also shows the innovative design of the Marchwood EfW plant in Hampshire, UK.



Source: CIWM (2003)

**Figure 2.7 The Spittelau EfW plant (left) and Marchwood EfW plant (right)**

As presented in section 2.1.2, waste management practices vary considerably from one EU country to another. In addition, Table 2.3 shows that the number of incinerators and their average capacities also vary. Therefore, there is no 'optimum' scale for EfW facilities as this would depend on the environmental and economic circumstances within the local urban environment. There are currently 19 operational waste combustion plants in the UK, with annual waste capacities ranging from 3,700 tpa (small-scale) to 500,000 tpa (large-scale) according to Defra (2007d). Other combustion plants which are being built include Allington, Belvedere and Lakeside. These are all summarised in Table 2.4.

**Table 2.3 Number of MSW incinerators and average plant capacities**

| Country | No. of incinerators | Average plant capacity (ktpa) |
|---|---|---|
| Austria | 3 | 178 |
| Denmark | 32 | 114 |
| France | 210 | 132 |
| Germany | 59 | 257 |
| Italy | 32 | 91 |
| Portugal | 3 | 390 |
| The Netherlands | 11 | 488 |
| UK | 17 | 246 |

Adopted from Williams (2005)

**Table 2.4 MSW incinerators in the UK**

| **Plant** | **Scale (ktpa)** | **Technology** | **Energy recovered** | **Start-up** |
|---|---|---|---|---|
| Edmonton | 500 | Moving-grate | 55 MWe | 1975 |
| SELCHP | 420 | Moving-grate | 35 MWe | 1994 |
| Tyseley | 350 | Moving-grate | 32.6 MWe | 1996 |
| Cleveland | 245 | Moving-grate | 21.2 MWe | 1998 |
| Coventry | 240 | Moving-grate | 17.7 MWe & Heat | 1975 |
| Stoke | 200 | Moving-grate | 15.4 MWe | 1997 |
| Marchwood | 165 | Moving-grate | 17.1 MWe | 2004 |
| Portsmouth | 165 | Moving-grate | 16.9 MWe | 2005 |
| Nottingham | 150 | Moving-grate | Electricity & Heat | 1973 |
| Sheffield | 225 | Moving-grate | 19 MWe (max) & 39 MWth (max) | 2006 |
| Dundee | 120 | Fluidized bed | 10.5 MWe | 2000 |
| Wolverhampton | 105 | Moving-grate | 8.7 MWe | 1998 |
| Dudley | 90 | Moving-grate | 7.3 MWe | 1998 |
| Chineham | 90 | Moving-grate | 13.7 MWe | 2003 |
| Kirklees | 136 | Moving-grate | 10.9 MWe | 2002 |
| Isle of Man | 60 | Moving-grate | 6 MWe | 2004 |
| Grimsby | 56 | Oscillating kiln | 3 MWe & 3 MWth | 2004 |
| Shetland | 23 | Moving-grate | Heat | 2000 |
| Isles of Scilly | 3.7 | Moving-grate | No energy recovery | 1987 |
| Allington | 500 | Fluidized bed | 43.2 MWe | 2007 |
| Belvedere | 585 | Moving-grate | 66 MWe | 2010 |
| Colnbrook | 400 | Moving-grate | 32 MWe | 2008 |

Adapted from Defra (2007d) and updated by Liban Yassin

The main combustion technologies are moving-grate, fluidized bed and rotary kiln combustors, which are all proven and 'bankable' processes. They are widely used commercially because of their applicability to large-scale use and versatility. In the UK, the majority of combustion technologies are moving-grate, as illustrated in Table 2.4. This reflects the greater operational reliability of moving-grate systems, which have been operating in the UK on a commercial basis longer than any other technology. Therefore, it is a well-proven technology, with known associated costs and is available from a number of reputable companies (Juniper, 2003). Major moving-grate technology suppliers in the UK include Babcock Wilcox Vølund, Keppel-Seghers, Lurgi, Martin Engineering and Von Roll-Inova. Cyclerval UK are the main suppliers of oscillating kiln units.

Fluidized bed technology on the other hand, offers an alternative waste treatment option to moving-grate and is also a well-proven technology for generating energy from a wide range of fuels. Although the technology has a limited track record in the UK for MSW treatment, there are over 150 plants in commercial operation in Europe and Japan. This is because fluidized beds have the ability to handle waste of widely varied properties and the many advantages in controlling emissions (McLanaghan, 2002).

### 2.2.2.2 Fluidized bed combustion (FBC)

As opposed to moving-grate, fluidized beds combustion processes require the pre-sorting and processing of MSW into RDF, which is then floated in a bed of sand that is suspended by air. There are generally two types of fluidized bed systems, which have the same principle but different design parameters; the bubbling fluidized bed (BFB) and circulating fluidized bed (CFB). The main differences are summarised in Table 2.5. Other advantages of fluidized beds include higher combustion efficiency that is comparable to pulverised fuel-fired combustors; reduction in boiler size; low corrosion and erosion with easier ash removal; and simple operation with fast response to load fluctuations.

**Table 2.5 Design parameters for BFB and CFB**

| **Design parameter** | **BFB** | **CFB** |
|---|---|---|
| Combustion temperature (°C) | 760-870 | 800-900 |
| Fuel particle size (mm) | 0-50 | 0-25 |
| Fluidization velocity (m/s) | 1-3 | 3-10 |
| Solid circulation | No | Yes |

Adapted from Koornneef et al. (2007)

Since the introduction of FBC, there has been a series of mergers and acquisitions resulting in four major market players; Alstom, Foster Wheeler, Lurgi and Kvaerner Pulping, as shown in Table 2.6. Alstom and Foster Wheeler are the largest producers of CFB technology, while Kvaerner is the market leader for BFB technology. Bharat Heavy

Electricals and Energy Product of Idaho (EPI) are only active in their own regions in India and North America, respectively (Koornneef et al., 2007).

**Table 2.6 Overview of fluidized bed combustion technologies**

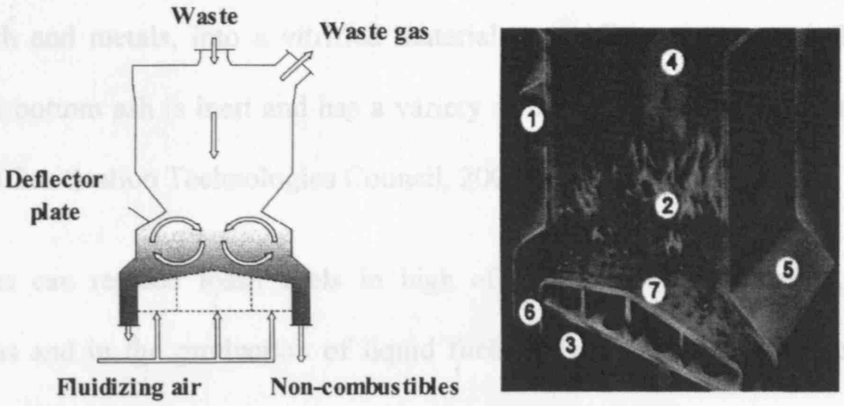
| Manufacturer | Technology | Capacity (MWe) | | No. of Installations | Start-up |
|---|---|---|---|---|---|
| | | Min | Max | | |
| Alstom | BFB | 17 | 142 | 7 | 1988-99 |
| | CFB | 2 | 520 | 51 | 1986-2005 |
| Babcock and Wilcox | CFB | 3 | 76 | 22 | 1982-2002 |
| Babcock Borsig | BFB | 0 | 35 | 5 | 1982-2000 |
| | CFB | 9 | 120 | 10 | 1989-99 |
| Bharat Heavy Electricals | BFB | 5 | 50 | 18 | 1987-98 |
| EPI | BFB | 10 | 45 | 9 | 1981-93 |
| Foster Wheeler | BFB | 0 | 117 | 51 | 1976-2002 |
| | CFB | 0 | 460 | 161 | 1981-2006 |
| Kvaerner Pulping | BFB | 6 | 117 | 56 | 1985-2005 |
| | CFB | 0 | 240 | 32 | 1984-2002 |
| Lurgi | CFB | 9 | 225 | 35 | 1982-2004 |

Adapted from Koornneef et al. (2007)

The commercial capacity of the fluidized bed combustors are influenced mainly by the cross-sectional area of the vessel. Therefore, fluidized bed designs need to be optimised with the emphasis on outstanding engineering innovations to achieve economical vessel arrangements and reach large commercial scales. An emerging technology in this field, is the Twin-internally Circulating Fluidized bed Furnace (TIF) developed by Ebara. The technology is licensed to Lurgi and trades in Europe under ROWITEC®, which is now a well-proven process and economically a competitive option compared to moving-grate combustion.

The Madrid EfW incineration facility in Spain is one of the highly successful operational plants employing the ROWITEC® process and proving its operational availability in excess of 90% (Lischke & Lehmann, 2001). The plant handles 20 tonnes of waste per day, which is approximately one third of the city's waste and generates 25MWe of electricity that can be fed into the public grid. It also consists of sorting lines for material recycling and a composting unit.

Other successful facilities employing the ROWITEC® process include plants in Gien and Mulhouse (France), Moscow (Russia), Vienna (Austria) and not to mention, the Allington plant in the UK (Fujimura & Naruse, 2001). The TIF/ ROWITEC® fluidized bed is illustrated in Figure 2.8. The technology has a fairly simple mechanism with no moving parts inside the furnace. It has a slanted bed floor and the air flow rate is controlled to produce a revolving sand motion. It is this mixing effect that produces a combustion performance superior to that of conventional fluidized bed furnaces (Tame, 2001).



1. Waste feeder, 2. Revolving fluidized bed, 3. Fluidized air, 4. Flue gas, 5.Deflector plate, 6. Non-combustibles discharge chute, 7. Inclined nozzle plate

Adapted from Tame (2001) and Lurgi-Lentjes (2005)

**Figure 2.8 An internally circulating fluid bed**

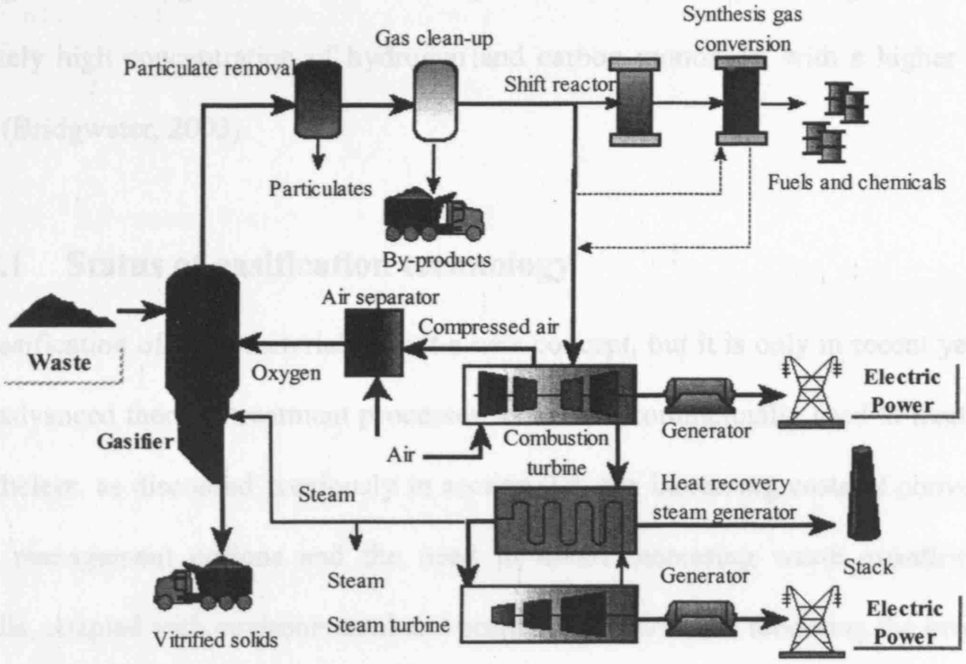
## 2.2.3 Gasification

Gasification is the thermal conversion of organic matter by partial oxidation into a gaseous product called syngas. The syngas consists mainly of hydrogen, carbon monoxide and small amounts of methane, water vapour, carbon dioxide, nitrogen and tar. The reactions are carried out at temperatures of about 500-1400°C and pressures up to 33 bar. The high temperature in the gasifier converts the inorganic materials in the waste, such as ash and metals, into a vitrified material resembling coarse sand. The vitrified material or bottom ash is inert and has a variety of uses in the construction and building industries (Gasification Technologies Council, 2006).

The syngas can replace fossil fuels in high efficiency power generation, heat, CHP applications and in the production of liquid fuels and chemicals via synthesis gas. For power generating applications, the syngas is combusted and used with conventional steam turbines or utilised directly in dedicated gas engines and turbines. As opposed to steam turbines, gas engines and turbines have higher electrical conversion efficiencies, ranging from 25% for gas engines and up to 40% for CCGT, as reported in Table 2.2. It is also possible to combine gasification processes with fuel cells for CHP applications, which also offers the perspective of very high efficiencies (Jörß et al., 2002).

It is important to note here that the overall system efficiencies of thermal treatment processes, does not only depend on the generation efficiencies of the prime movers, such as steam turbines, gas engines and CCGT, but also on the thermal conversion efficiencies for combustion and gasification processes, for example, and their internal energy consumption. Incinerators are well established processes and can achieve over 90%

combustion efficiencies, while gasifiers can achieve conversion efficiencies between 70-93% (Babu, 2006). The engineering consultancy group, Fichtner, has reported thermal conversion efficiencies for advanced thermal treatment processes in the range of 55-75% (Fichtner, 2004).



Adapted from Gasification Technologies Council (2006)

**Figure 2.9 A typical gasification process**

**Table 2.7 Main gasification applications**

| | |
|---|---|
| **Heat** | |
| District & industrial heating | |
| **Electricity only** | |
| District/industrial electricity | Integrated gasification combined cycle (IGCC) |
| **Combined heat and power** | |
| District heating/electricity | Pulp and paper industry |
| **Synthesis gas** | |
| Ammonia | Hydrogen |
| Fischer-Tropsch liquids | Methanol, ethanol, dimethyl ether (*DME*), etc. |
| Chemicals | |

A typical gasification process is illustrated in Figure 2.9, while the main gasification applications are summarised in Table 2.7. The oxidant used for the gasification process can be air, pure oxygen, steam or a mixture of these gases. Air-based gasifiers typically produce a product gas containing a relatively high concentration of nitrogen with a low heating value. Oxygen and steam-based gasifiers produce a product gas containing a relatively high concentration of hydrogen and carbon monoxide, with a higher heating value (Bridgwater, 2003).

#### 2.2.3.1 Status of gasification technology

The gasification of solid materials is not a new concept, but it is only in recent years that these advanced thermal treatment processes have been commercially used to treat MSW. Nonetheless, as discussed previously in section 2.2, the increasing costs of conventional waste management options and the need to divert increasing waste quantities from landfills, coupled with environmental and political pressures, are rendering the investment in ATT projects increasingly attractive. Although there is no commercial plant for MSW gasification in the UK, there are commercial scale plants in operation in Europe, North America and Japan (Defra, 2007e).

The main reactor types are fixed beds, either downdraft or updraft, and fluidized beds, either bubbling or circulating. For large scale applications, above 25-50 MWe, CFB gasifiers are preferred, while for the small scale applications, up to 0.5 MWe, downdraft gasifiers are mainly used. BFB gasifiers can be competitive in medium scale applications (Bridgwater, 2003). Gasifiers are available from Foster Wheeler and Bioneer (now market by Condens Oy) in Finland, Lurgi in Germany, Vølund in Denmark, Termiska Processor in Sweden, PRM Energy in USA, Repotec in Austria and Ebara in Japan. In most of theses cases, the syngas is used for combustion in boilers and district heating purposes, i.e. heat gasifiers (Kwant & Knoef, 2004).

In addition, there is extensive research and development at universities, research institutes and companies around the world. In the UK, the marketed gasification technologies for MSW treatment are developed by Advanced Plasma Power, Compact Power, Ener-G, KBI, THERMOSELECT and Enerkem (see section 2.2.3.2).

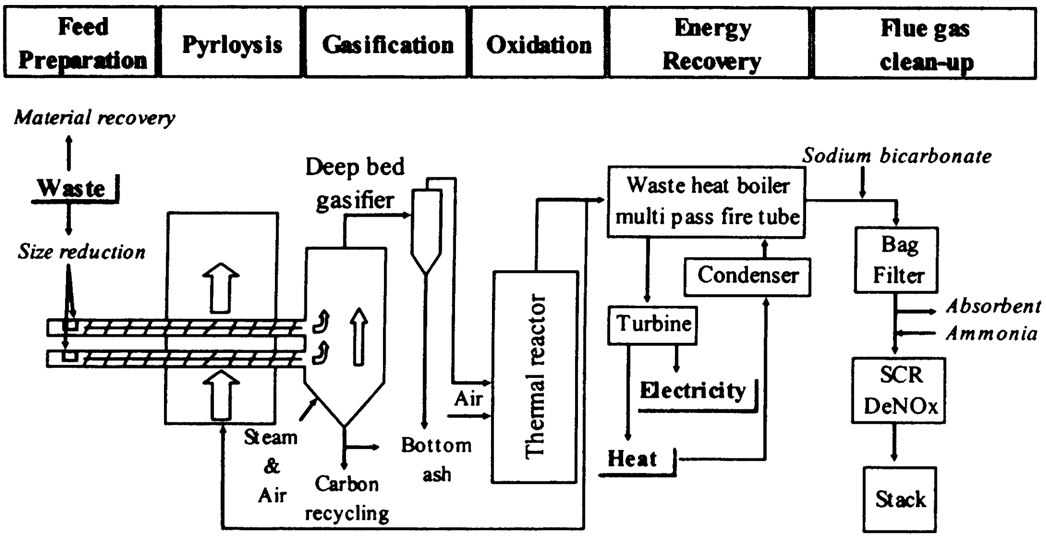
#### 2.2.3.1.1 Advanced Plasma Power (APP)

Plasma-arc furnaces can treat waste by gasifying it at very high temperatures. This technology is widely used in Japan for hazardous waste and is now being touted as an option for local authorities in the UK to dispose of MSW and meet their LATS targets, without resorting to incineration or combustion. Plasma-arc is a capital and heat intensive technology and is at an early stage of commercialisation. Nonetheless, the UK firm Advanced Plasma Power has announced its interest in building a 50,000 tpa commercial demonstration plant using a plasma technology (The Gasplasma Process), during an industrial visit to their site.

The Gasplasma process was originally developed by sister company Tetronics. The plant would feed RDF into a fluidized bed gasifier at around 800°C, producing syngas and ash. These waste streams are then passed into a plasma-arc furnace, where they are exposed to very high temperatures and ultra-violet light that breaks them down further. This leaves a clean hydrogen rich syngas and an inert vitrified ash that could be used as an aggregate. A 50,000 tpa plant would generate 8MWe of electricity, with 3MWe being consumed internally and the rest exported to the grid. Fichtner, the consulting engineers, are independently validating the technology and reviewing the design, operation and economics of a full-scale commercial plant (APP, 2006).

### 2.2.3.1.2 Compact Power

The Compact Power technology in the UK uses pyrolysis, gasification and high temperature oxidation to convert a wide range of wastes to fuel gas and other usable products, such as activated carbon and lightweight aggregates (see Figure 2.10). Pyrolysis takes place at 800°C in an externally heated screw tube pyrolyser and the residues are gasified with air and steam. The syngas is then combusted in a thermal reactor to generate heat and power via a steam turbine.



Adapted from Compact Power (2006)

**Figure 2.10 The Compact Power Process**

A single reference plant is operating commercially at Avonmouth in Bristol for high fee material, such as clinical waste, but at a small scale of 8000 tpa (Compact Power, 2006). The Compact Power technology is marketed for treatment of small quantities of waste and hence, it reduces scale-up risks. In late 2006, Compact Power has received funding approval from Defra's New Technologies Demonstrator Programme for its new Avonmouth plant. The new facility will be capable of treating 34,000 tpa of Bristol's residual waste, generating 3.8 MWe of electricity and 15MWth of heat for use by local industry.

#### 2.2.3.1.3 ENER-G

The Energos technology is marketed in the UK by ENER-G, which already has six operational plants in Germany and Norway. Typical plant capacities range from 35,000-40,000 tpa, with the largest plant at 80,000 tpa and consisting of two stream operations. The gasification unit is equipped with a fixed horizontal oil-cooled grate that is divided into several separate sections, each with a separate primary air supply. Waste is gasified at sub-stoichiometric conditions and the syngas generated is transferred to a second chamber, in which it is fully oxidised. The recovered heat is used to generate steam for internal consumption, district heating and/or electricity. The flue gas is passed through a dry flue gas cleaning system with injection of lime and active carbon (ENER-G, 2007).

#### 2.2.3.1.4 KBI Waste and Energy Solutions GmbH

KBI offers a High Temperature Conversion of Waste (HTCW) system, which employs a down draught oxygen-blown gasifier. The gasifier achieves temperatures of around 1500°C and can process a wide range of feeds including un-sorted MSW. Coke and limestone are mixed with the feed prior gasification to provide some structural integrity to the gasifying material and remove impurities, such as sulphur, respectively (Environment Agency, 2007b). The syngas can be fed into a gas turbine for power generation. The Environment Agency recognises the HTCW technology as a suitable process for the treatment of waste; however, it is very expensive and need a demonstration plant to be built for further testing.

#### 2.2.3.1.5 THERMOSELECT

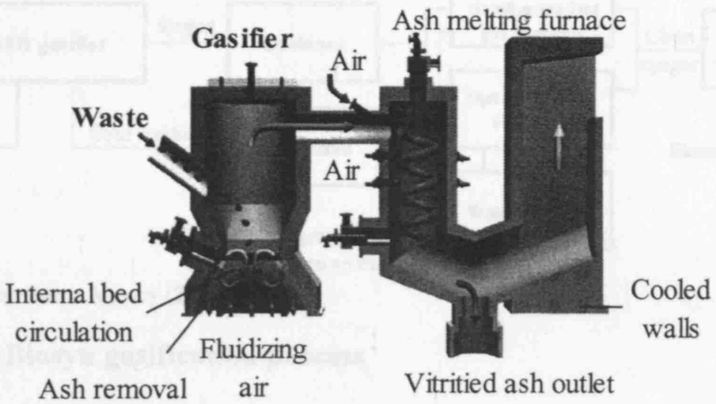
The THERMOSELECT process has been developed and commercialised by THERMOSELECT S.A. over the past decade. The process is proven in a large scale demonstration facility and processes solid wastes, including MSW, in a fixed bed oxygen-blown gasification and residue melting reactor. The process recovers pure synthesis gas, useful mineral and iron rich materials as products. The syngas passes through multi-stage cleaning, in which the contaminants are absorbed or condensed. The clean synthesis gas is then available as an energy carrier or as a raw material for the synthesis of primary chemical materials, such as methanol. Commercial plants have been built in Karlsruhe in Germany and in Tokyo-Chiba in Japan, with waste treatment capacities of 225,000 tpa and 100,000 tpa, respectively (Drost et al., 2004).

### 2.2.3.2 Fluidized bed gasification (FBG)

Large scale fluidized bed systems have become commercial due to the successful co-firing projects, such as the Kymijärvi Power Plant at Lahti in Finland. Furthermore, fluidized beds have the advantage of extremely good mixing and high heat transfer, resulting in very uniform bed conditions and efficient reactions. CFB gasifiers, in particular, are targeted for larger scale applications (Juniper, 2007), as they can be used with different fuels, require relatively compact combustion chambers and allow for good operational control. There are several leading and state-of-the-art biomass and waste fluidized bed gasification projects across the world. The following section summarises some of the main FBG technology developers.

#### 2.2.3.2.1 Ebara Corporation

Ebara has developed a 'new' generation gasification technology based on its internally circulating BFB incinerator and, in 2004, had 21 process lines in commercial operation in Japan and Germany. The technology, branded TwinRec, is a state-of-the-art twin internally circulating fluidized bed gasifier. It is designed with ash vitrification technology for material recycling, energy recovery and detoxification of waste in an integrated and economical process.



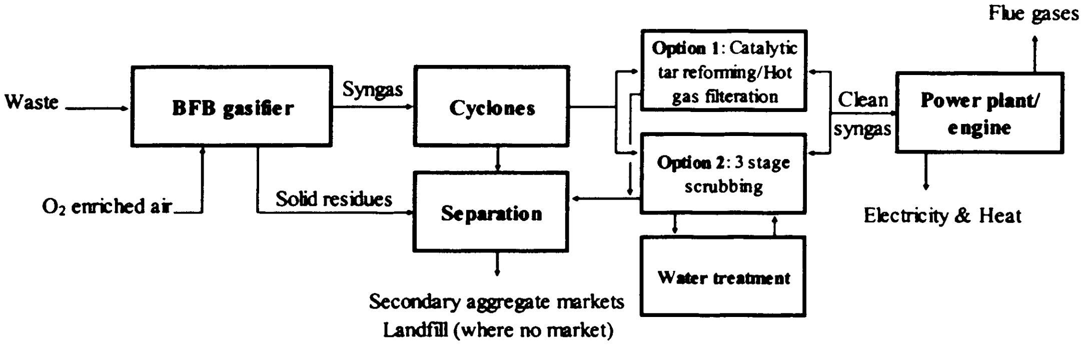
Adapted from Selinger & Steiner (2004)

**Figure 2.11 Ebara's TwinRec**

The gasifier, shown in Figure 2.11, is a revolving fluidized bed, which gasifies waste and produces heat that is used to raise the temperature in the next-stage slag combustion furnace. Due to the high temperatures inside the furnace, dioxins are decomposed and the ash is vitrified and recycled as stable glass granulates. Aomori is the largest gasification and slagging combustion system in Japan, with a capacity of 450 tonne per day and a power output of 17.8MWe using a steam turbine (Selinger & Steiner, 2004).

### 2.2.3.2.2 Enerkem Technologies Inc.

Enerkem's Biosyn gasification process is based on a BFB gasifier that operates at 700-900°C and up to 1.6 MPa. The process, shown in Figure 2.12, proved the technical feasibility of gasifying biomass from forest and agricultural residues, as well as RDF, rubber resides and sludge (Enerkem, 2006). The technology is available in the UK and Ireland under license by Novera Energy Europe.



Adapted from Environment Agency (2007b)

**Figure 2.12 The Biosyn gasification process**

The Novera/Enerkem gasification technology is built cost-effectively at a smaller scale than combustion processes so it complies well with the proximity principal for waste disposal. The process has a low emission profile and is easily operable well inside the emission limits set under the Waste Incineration Directive. In late 2006, Novera Energy has signed a contract with Defra to build a gasification plant at the Ford plant in Dagenham in partnership with East London Waste Authority (ELWA), Shanks and the Ford Motor Company. The plant will process 90,000-100,000 tpa of RDF supplied from the nearby Shanks MBT (mechanical biological treatment) plant at Frog Island. It will provide Ford with 8-10 MWe of electricity, which is equivalent to approximately £4 million per annum worth of electricity purchased from the national grid, while ELWA will benefit through LATS (Novera Energy, 2006).

### 2.2.3.2.3 Foster Wheeler Energy International Inc.

Foster Wheeler (FW) has been supplying FBG systems for many years. The Kymijärvi Power Plant at Lahti in Finland is one of the most successful commercial demonstration plants coupling gasification with co-firing. The plant, described in Figure 2.13, is a pulverised coal fired steam plant that generates up to 167 MWe of electricity and up to 240 MWth of district heat. It uses CFB gasifier to produce a low calorific product gas, which is combusted in the coal-fired boiler, thus replacing about 30% of the coal.

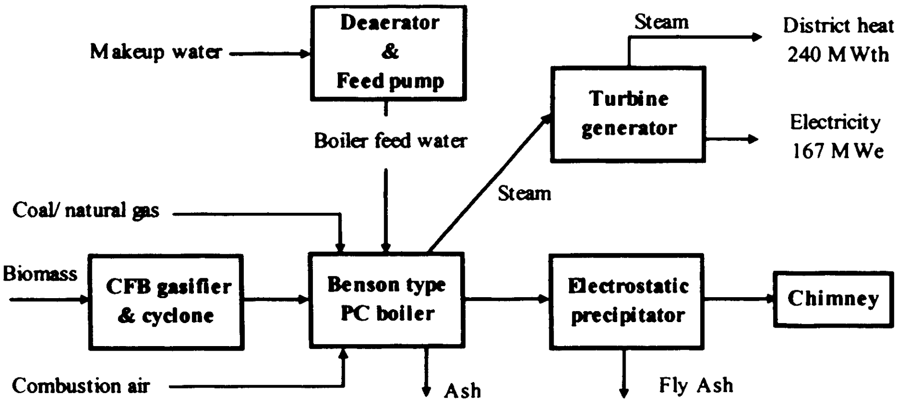
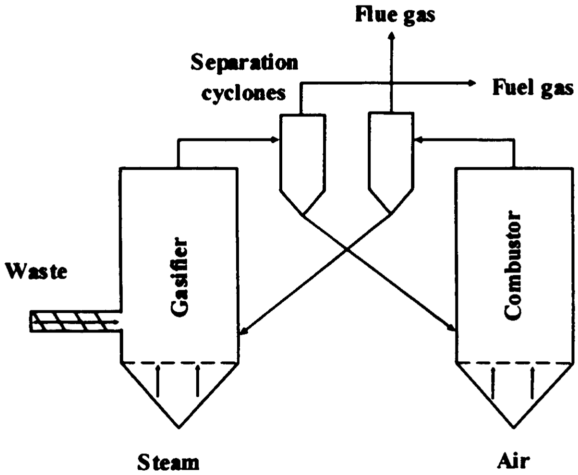


**Figure 2.13 Kymijarvi Power Plant, Lahti, Finland**

The gasifier uses biofuels, such as saw dust, wood residues and recycled fuels comprising of cardboard, paper and plastics (Spliethoff, 2001). In addition, FW has contributed to the construction of the first complete Integrated Gasification Combined Cycle (IGCC) power plant at Värnamo in Sweden. The demonstration plant employed a pressurised air-blown CFB gasifier operating at 950-1000°C and 2 MPa (Ståhl et al., 1998). It fed about 6 MWe of electricity to the grid and 9 MWth of heat to the district heating network of the city of Värnamo.

#### 2.2.3.2.4 Future Energy Resources Company (FERCO)

FERCO has acquired the SilvaGas process from Battelle, who started developing this gasification process in 1977. The process uses forest residue, MSW, agricultural waste and energy crops and converts them into a syngas. The SilvaGas process consists of two interconnected atmospheric pressure CFB reactors for steam gasification in one reactor, and a residual char oxidation with air in the second one, with solids exchange between the two reactors, as shown in Figure 2.14.



Adapted from Paisley et al. (1997)

**Figure 2.14 Simple schematic diagram of the SilvaGas process**

The first commercial scale biomass gasification demonstration plant based on the SilvaGas process was built at the McNeil Power Station in Burlington, Vermont (USA). The syngas was used as a co-fired fuel in the existing McNeil power boilers and in a combined cycle with a gas turbine power generation system (Paisley et al., 1997).

#### 2.2.3.2.5 Gas Technology Institute (GTI) / Carbona Inc.

GTI, through its predecessor organisations (the Institute of Gas Technology and Gas Research Institute), has originally developed the air-blown Renugas technology for IGCC applications. The technology is based on a single stage pressurised BFB gasifier, with a deep bed of inert solids, which is also capable of producing a hydrogen-rich fuel. A 15 MWth pilot plant was commissioned in 1993 in Tampere (Finland) by Carbona, who licensed the Renugas technology from GTI. The plant has operated for more than 2000 hours on paper mill wastes, straw and coal mixtures, alfalfa stems and a variety of wood fuels (Arrieta and Sanchez, 1999). In 2004, Carbona has signed a contract to build a biomass CHP gasification plant in Skive (Denmark). The plant will produce 5.5 MWe of electricity using gas engines and 11.5 MWth of district heat for the town of Skive (Babu, 2005).

#### 2.2.3.2.6 Lurgi

The Lurgi CFB gasifiers operate at near atmospheric pressure and are well suited for capacities up to 30 t/h of feedstock. The main European projects based on the Lurgi technology are reported in Table 2.8. The gasification plants in Pöls (Austria) and Rüdersdorf (Germany) were designed and constructed for use in cement industry. The Bioelecttrica project in Italy uses an atmospheric CFB gasifier integrated with a combined cycle of a 10.9 MWe gas turbine and a heat recovery steam generator (HRSG) of 5 MWe. The fuel used is a mixture of wood chips, as well as forest and agricultural residues. The project was aimed at the demonstration of the technical and economic feasibility of power generation from biomass using IGCC. In 2000, Lurgi has contributed to the construction of the 85 MWth CFB wood gasification process at the AMER9 power plant in the Netherlands. The syngas from the gasification process is co-fired in a pulverised coal combustor unit replacing 70,000 tpa of coal (Willeboer, 1998).

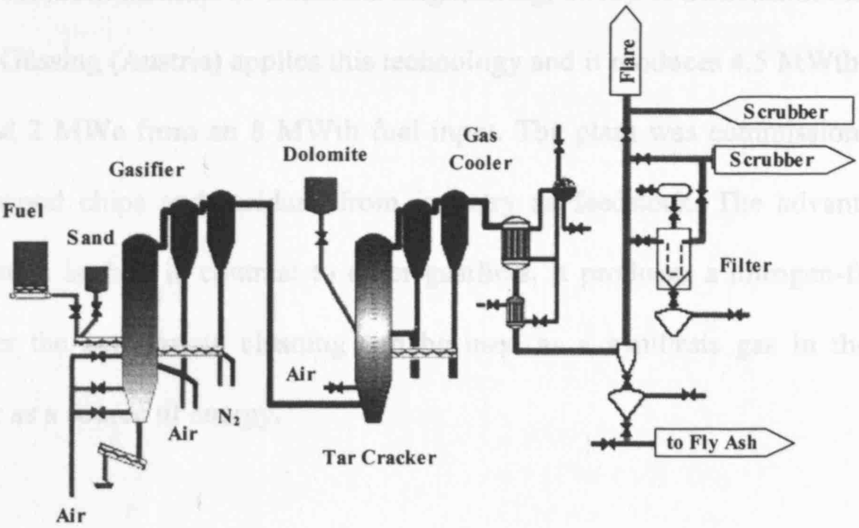
**Table 2.8 Main applications of the Lurgi CFB gasifiers**

| Location | Capacity | Fuel | Start up |
|---|---|---|---|
| Pöls, Austria | 27 MWth | Tree bark | 1987 |
| Rüdersdorf, Germany | 100 MWth | Wood, RDF, lignite waste | 1996 |
| Bioelettrica, Pisa, Italy | 12 MWe | SRF*, wood | 2000 |
| Amer, Netherlands | 85 MWth | Waste wood | 2000 |

* SRF refers to solid recovered fuels

### 2.2.3.2.7 Termiska Processer Sweden AB (TPS)

The gasification process developed by TPS is based on an atmospheric CFB gasifier operating at 850 to 900°C and is coupled to a dolomite-containing tar-cracking vessel, as illustrated in Figure 2.15 (TPS, 2005). A pilot-scale RDF gasification plant was commissioned in Grève-in-Chianti (Italy) in 1992. The plant processes 200 tonnes of waste RDF per day, which is fed into two air-blown CFB gasifiers, each with a fuel capacity of 15 MWth. The syngas is used in a steam boiler to drive a 6.7 MWe steam turbine. In the UK, the gasification technology of TPS is installed in a wood-fuelled IGCC plant at ARBRE, Eggborough in Yorkshire.



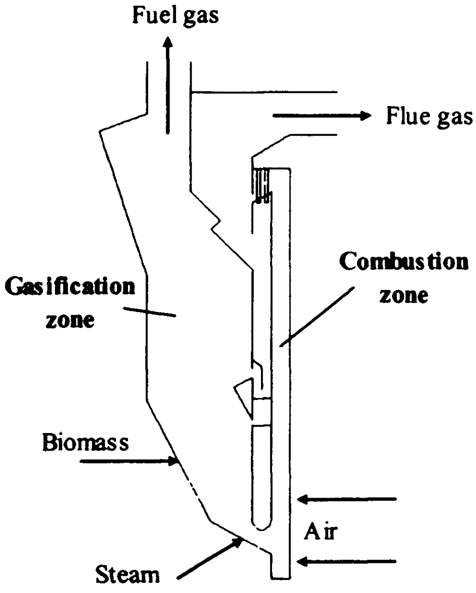
Adapted from TPS (2005)

**Figure 2.15 TPS CFB gasification and gas cleaning system**

The syngas from the process is compressed and combusted in a combined cycle gas turbine to produce 8MWe of electricity. In Brazil, there are two projects based on the TPS technology, which aim to demonstrate the commercial viability of biomass fuelled IGCC using gas turbines. The first is a 32 MWe plant that utilises wood as a feedstock, while the second plant uses sugar cane baggasse and cane trash, with the intention of integrating the biomass IGCC system into a typical sugar mill.

#### 2.2.3.2.8 The Austrian Institute of Chemical Engineering

The Austrian Institute of Chemical Engineering at the Technical University of Vienna (TUV) and AE Energietechnik have developed a novel FBG reactor producing a product gas with a high calorific value of up to 15 MJ/Nm$^3$. The gasification process is based on fast internal circulating fluidized bed (FICFB) and consists of a gasification zone fluidized with steam and a combustion zone fluidized with air, as shown in Figure 2.16. The circulating bed material acts as heat carrier from the combustion to the gasification zone (The Austrian Institute of Chemical Engineering, 2005). A demonstration CHP plant located in Güssing (Austria) applies this technology and it produces 4.5 MWth for district heating and 2 MWe from an 8 MWth fuel input. The plant was commissioned in 2001 and uses wood chips and residues from industry as feedstock. The advantage of the FICFB system is that, in contrast to other gasifiers, it produces a nitrogen-free syngas, which after the appropriate cleaning can be used as a synthesis gas in the chemical industry or as a source of energy.



Adapted from The Austrian Institute of Chemical Engineering (2005)

**Figure 2.16 The FICFB gasifier**

Finally, the main biomass and waste fluidized bed gasification projects covered in this section are summarised according to their configuration in Table 2.9.

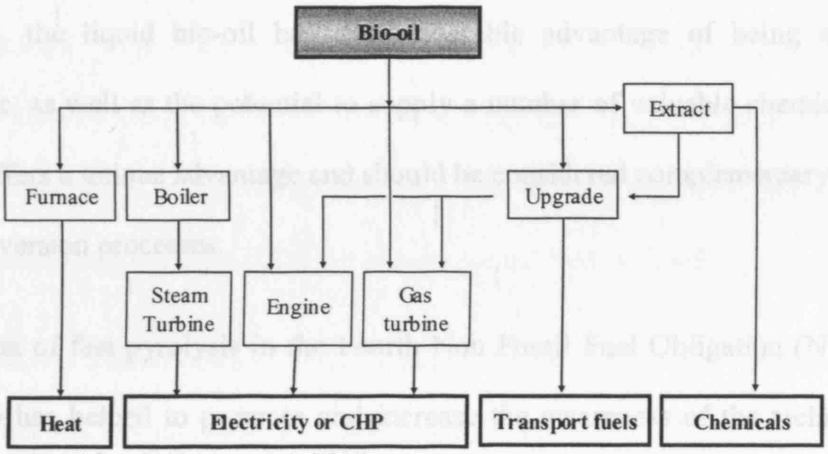
**Table 2.9 Summary of main biomass and waste fluidized bed gasification projects**

| Gasification Type | Technology developers |
|---|---|
| **Heat gasifiers (syngas combustion)** | |
| Pöls, Austria | 27 MWth CFB, Lurgi |
| Rüdersdorf, Germany | 100 MWth CFB, Lurgi |
| **Co-firing gasifiers** | |
| Amer, Netherlands | 85 MWth CFB, Lurgi |
| Burlington, USA | 50 MWe CFB, Battelle |
| Lahti, Finland | 40-70 MWth CFB, FW |
| Ruien, Belgium | 50 MWth CFB, FW |
| Zeltweg, Austria | 10 MWth ACFB, AEE |
| **IGCC plants** | |
| ARBRE, UK | 8 MWe CFB, TPS |
| Grève-in-Chianti, Italy | 6.7 MWe CFB, TPS |
| Pisa, Italy | 12 MWe CFB, Lurgi |
| Värnamo, Sweden | 18 MW PCFB, FW |
| **CFB gasifiers with gas engine** | |
| Güssing, Austria | 8 MWth FICFB, AICE |
| Skive, Denmark | 11.5 MWth PBFB, Carbona |

PBFB = Pressurised bubbling fluid bed
AICE = Austrian Institute of Chemical Engineering, TUV

## 2.2.4 Pyrolysis

Pyrolysis is the thermal conversion of organic matter in the total absence of oxygen at relatively low temperatures of 500-800°C and short vapour residence times of 3-1500 s. It produces a liquid fuel, a solid char and some combustible gas, which are usually used within the process to provide the process heat requirements. The liquid fuel or bio-oil can be used directly as a substitute for fuel oil in heat and power applications or to produce a wide range of speciality and commodity chemicals. This is illustrated in Figure 2.17.



Adapted from Bridgwater et al. (1999)

**Figure 2.17 Bio-oil applications**

Bio-oil is a dark brown liquid, which has a high heating value (HHV) of 16-19 MJ/kg as compared to 42-44 MJ/kg for conventional fuel oil. The composition of pyrolysis products depends on the heating rate, residence time and temperature, as well as on the composition of the fuel, as shown in Table 2.10. Although most of the work is carried out on wood due to its consistency and comparability between tests, nearly 100 different biomass types have been tested by many laboratories, ranging from agricultural to solid wastes (Bridgwater, 2003).

**Table 2.10 The different modes of the pyrolysis**

| Mode | Conditions | Liquid | Char | Gas |
|---|---|---|---|---|
| Fast pyrolysis | Moderate temp, short residence time | 75% | 12% | 13% |
| Carbonation | Low temperature, very long residence time | 30% | 35% | 35% |
| Gasification | High temperature, long residence times | 5% | 10% | 85% |

Source: Bridgwater (2003)

### 2.2.4.1 Status of pyrolysis technology

Pyrolysis is a technology at its '*teen*' when compared to gasification and combustion and has a limited track record in the UK on the treatment of MSW. Whilst established pyrolysis technologies for the treatment of certain specific waste streams exist, it is only in recent years that pyrolysis has been commercially applied to the treatment of MSW. Nonetheless, the liquid bio-oil has a considerable advantage of being storable and transportable, as well as the potential to supply a number of valuable chemicals. In this respect, it offers a unique advantage and should be considered complementary to the other thermal conversion processes.

The inclusion of fast pyrolysis in the Fourth Non Fossil Fuel Obligation (NFFO) in the UK in 1996 has helped to promote and increase the awareness of the technology. The NFFO requires regional electricity companies to buy a certain quantity of non-fossil fuelled electricity, even if this electricity is more expensive than conventional supplies (Plesch et al., 2005). The most promising application of bio-oil is power generation. This is mainly because of its high value, ease of distribution and adoption to local and national market applications. Power generated from waste and biomass can also qualify for Renewables Obligation and Climate Change benefits.

Another advantage of liquid production is that fuel production can be de-coupled from power generation, so peak power provision is possible with smaller pyrolysis plants or liquids (Bridgwater et al., 1999). Several hundreds of hours and over 13,000 litres of bio-oil have been combusted in gas engines and turbines and another 8,000 litres in testing rigs. This has developed crucial experience and knowledge in the application of bio-oil, hence, opening up a niche market in power generation, and particularly, in decentralised power. A comprehensive survey of fast pyrolysis processes has been published by Bridgwater & Peacocke (2000), which describes all the pyrolysis processes for liquids production that have been built and tested in the last 10-15 years.

The current marketed pyrolysis processes for the treatment of MSW in the UK include Nexus and Thide Environment, which are slow pyrolysis systems. Both of these processes are on a small-to-medium scale, with a semi-commercial status. In the Nexus Softer Process, unsorted MSW is pyrolysed in containers at 500°C and up to 8 hours for humid MSW. The process can either combust the syngas and char to generate electricity or produce Combusther®, a solid transportable fuel made from char and other heavy hydrocarbons condensate from the pyrolysis reactions (Nexus, 2004).

The Thide-Eddith Process also produces a transportable solid fuel or Carbor®, which can be used for heating cement kilns or co-combusted in power plant. Pyrolysis takes place in an externally heated rotating drum operating at 400-600°C, with a 30 minute residence time. A 10,000 tpa unit has been sold commercially to Hitachi and is in operation in Nakaminato, Japan (Thide Environment, 2004).

Marketed fast pyrolysis systems in the UK are supplied by Graveson Energy Management (GEM). The GEM system consists of RDF reception and storage, shredding and drying to 5% moisture, fast pyrolysis, gas cleaning and energy recovery using gas engines. The pyrolyser consists of an indirectly heated large vertical cylinder, with a close fitting drum rotated within it (Defra, 2007e). GEM has built a 12,500 tpa CHP plant near Bridgend (South Wales) in 2000 that is capable of producing 2.5 MWe and 2.7 MWth (GEM, 2004).

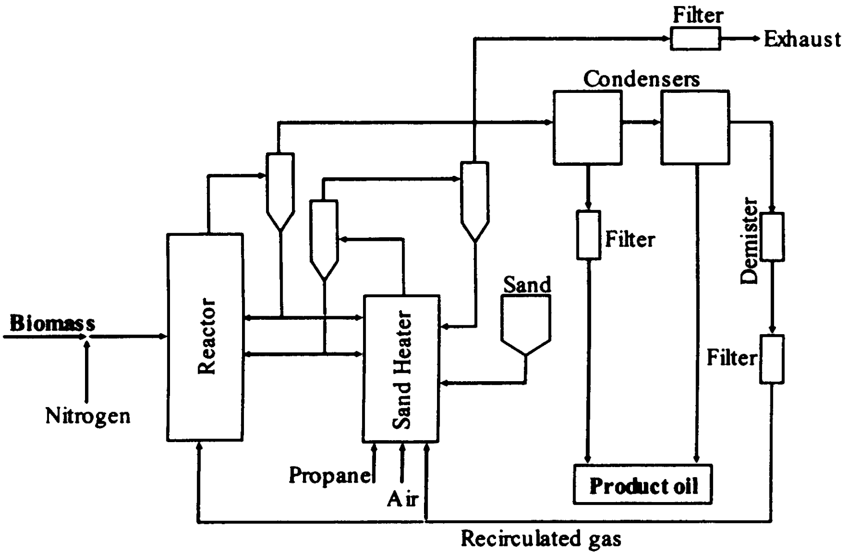
Another marketed processes for waste treatment are the Tech Trade and R21, which are rotary kiln systems. The Tech Trade technology is marketed in the UK by WasteGen Ltd. This pyrolysis process has been utilised in the Burgau plant in Germany since 1989. It can process a wide variety of waste using a sequential combination of shredding, pyrolysis and metal separation, with syngas combustion to produce electricity using a steam turbine (Tech Trade, 2004).

The R21 technology is developed by Mitsui Babcock Energy. The process treats shredded MSW and commercial waste in an indirectly heated rotary kiln at 450°C for 1 hour. The syngas and char produced are combusted at over 1300°C to melt ash into a slag and generate power via a steam turbine. Mitsui Babcock has built over 6 plants in Japan, with capacities ranging from 50,000-150,000 tpa. The first R21 technology has been operating commercially since 2000 (Mitsui Babcock Energy, 2003).

Although the best reactor configuration is not yet established, fluidized bed technology, as for gasification, is one of the most efficient and economic technologies of actualising fast pyrolysis as it offers high heating rate, rapid devolatilisation and convenient char collection and re-utilisation. Ensyn and Dynamotive are major developers of fluidized bed pyrolysis technologies and these are presented in the next section.

#### 2.2.4.1.1 Ensyn Group Inc.

Ensyn has been producing commercial quantities of bio-oil from its Rapid Thermal Process (RTP™), which uses a CFB reactor, since 1989. The RTP™ produces liquid bio-oil, gas and charcoal, which can be sold as fuel. Ensyn has developed natural chemical products from the liquid that have a much higher value. These include food flavourings and other products that can replace petroleum-based chemicals. In addition, the charcoal by-product is easily and economically upgraded to a higher value carbon product.



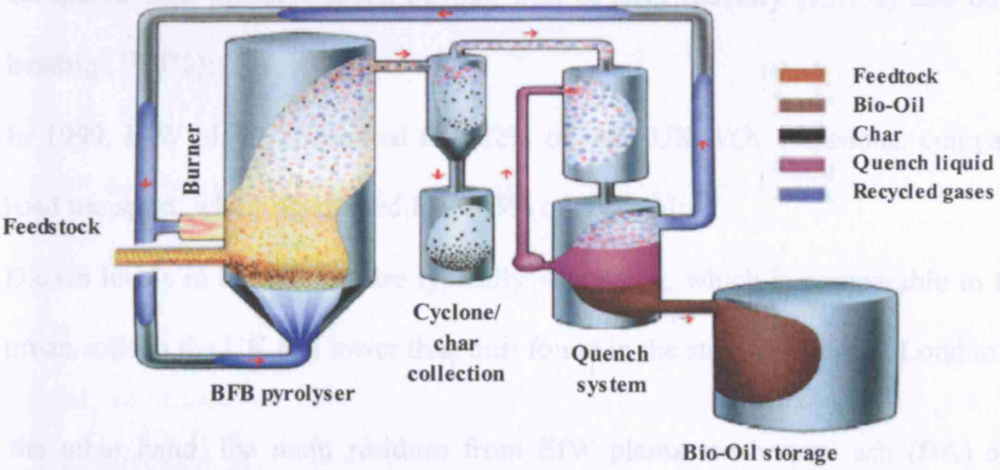
Adapted from Ensyn Group (2004)

Figure 2.18 The RTP™ process

The RTP™, shown in Figure 2.18, is characterised by a very rapid heat addition and very short processing times of typically less than one second at moderate temperatures and atmospheric pressure. The 70 tonne per day RTP™ facility in Wisconsin produces a number of food, natural chemical and liquid bio-fuel products and operates with an availability exceeding 95%. Ensyn has supplied a 650 kg/h unit to ENEL in Italy and a 350 kg/h unit to Fortum in Finland (Ensyn Group, 2004).

### 2.2.4.1.2 Dynamotive Technologies Corporation

Dynamotive owns the rights for its BioTherm™ process, which incorporates a BFB pyrolyser, originally developed by Resources Transforms International (RTI). The process, shown in Figure 2.19, produces high quality bio-oil, char and non-condensable gases, which are recycled to supply 75% of the energy required by the process. The bio-oil can be used directly in gas turbines or diesel engines for power generation. The company is also developing a range of derivative bio-oil products including blended fuels, slow release fertilisers and speciality chemicals, such as BioLime®, a reagent used to control *SOx* and *NOx* emissions in coal combustion systems. In 2005, Dynamotive has entered the commercialisation phase with the launch of its 2.5MWe CHP facility in West Lorne, Ontario (Canada). This is the first bio-oil CHP facility and is capable of processing 100 tonnes per day of bio-fuel, mainly wood, and incorporating a 2.5 MWe gas engine (Dynamotive, 2005).



Adapted from Dynamotive (2005)

**Figure 2.19 The BioTherm™ process**

## 2.3 Emissions & residues

All the thermal treatment processes of waste result in residues and emissions. These are unavoidable but nevertheless, their capacity to impact upon the environment can be effectively controlled. Ares & Bolton (2002) has reported that combustion of one tonne of MSW in a modern grate furnace can generate between 5200-6000 $Nm^3/h$ of combustion gases (flue gases), with various compositions, as shown in Table 2.11. Emissions from EfW facilities are tightly controlled by the Environment Agency, who makes sure that they are kept well below stringent levels set by UK and EU legislations. These emissions are often significantly lower than emissions from other sectors. According to the Environmental Services Association (ESA, 2006):

- In 2000, UK EfW plants contributed to 0.8% of total regulated dioxin emissions compared with power stations (4.7%), iron & steel industry (13.1%) and domestic heating (19.4%);
- In 1999, EfW plants accounted for 0.2% of total UK $NOx$ emissions, compared to road transport, which accounted for 44.5% of the total;
- Dioxin levels in bottom ash are typically <10 ng/kg, which is comparable to typical urban soils in the UK and lower than dust found in the streets of central London!

On the other hand, the main residues from EfW plants are bottom ash (BA) and air pollution control residues (APC) including fly ash. Bottom ash and APC residues usually account for approximately 25% and 3% by weight of incoming waste streams, respectively. Bottom ash from modern EfW plants is an inert waste discharged from the end of the grate. It is widely used throughout Europe as a secondary aggregate in road construction and building industry. APC residues are generated after the flue gas treatment. These residues are hazardous and must be safely disposed of to a licensed and specialist landfill under very strict regulatory conditions.

The EU Waste Incineration Directive (WID) came into force on December 2000 and it sets the permitted emission levels for incinerators. The Directive is summarised in Table 2.12 and is translated into the UK through The Waste Incineration Regulations 2002, which came into force on 28 December 2002 (Defra, 2007d). The following sections provide an overall review of the current practices in the management of emissions and residues from EfW facilities. The residue market and its economics are also reviewed.

**Table 2.11 Composition of a typical flue gas stream from MSW combustion**

| **Fly ash (dust)** | 3000-6000 mg/Nm$^3$ |
|---|---|
| **Acidic gases** | |
| $HCl$ | 600-1800 mg/Nm$^3$ |
| $SO_2$ | 200-800 mg/Nm$^3$ |
| $HF$ | 10-30 mg/Nm$^3$ |
| $NOx$ ($NO + NO_2$) | 250-500 mg/Nm$^3$ |
| **Heavy metals** | 40-60 mg/Nm$^3$ |
| **Volatile organic compounds (*VOCs*)** | 40-100 mg/Nm$^3$ |
| **Dioxins/furans** | 1-10 mg/Nm$^3$ |

Source: Ares & Bolton (2002)

**Table 2.12 Emission limits set by the Waste Incineration Directive 2000**

| **Daily Average Values** | | |
|---|---|---|
| Total Organic Carbon | | 10 mg/m$^3$ |
| Total dust | | 10 mg/m$^3$ |
| Hydrogen Chloride | | 10 mg/m$^3$ |
| Hydrogen Fluoride | | 10 mg/m$^3$ |
| Sulphur Dioxide | | 50 mg/m$^3$ |
| $NO_2$ (New or Large incinerators)* | | 200 mg/m$^3$ |
| $NO_2$ (Existing smaller incinerators) | | 400 mg/m$^3$ |
| **Average Values over sample period:** | **30 minutes** | **8 minutes** |
| Cadmium and Thalium Compounds (total) | 0.05 mg/m$^3$ | 0.1 mg/m$^3$ |
| Mercury Compounds | 0.05 mg/m$^3$ | 0.1 mg/m$^3$ |
| Other Metalloid Compounds (total) | 0.5 mg/m$^3$ | 1 mg/m$^3$ |
| **Average Values measured over 6-8 hours** | | |
| Dioxins and Furans (in toxic equivalents) | | 0.1 ng/m$^3$ |

* Some exemptions for nitrous oxides and dust may be authorised for existing incineration plants until 2008.
Source: Ares & Bolton (2002)

## 2.3.1 Emissions

### 2.3.1.1 What is in the flue gas?

Flue gases are a mixture of combustion products including water vapour, carbon dioxide, particulates, heavy metals and acidic gases. Carbon monoxide and volatile organic compounds (*VOCs*) are also products of combustion but they are indicators for incomplete combustion and can be easily monitored and rectified through process control (Ares & Bolton, 2002). The main emissions are:

- *Particulates* - Particulate matter consists of a non-combustible fraction of waste combined with the solid products of incomplete combustion, often carbon.
- *Organic carbon compounds* - The main compounds of concern, other than dioxins and furans for which separate limits exist, are polycyclic aromatic hydrocarbons (*PAHs*). These are products of incomplete combustion of organic compounds. They are non biodegradable, accumulate in fatty tissues and several of them have been linked to increased risk of cancer.
- *Acid gases* - MSW contains corrosive and toxic acid gases, such as hydrogen chloride (*HCl*), hydrogen fluoride (*HF*), sulphur dioxide ($SO_2$) and nitrogen oxides ($NO_x$). The removal of these gases from the flue gas stream is relatively simple and very efficient.
- Heavy Metal Compounds - Heavy metals exert a range of chronic and acute toxic health effects including carcinogenic and neurological. Toxic effects associated with these metals generally occur at higher concentrations than those emitted by incinerators, but concentrations present in fly ash can be high, which makes correct

disposal very important. This is particularly so, as the metals are often present in water-soluble forms, which can leach into surrounding areas.

- *Dioxins* – These are commonly used for a family of 210 closely-related chlorinated chemical compounds. They can be formed as by-products in some chemical processes and in various combustion processes. Although the actual quantities of these compounds produced by modern thermal waste treatment processes are very low, their high toxicity requires their effective removal from the flue gas.

### 2.3.1.2 Flue gas treatment processes

There are a number of physical and chemical processes that are used in the removal of pollutants and particulates that are present in flue gas streams. These are generally based around the following basic steps: addition of ammonia to combustion chamber; cooling; acid neutralisation; addition of activated carbon; filtration. Starting from the combustion chamber, $NO_x$ emissions are accelerated by high flame temperatures (e.g. by air preheat) and high excess air (Niessen, 2002). The $NO_x$ emissions can be reduced by:

- Water or steam injection or flue gas recirculation (to lower flame temperature);
- Operation at low excess air to reduce oxygen concentration;
- Staged combustion where the combustion environment is controlled to maintain a reducing condition or low oxygen condition, such that the fuel nitrogen is released as molecular nitrogen before entering a zone with a significant oxygen concentration.

The use of ammonia improves the situation and can result in significantly lower $NO_x$ emissions, with reductions of up to 60%. $NO_x$ levels lowered using a catalyst is called selective catalytic reduction (SCR), while the injection of a reagent into the flue gas at locations within the boiler is called selective non-catalytic reduction (SNCR). Cooling and conditioning of the flue gases is essential before they are filtered. Shock cooling the flue gases limits the formation of dioxins/furans by so called de novo synthesis (U.S. EPA, 2006). It also results in reduced volumetric flow rates and therefore, it lowers demands on the flue gas cleaning system. Cooling of flue gases may be achieved simply by passing them through a large chamber, which is fitted with cooling water sprays. Here, the flue gases must pass several levels of water sprays before they are allowed to the next stage of the cleaning process.

**Table 2.13 Reagents used in the flue gas treatment systems**

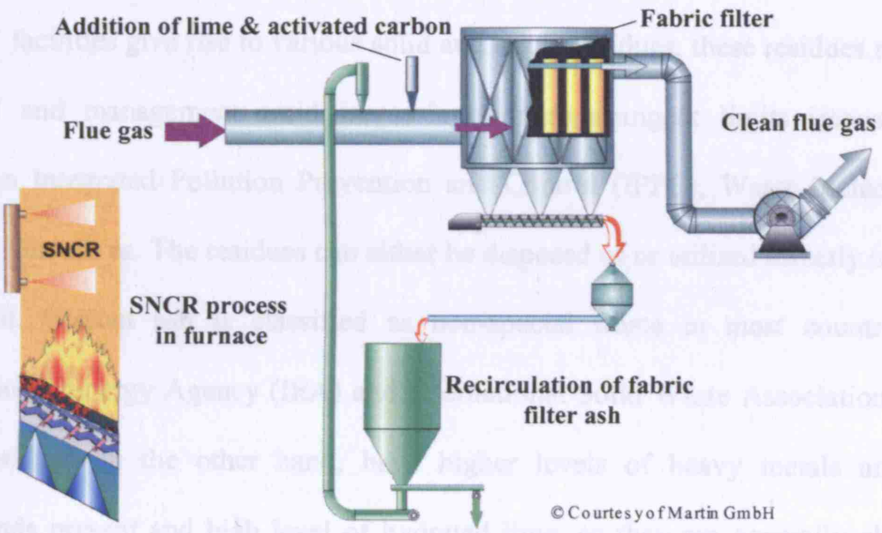
| **Application** | **Reagent** |
|---|---|
| **Neutralisation/ removal of acid gases**<br>e.g. $HCl$, $SO_2$, $HF$ | Lime<br>Hydrated lime<br>Limestone<br>Magnesium oxide<br>Sodium bicarbonate<br>Sodium hydroxide |
| **Reduction of $NO$ & $NO_2$ to $N_2$** | Ammonia<br>Urea |
| **Capture of dioxins/furans, *VOCs* and mercury** | Activated carbon |

Source: CIWM (2003)

Dioxins and furans, as well as heavy metals, such as mercury, are captured from the flue gas by the addition of activated carbon in a finely powdered form. The removal of acidic pollutants, such as $HCl$, $HF$ and $SO_2$, can occur in a venturi reactor by adding a neutralising agent, such as hydrated lime or sodium bicarbonate. Some of the reagents used in the flue gas treatment processes are shown in Table 2.13. In the filtration stage, the particulate matter is removed from the flue gas stream, as well as the spent activated carbon and lime, using cyclones, electrostatic precipitators and fabric bag filters.

### 2.3.1.3 Flue gas treatment systems

Flue gas treatment systems are wet, dry and semi-dry systems. Wet systems use cooling water sprays, to which acid neutralising reagents have been added to cool the flue gases and remove acid components. Therefore, they require water treatment systems to renew and recycle the water used within the plant. In dry flue gas cleaning systems, hydrated lime is added as a powder alongside activated carbon to the flue gas stream. The resulting solids are generally removed by fabric filters. A typical dry flue gas cleaning system is shown in Figure 2.20.



© Courtesy of Martin GmbH

**Figure 2.20 A typical dry flue gas cleaning system**

The retention of the reagents in the filter cake formed on the filter surfaces contributes to an additional pollutants capture capability, particularly for dioxin/furans and mercury compounds (CIWM, 2003). Semi-dry flue gas cleaning uses an acid neutralising agent, which is in a slurry form. This becomes entrained in the flue gases and therefore must be removed with the rest of the particulate matter. The $SO_2$ removal efficiencies with a semi-dry system are more than 20% higher than a dry system. Removal efficiency for $HCl$ and $HF$ is similar for both systems.

The quantity of residuals from the wet process is approximately half that for a semi-dry system and $SO_2$ removal efficiency is also higher. Therefore, among the three processes, this is the most effective. However, the cost of installing a wet flue gas cleaning system will be approximately 10% greater than for the semi-dry process, so this increased cleaning efficiency comes at a cost. Nevertheless, each of these systems can meet the standards contained in the Waste Incineration Directive.

## 2.3.2 Residues

As EfW facilities give rise to various solid and liquid residues, these residues require safe disposal and management amid increasingly more stringent limits imposed by the European Integrated Pollution Prevention and Control (IPPC), Waste Incineration and Landfill Directives. The residues can either be disposed of or utilised directly or after pre-treatment. Bottom ash is classified as non-special waste in most countries in the International Energy Agency (IEA) and International Solid Waste Association (ISWA).[1] APC residues on the other hand, have higher levels of heavy metals and organic compounds present and high level of hydrated lime, so they are generally classified as special waste.

### 2.3.2.1 Residues treatment

There are different residue treatment processes that are in current practice; however, it is important to distinguish between these processes for the disposal and utilisation purposes. For example, it is beneficial to limit the use and cost of material, such as additives, when

---

[1] These countries are Austria, Belgium, Canada, Finland, France, Hungary, Japan, Netherlands, Norway, Spain, Sweden and the UK.

treating for the purpose of disposal, while maintaining compliance with regulations. These treatment techniques include crushing, weathering, separating, mixing, chemical processes, thermal processes and solidification/stabilisation of the ash residues. Pre-treatment techniques to screen oversized components; remove ferrous metal and allow weathering of the material are recognised as low cost procedures. These improve the chemical integrity and structural durability of the material prior to disposal or re-use applications. Other procedures, like solidification/stabilisation, have additional processing requirements and therefore, have higher processing costs (CRE Group, 2000).

**Table 2.14 An over view of residue utilisation applications**

| Waste Material | End Product | Use Comments |
|---|---|---|
| **Bottom Ash** | Road Construction | |
| | • Base Course | • Used in cement stabilised bases |
| | • Asphalt Pavement | • Larger sizes used as filler for asphalt |
| | • Embankment | • Used as granular base |
| | Landfill Cover | • Requirements for coarse material are categorised according to permeability and/or particle size distribution |
| | Building Construction | • Lightweight aggregate for construction material, filling material, interlocking blocks and concrete blocks<br>• Railway station construction |
| **Ferrous Fraction** | Metallurgic Industry | • Ferrous fraction recycled in a smelting plant |
| **Fly Ash** | Civil Engineering | • Asphalt filler, top sealing of landfill sites<br>• Concrete applications but requires pre-treatment, due to high Cl content |
| **APC Residues** | Civil Engineering | • Potential for use as grout in coal mines |

Source: CRE Group (2000)

As reported in section 2.3, bottom ash is widely utilised throughout Europe as a secondary aggregate in road construction and building industry (see Table 2.14). Inexpensive procedures, such as ageing, crushing, magnetic separation, screening and weathering, are usually practised. APC residues and fly ash on the other hand, are hazardous and must be safely disposed of to specialist landfills. However, because of the higher costs for hazardous waste disposal in some countries and the prohibition of landfilling untreated residues in others, pre-treatment of the residues by solidification and stabilisation processes are preferred (CRE Group, 2000).

## 2.3.2.2 Residues treatment costs

### 2.3.2.2.1 Disposal costs

Disposal costs for ash residues vary significantly from one country to another. The disposal costs of bottom ash can range from 7.5-180 €/tonne, depending on national landfill taxes and whether the residue is classed as a special or non-special waste. The disposal costs for fly ash and APC residues are significantly higher. This is mainly due to the additional treatment process costs or higher landfill taxes. In countries employing high disposal charges, the cost benefits incurred from down-grading of the waste disposal categorisation for treated APC residues, from special to non-special waste, can outweigh the treatment costs. Total costs for disposal of APC residues and fly ash to landfill range from 47.25-225 €/tonne of residue (CRE Group, 2000).

### 2.3.2.2.2 Utilisation costs

Costs for utilising bottom ash in road construction and civil engineering applications are generally lower than those incurred for disposal to landfill. This is assuming that the ashes are in an untreated form. Here, the utilisation costs are in the range of 6-18 €/tonne of residue according to CRE Group (2000), which are cheaper than the disposal costs of 7.5-180 €/tonne reported in the previous section. On the other hand, re-use techniques, which involve melting or thermal treatment have significantly higher treatment costs, but can make an economic sense in countries with very high disposal costs.

In Japan, for example, the cost of utilising bottom ash can range from 99-147 €/tonne of residue. However, this is still cheaper than the cost of disposal of 180 €/tonne for the untreated residue. Table 2.15 summarises the disposal and utilisation costs for different countries.

**Table 2.15 Costs of utilisation and disposal of residues**

| Country | Disposal Costs, €/ tonne of residue | Utilisation Costs, €/ tonne of residue | Utilisation applications |
|---|---|---|---|
| Austria | 92-128 | > 10 | Smelting (iron) |
| Canada | >4-77 | 5 | Smelting (iron) |
| France | 8-225 | 12-18 | Road (sub-base) |
| Japan | 180 | 99-147 | Road construction, aggregate for concrete, interlocking block |
| Nether lands | 75-120 | | |
| Norway | 135 | 6 | Road (sub-base) |
| Spain | 38-165 | 11 | Road (sub-base) |
| Sweden | 15-47 | - | - |
| UK | 24-74 | 9 | Concrete block manufacture, bulk fill/sub-base, coated material component |

Source: CRE Group (2000)

Although residue utilisation practices are widespread and it makes an economic sense to create value-added products from these residues, there are many limitations hindering their market development. These limitations include:

- A negative public opinion that recycled products from waste are of inferior quality;
- The lack of consistent regulations and specification standards for residue re-use applications;
- Economic barriers including low costs of natural minerals compared to ash residues, higher treatment costs of residues and low cost of landfill.

## 2.3.3 Discussion & conclusions

The way we manage and dispose of our waste has a direct influence on greenhouse gas emissions, and as a consequence, alters the Earth's climate. Therefore, if we are to deliver a more sustainable economy, we must do more with less by reducing our waste and making better use of resources. Waste that is not created in the first place does not need to be reused, recycled or disposed of, and is ultimately, the most environmentally desirable option.

Waste treatment should also move up the hierarchy from landfill to recycling and energy recovery, especially, if the UK is to achieve its commitment under the Kyoto Protocol to reduce greenhouse gas emissions by 12.5% in 2008-2012. Alongside the Government's contribution to global efforts in tackling climate change, it has recognised the latter's link to waste management and has set regulatory drivers for sustainable waste practices. These include the Landfill Regulation 2002, Landfill Allowance Trading Scheme and National Recycling & Composting Targets.

The use of MSW to produce energy or fuel plays an important role in the UK's waste strategy when integrated with recycling and re-use initiatives. Experience in other countries more advanced in recycling policy implementation than the UK, such as Sweden, Belgium, and Germany, indicates that high recycling rates can co-exist with high EfW rates. EfW not only reduces our reliance on landfill but it is also an alternative source of energy, which by displacing fossil fuels, can help achieve the UK Government's targets of 60% reduction in carbon emissions by 2050 and 10% of UK electricity generation from renewable sources by 2010. EfW also contributes to energy security through diversification of supply, as up to 17% of the total UK electricity consumption can be supplied by EfW in 2020. Therefore, waste management should not be seen as a one-step disposal process but rather as an integrated strategy that incorporates several handling and treatment steps, such as waste separation, recycling, energy recovery and residue management.

Sustainable and carefully planned long-term objectives are also needed if we are to maximise resource efficiency, recycling and recovery. This will ensure that we achieve the most cost-efficient solutions that incorporate waste reduction and return of waste to the environment, in a way that enables them to be extracted and used again. We also need to recognise that recycling and energy recovery are like any other business activities and require economic drivers and the right personnel. For example, RDF needs to be standardised so it can be traded as a fuel in the energy market, guaranteeing the quality of the fuel for energy producers and establishing a market for biomass and waste. Secondary materials, such as bottom ash, needs to be processed efficiently and safely, so it can be able to compete economically with primary materials.

However, the most important issue in my opinion is that although we have the right technologies to deliver an increase in resource efficiency, which can be mechanical, thermal or biological, these technologies are not competitive enough compared to landfill. Therefore, unless the landfill tax, which constitutes the largest part of the landfill cost, is increased substantially, no companies will invest in technologies that will be competitively attractive in 10-15 years time, as these companies need their return on investment or simply go bust. The exception here is the public sector and local authorities, who are willing to invest now in order to avoid heavy penalties from LATS (Jones, 2006). However, their decisions will most likely be based on short-to-medium term goals and squander the opportunity to ensure that we achieve the most cost-efficient solutions that incorporate waste reduction and return of waste to the environment, in a way that enables them to be extracted and used again. This also highlights the importance of appointing the appropriate personnel, not only for the efficient running and maintenance of the new technologies, but also for leading the vision for long term sustainability objectives.

Thermal treatment processes including combustion, gasification and pyrolysis recover energy from waste in the form of heat and/or power. The heat can be used for district heating and the power can be easily distributed and sold via the national grid. Gasification and pyrolysis have the added advantage of producing a syngas that can be burned in conventional steam turbines or utilised in high efficiency gas engines and turbines. The syngas can also be further processed via gas synthesis to produce speciality chemicals and liquid fuels. Out of the three processes, incineration or combustion processes are the most established one, followed by gasification, while pyrolysis is at an early stage of commercialisation and therefore, will not be studied further.

In the UK, EfW technologies are predominately combustion processes employing moving-grate systems. These systems are well proven worldwide and are available from credible suppliers with a proven track record. Fluidized bed combustion technologies offer alternative and reliable options to moving-grate because of their ability to handle waste of widely varied properties and the many advantages in controlling emissions. Although the technology has a limited track record in the UK for MSW treatment, there are over 150 plants in commercial operation in Europe and Japan. Public perception of incineration, however, is not great and has to some extent hindered the development of EfW technologies in the UK.

Gasification offers more scope for recycling and recovering value from waste than combustion with better energy efficiency and with more flexibility of scale. However, there is no commercial plant for MSW gasification in the UK, and it is this unavailability of proved track record that is rendering the process not 'bankable' in the current market state. This said, gasification processes are being favoured as clean energy recovery technologies ahead of landfilling and incineration, as the UK Government pursues its mandates to the diversion of biodegradable waste from landfill and recognises EfW as alternative source of national energy.

Various leading biomass and waste fluidized bed technologies have been presented in this chapter. The review demonstrates their technical feasibility and encourages their integration into existing or newly developed systems, where they can demonstrate that the overall system would yield better prospects for economic development and environmental performance. From the review, it can be concluded that although there is no obvious "best" technology, fluidized beds offer robust and scalable reactors with better energy efficiencies and greater pollution controls.

As discussed earlier, there is a need for the diversification of waste management approaches in order to meet to the recycling, composting and recovery targets. This in turn, necessitates the establishment of facilities and sites that accommodate more than one waste management option. Since fluidized beds can be incorporated into such systems, they have the potential to contribute towards sustainable waste management practices across the UK.

The public opinion of EfW facilities, particularly incineration, is still divided and can be often at extreme ends of the scale. However, because of the increased publicity of climate change, which helped sustainable waste practices to move up the political agenda, the public are starting to embrace the need for waste reduction, recycling and energy recovery. The emission performances of the earlier generation of incinerators have clouted the public perception for many years. Nowadays, modern EfW plants have efficient energy recovery systems, with sophisticated gas clean-up processes, produce energy and reduce waste to inert residues. Emissions are tightly controlled by the Environment Agency, who makes sure that they are kept well below stringent levels set by UK and EU legislations.

Bottom ash is widely used throughout Europe as a secondary aggregate in road construction and building industry, while APC residues including fly ash are treated and disposed of safely. However, further efforts must be placed to move the treatment of these residues up the waste hierarchy, with more emphasis on recycling and recovery. This would require the establishment of consistent regulations and specification standards for residue re-use applications. The negative public opinion and economic barriers, such as the low cost of landfill, should be also addressed.

The performances of the different waste treatment options are summarised below in Table 2.16.

**Table 2.16 Performance summary of thermal treatment processes of waste**

| **Criteria** | **Combustion** | **Gasification & Pyrolysis** |
|---|---|---|
| Commercial availability | Proven technology worldwide | No proven track record in the UK, although, there are few operating plants on a commercial basis |
| Capacities (ktpa) | 100-600 (Moving-grate)<br>70-150 (500)(1) (FBC) | 10-120 |
| Efficiencies (%) | 14-27 | 10-20 (Syngas combustion)<br>13-28 (using gas engine)<br>30% (using CCGT)<br>Up to 27% (co-firing in existing power plant) |
| Economics | £35m for 136 ktpa (Moving-grate)<br>£51m for 256 ktpa (Moving-grate)<br>£35m for 120 ktpa (FBC) | £9m for 25 ktpa (FBG)<br>£45-5m for 60 ktpa (Rotary kiln pyrolysis)<br>£69m for 200 ktpa (Combined gasification/pyrolysis) |
| Bankability | Highly bankable | Not bankable in current market state. However, it may become bankable if promoted by reputable companies |
| Planning permission | Highly uncertain | Less uncertain than combustion |
| Visual impact | | |
| *Footprint* | Medium-large (moving-grate requires smaller footprint per unit capacity compared to fluidized bed) | Small-large |
| *Stack height (m)* | 60-120 | Short exhaust pipe to 50m depending on energy recovery system |
| *Plant siting issues* | High | Medium |
| Environmental impact | | |
| *Air emissions* | Achieve emissions significantly lower than WID limits | As combustion but generally emit lower levels of dioxins and metals than combustion(2) |
| *GHG reduction* | Recovers energy from waste, which would have came from fossil fuels | As combustion. If syngas is utilised in gas engines and turbines, then further benefits would be achieved. |
| *Landfill diversion* | Can extract metals before or after combustion and divert 70-96% by weight of waste from landfill, if BA is recycled | As combustion, but can divert 75-99% by weight of waste from landfill, if BA or slag is recycled |
| *Reside management* | Produce BA, which is recyclable and APC residues, which are sent to special landfills | As combustion, however, the residues are more suitable for re-use than combustion |
| *Traffic impacts* | Waste management systems should be integrated and located closer to waste origin | As combustion. Smaller facilities have less traffic impacts |
| *Nuisance* | Good housekeeping and adequate counter measures can reduce the potential nuisance from odour, dust, vermin and flies | As combustion |

(1) The Allington Plant, which is designed to treat 500 ktpa of MSW, will be fully operational in late 2007.

(2) The benefits of lower emissions are reduced if the syngas if combusted.

Sources: Fichtner (2004), GLA (2003), CRE Group (2000), Juniper (2003), Defra (2007d), Defra (2007e)

# 3 Scales and technologies for EfW & clean biomass processes

## Summary

This chapter reports the work carried out during my five-month placement programme as part of this research project at Germanà & Partners Consulting Engineers in Rome (Italy). The work investigates both the scales and technologies for EfW and clean biomass processes. The chapter begins with a study that has contributed to the process design of a commercial-scale moving-grate combustion plant in Italy, which can process 260,000 tpa of MSW and produce 34 MWe of electric power using a steam turbine. This enabled the study of mass and energy balances of a more "traditional" combustion plant and identified the key issues in the design of such processes, which usually relate to the cleaning and treatment of the output gas stream. Subsequently, more advanced technologies, such as fluidized bed combustion and gasification are considered, with particular emphasis on the appropriate use according to scale of different energy conversion systems, namely steam turbines, gas engines, fuel cells and combined cycle gas turbines.

*Parts of this chapter have been published in:*

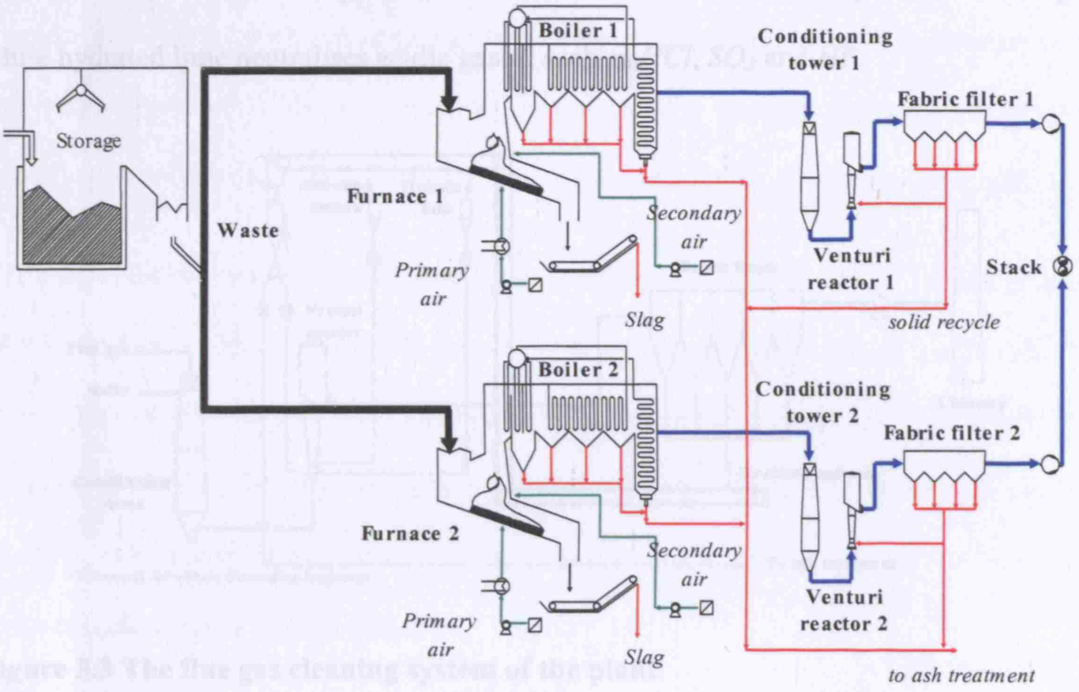
Yassin, L., Lettieri, P., Simons, S., Germanà, A. (2007). Study of the Process Design and Flue Gas Treatment of an Industrial-Scale EfW Combustion Plant. *Ind. Eng. Chem. Res.*, **46**, 2648-2656.

## 3.1 Moving-grate combustion plant (Case study 1)

As reported in section 2.2, modern combustion plants have efficient energy recovery systems with sophisticated gas clean-up processes, produce energy and reduce waste to inert residues. This case study presents the work carried out at Germanà and Partners Consulting Engineers in Rome in Italy, during which the scales and technologies of different EfW and biomass processes were examined. The main aim of the collaboration was to gain an in-depth understanding of design methodologies and engineering principles applied in the detailed design of real industrial energy recovery plants. Germanà & Partners have a long-established track record in the process design of EfW facilities and it is one of the few engineering consultancies in Italy that can provide the full range of design skills (including process, mechanical, electrical and civil engineering expertise) necessary to take an EfW project from concept through to full design.

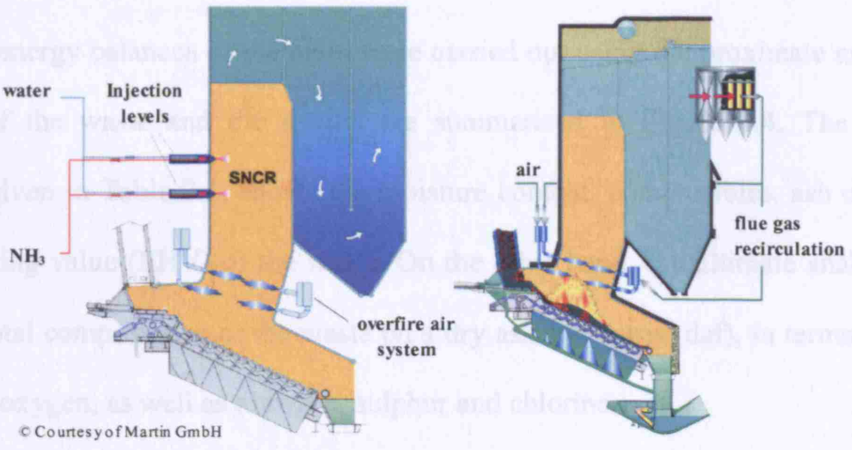
The combustion plant, shown in Figure 3.1, is designed by Germanà & Partners and is an example of a state-of-the-art EfW plant. It uses two moving-grate combustors fitted with a SNCR system (refer to section 2.3.1.2). Each process line is designed to treat 17.24 t/h of MSW and has a net power generation of 34 MWe. The plant consists of waste reception and storage, combustion chambers, energy recovery, flue gas treatment and residue handling.

The SNCR process, shown in Figure 3.2, reduces the gaseous nitrogen oxides produced by the combustion process to nitrogen and water by injecting aqueous ammonia, a reduction agent, into the furnace. The flue gas cleaning system of the plant consists primarily of a conditioning tower, a dry venturi reactor, fabric filters, a recirculation loop and storage silos for hydrated lime and activated carbon. This is illustrated in Figure 3.3.



© Germanà & Partners Consulting Engineers

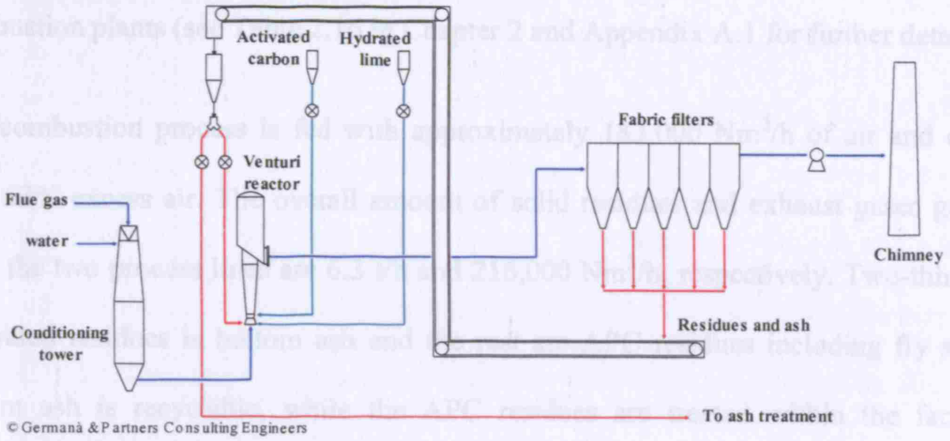
Figure 3.1 Schematic diagram of the EfW combustion plant



© Courtesy of Martin GmbH

Figure 3.2 The SNCR process (left) and flue gas recirculation (right)

The recycle loop is incorporated into the plant design to ensure maximum reagent utilisation by sending partly reacted material collected by the bag filters to the boiler. This is an advanced feature of the plant, as it increases the thermal efficiency of the system because the excess air and oxygen content are significantly reduced. This in turn reduces the formation of dioxins/furans. As discussed in section 2.3, activated carbon is injected into the venturi reactor to capture dioxins/furans and residual mercury from the flue gas, while hydrated lime neutralises acidic gases, such as $HCl$, $SO_2$ and $HF$.



© Germanà & Partners Consulting Engineers

Figure 3.3 The flue gas cleaning system of the plant

### 3.1.1 Mass and energy balances

Mass and energy balances of the plant were carried out using the proximate and ultimate analysis of the waste and the results are summarised in Figure 3.4. The proximate analysis, given in Table 3.1, shows the moisture content, combustibles, ash content and lower heating value (LHV) of the waste. On the other hand, the ultimate analysis, gives the elemental compositions of the waste on a dry ash free basis (daf), in terms of carbon, hydrogen, oxygen, as well as nitrogen, sulphur and chlorine.

**Table 3.1 Waste composition of the moving-grate plant**

| Proximate analysis | | | | Ultimate analysis (wt % daf) | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| *Moisture (%)* | *Combustibles (%)* | *Inerts (%)* | *LHV (MJ/kg)* | *C (%)* | *H (%)* | *O (%)* | *N (%)* | *S (%)* | *Cl (%)* |
| 31.9 | 56.6 | 11.5 | 12.6 | 56.7 | 7.9 | 32.4 | 1.4 | 0.4 | 1.2 |

The plant treats 260,000 tpa of MSW in two process lines, each with a thermal capacity of 60.1 MWth. It generates 34 MWe of net electric power using a steam turbine. The power can be exported to the national grid or supplied to an industrial park. This gives an overall system efficiency of 28.3%, which is higher than the average performances for EfW combustion plants (see Table 2.16 in Chapter 2 and Appendix A.1 for further details).

The combustion process is fed with approximately 183,000 Nm$^3$/h of air and operated with 53% excess air. The overall amount of solid residues and exhaust gases generated from the two process lines are 6.3 t/h and 216,000 Nm$^3$/h, respectively. Two-third of the generated residues is bottom ash and the rest are APC residues including fly ash. The bottom ash is recyclable, while the APC residues are treated within the facility by solidification before final disposal.

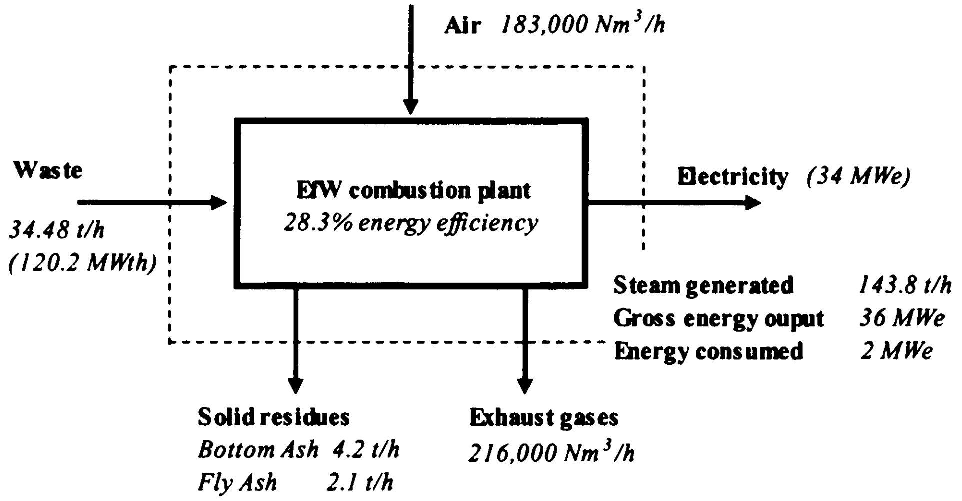


Figure 3.4 Mass and energy balance of the combustion plant

## 3.1.2 Flue gas treatment

In the original design of the combustion plant, hydrated lime was proposed for the removal of acidic gases from the flue gas stream. Hydrated lime is an inexpensive reagent and widely used in air pollution control systems. However, it is inefficient and corrosive. Therefore, Germanà & Partners commissioned us to conduct this study to investigate the effects of replacing the conventional hydrated lime with sodium bicarbonate, which is a more efficient, although more expensive reagent.

The study compares the performance of the two reagents in terms of cost and efficiency. A simplified kinetic model has been applied to simulate the reactions between the reagents and the acidic gases in a venturi reactor. Input design conditions and parameters of the combustion plant have been incorporated into the model to predict the effect of the different controlling steps of the reactions on the conversion rate. The model also predicts the time taken to neutralise and remove these pollutants, as well as the number of recycle stages required for the removal process. The treatment costs of using both reagents have also been carried out.

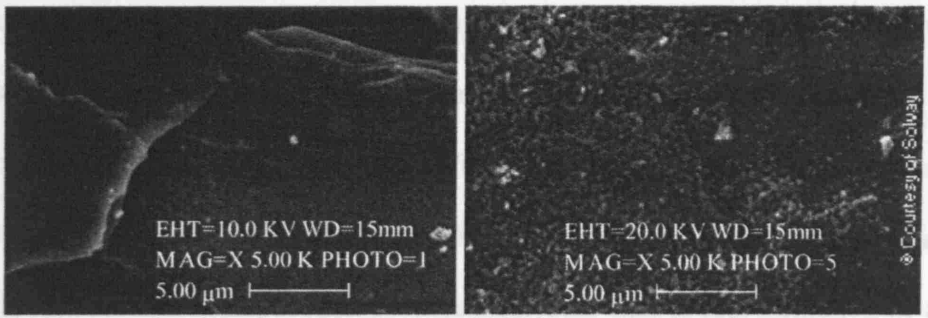
### 3.1.2.1 Hydrated lime or sodium bicarbonate?

As presented in section 2.3, the removal of acidic pollutants, such as $HCl$, $HF$ and $SO_2$, can take place in a venturi reactor by adding a neutralising reagent, such as hydrated lime ($Ca(OH)_2$) or sodium bicarbonate ($NaHCO_3$). Hydrated lime is widely used in all major air pollution control systems as it is readily available and is much cheaper than sodium bicarbonate; however, it is corrosive and needs to operate at low temperatures. The reactions of hydrated lime with the acidic pollutants, and hence the removal process, have also been reported to have relatively low conversion efficiencies (Yan et al., 2003). This is mainly because of the short residence time of the hydrated lime reactions, which in turn requires the reagent to be used in excess. The high usage of the reagent also results in the generation of more APC residues, which inevitably increases the overall treatment cost. Sodium bicarbonate on the other hand, is less corrosive and has higher removal efficiencies at a wider range of temperatures, thus requiring lower quantities than hydrated lime to be used. Liuzzo et al. (1993) also reported that sodium bicarbonate can partially reduce the amount of $NOx$ in the flue gas by reacting with nitrogen dioxide ($NO_2$) and forming sodium nitrate ($NaNO_3$), which is a solid salt.

Although the superior performance of sodium bicarbonate has not been fully explained in the literature, its reactivity can be attributed to the physical nature and chemical behaviour of the reagent. The reactions of the reagent with the acidic gases involve a thermal activation stage, where sodium bicarbonate decomposes to sodium carbonate ($Na_2CO_3$) when brought into contact with the hot flue gases (see Table 3.2). $Na_2CO_3$ then neutralises the acidic gases, namely $HCl$ & $SO_2$, to form inert solid salts. The Scanning Electron Microscope Analysis (SEM) of sodium bicarbonate is presented in Figure 3.5 and shows the surface structure of the reagent before and after the thermal activation stage. The high specific surface area and porosity may explain its superior performance when compared to hydrated lime.

**Table 3.2 Reactions of reagents with the acidic gases**

| | |
|---|---|
| Sodium bicarbonate reactions | |
| $2\,NaHCO_3 \rightarrow Na_2CO_3 + CO_2 + H_2O$ | *initial decomposition at 130-180 °C* |
| $Na_2CO_3 + 2HCl \rightarrow 2NaCl + CO_2 + H_2O$ | |
| $Na_2CO_3 + SO_2 + {}^1/_2\,O_2 \rightarrow 2Na_2SO_4 + CO_2$ | |
| Calcium hydroxide reactions | |
| $Ca(OH)_2 + 2HCl \rightarrow CaCl_2 + 2H_2O$ | |
| $Ca(OH)_2 + SO_2 + {}^1/_2\,O_2 \rightarrow CaSO_4 + 2H_2O$ | |



(a) Very smooth grain surface (a) Highly porous grain surface

Source: Solvay (2004)

**Figure 3.5 SEM Analysis for $NaHCO_3$ (a) prior and (b) after thermal activation**

It is important to note here that the reactions between calcium-based reagents, such as hydrated lime, and *HCl* & $SO_2$ have been extensively investigated in the literature. Researchers such as Uchida et al. (1979), Karlsson et al. (1981), Daoudi & Walters (1991) and Mura & Lallai (1994), to mention a few, have performed experimental studies at lab-scale covering a wide range of operating conditions and systems. However, there are limited studies on the capture of acidic gases by sodium bicarbonate and there are no available data on the scale-up effects when the reagents are used at industrial-scales. Therefore, the following sections seek to address these issues and compare the performance of hydrated lime and sodium bicarbonate in terms of efficiency and cost for an industrial-scale EfW combustion plant.

### 3.1.2.2 Application of kinetic model

The reactions between the reagent and the flue gas are of solid-gas, heterogeneous and non-catalytic reactions, as in the form of Equation 3.1. Hence, a simplified version of the unreacted-core model was used (Levenspiel, 1999). The neutralisation reactions for both sodium bicarbonate and calcium hydroxide are already shown in Table 3.2.

$$aA\ (gas) + bB\ (solid) \rightarrow Product\ (solid) \tag{3.1}$$

The model assumes: (i) the solid particles are spherical; (ii) the reactions are irreversible and first order, relative to $A$; and (iii) isothermal conditions are maintained. Two different cases for the reactions of $Ca(OH)_2$ and $NaHCO_3$ are considered. The first assumes that the continuous formation of solid product and inert material, without flaking off the reagent particles, would maintain a constant particle size. This case is representative of $Ca(OH)_2$ reactions.

In the second case, the particle size changes, as the reaction progresses due to the formation of gaseous products flaking off the solids. This case is representative of $NaHCO_3$ reactions. $NaHCO_3$ decomposes to $Na_2CO_3$ when it is injected into the venturi reactor and gets in contact with the hot flue gas. $Na_2CO_3$ reacts with the acidic gases and decompose further, producing $H_2O$ and $CO_2$ gases into the surrounding atmosphere. This creates a network of void spaces throughout the particle, which exposes fresh reactive sites and allows the acidic gases to diffuse through them. Consequently, the upward flow of the flue gas coupled with attrition between the reagent particles impose a stress in the ash layer, which then detaches and flakes off the particle.

For the fixed-size particles, three process steps are identified, which may control the overall reaction rate: (i) diffusion through gas-film; (ii) diffusion through ash layer; and (iii) chemical reaction. For the case where the particle size changes with time, two process steps are identified: (i) gas-film diffusion; and (ii) chemical reaction. The rate equations used for the gas-solid reactions are summarised in Table 3.3, where the term $\theta$ denotes the time (in seconds) required for complete conversion of unreacted particles into products.

The input data for the model depends on the flue gas properties, operating condition of the venturi reactor and kinetic parameters used. All the relevant data for the plant under examination are reported in Table 3.4. The data for the diffusivities ($D_e$) and mass transfer coefficients ($k_g$) were obtained from a similar EfW combustion plant also designed by Germanà & Partners (see De Nitto, 2003) and which was used as a term of reference for this study.

**Table 3.3 Conversion-time equations for the reagent-gas reactions**

| **Fixed-size particles for *Ca(OH)₂* reactions** | | |
|---|---|---|
| Diffusion through gas-film: | $\frac{t}{\theta}=x_B$ | where $\theta=\frac{a\rho_B R}{3bM_B k_g C_{Ag}}$ |
| Diffusion through ash layer: | $\frac{t}{\theta}=1-3(1-x_B)^{2/3}+2(1-x_B)$ | where $\theta=\frac{a\rho_B R^2}{6bM_B D_e C_{Ag}}$ |
| Chemical reaction: | $\frac{t}{\theta}=1-\frac{r_c}{R}=1-(1-x_B)^{1/3}$ | where $\theta=\frac{a\rho_B R}{bM_B k_s C_{Ag}}$ |
| **Variable-size particles for *NaHCO₃* reactions** | | |
| Diffusion through gas-film: | $\frac{t}{\theta}=1-(1-x_B)^{2/3}$ | where $\theta=\frac{y\rho_B R^2}{2bM_B D_e C_{Ag}}$ |
| Chemical reaction: | $\frac{t}{\theta}=1-(1-x_B)^{1/3}$ | where $\theta=\frac{a\rho_B R}{bM_B k_s C_{Ag}}$ |

**Table 3.4 Plant design conditions and model parameters**

| **Flue Gas Properties** | | | |
|---|---|---|---|
| temperature | °C | 150 | |
| flow rate | $m^3/s$ | 44.58 | |
| density | $kg/m^3$ | 0.87 | |
| viscosity | Pa s | 0.00002276 | |
| **Operating Conditions of the venturi reactor** | | | |
| inlet $SO_2$ flow rate | kmol/h | 1.01 | |
| inlet *HCl* flow rate | kmol/h | 3.30 | |
| particle diameter | μm | 120 | |
| **Model Parameters** | | | |
| | | *Ca(OH)₂* | *Na₂CO₃* |
| $k_{m,SO2}$ | m/s | 0.364 | 0.364 |
| $k_{s,SO2}$ | m/s | 0.461 | 1.272 |
| $D_{e,SO2}$ | $m^2/s$ | 0.0000029 | 0.000008 |
| $k_{m,HCl}$ | m/s | 0.476 | 0.476 |
| $k_{s,HCl}$ | m/s | 1.328 | 4.193 |
| $D_{e,HCl}$ | $m^2/s$ | 0.0000038 | 0.000012 |

### 3.1.2.3 Kinetic model predictions

The results obtained from the application of the model to predict the conversion rates of $HCl$ & $SO_2$ using $Ca(OH)_2$ & $NaHCO_3$ are discussed in this section. Figure 3.6 & 3.7 describe the predicted effects of the controlling steps on conversion rate when using $Ca(OH)_2$ as the reagent for $HCl$ & $SO_2$, respectively. Similarly, the predicted effects of the controlling steps on conversion rate when using $NaHCO_3$ as the reagent are shown in Figure 3.8 & 3.9 for $HCl$ & $SO_2$, respectively.

Figure 3.6 & 3.7 show that, for both reactions of $HCl$ & $SO_2$ using $Ca(OH)_2$, diffusion through the gas-film controls the early stages of the conversion process, while this becomes subsequently controlled by diffusion through the ash layer. The latter process step is accelerated by the formation of new product layers as the reaction progresses, thus preventing the reactant gas from reaching the unreacted core of hydrated lime.

This is in agreement with experimental evidence reported in the literature (see Weinell et al., 1992), who also showed that the reactions of $HCl$ with hydrated lime were controlled by diffusion through the ash layer. On the other hand, Figure 3.8 & 3.9 show that the reactions between $NaHCO_3$ and the acidic gases are entirely controlled by the chemical reaction step.

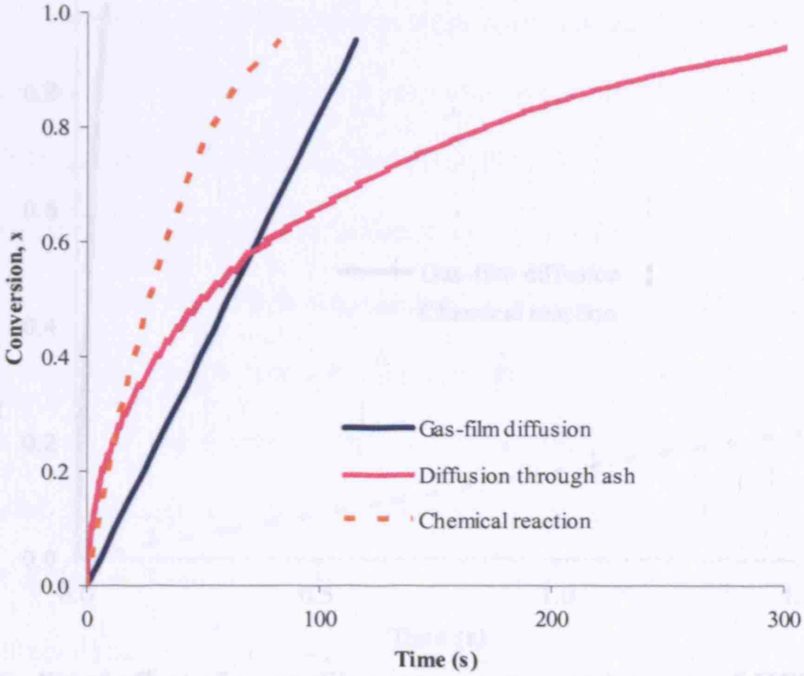


**Figure 3.6 Predicted effect of controlling steps on conversion rate of *HCl* using *Ca(OH)$_2$***

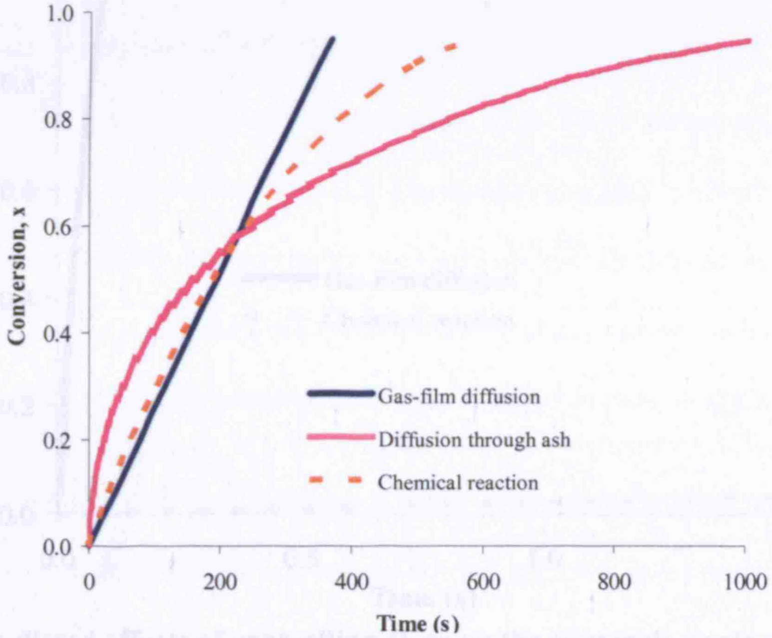


**Figure 3.7 Predicted effect of controlling steps on conversion rate of *SO$_2$* using *Ca(OH)$_2$***

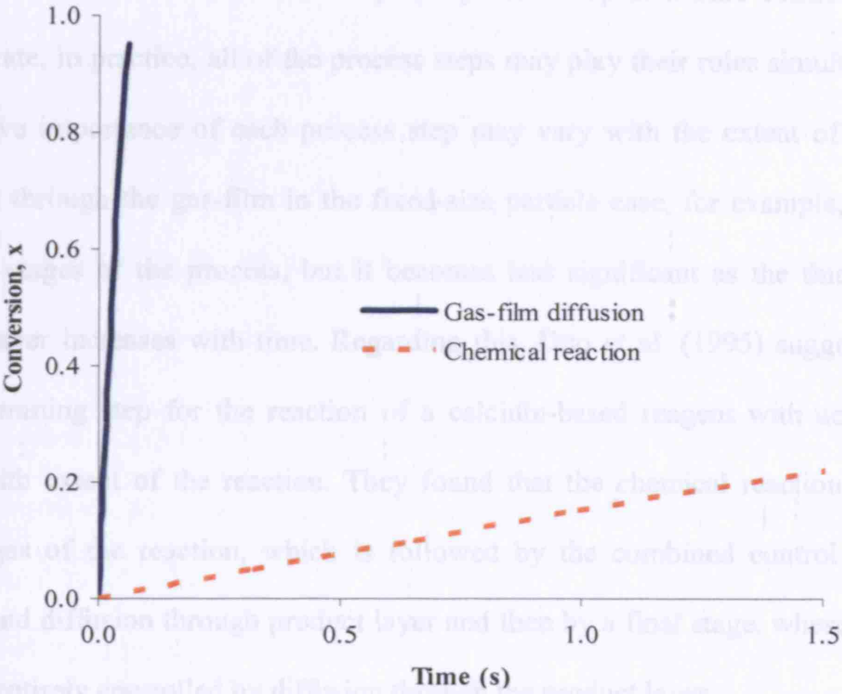


**Figure 3.8 Predicted effect of controlling steps on conversion rate of *HCl* using *$NaHCO_3$***

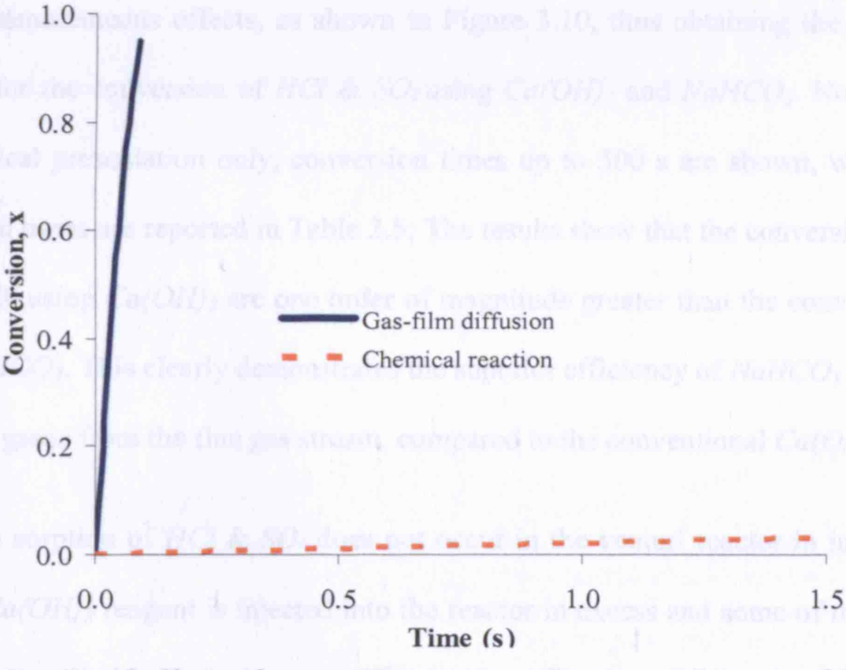


**Figure 3.9 Predicted effects of controlling steps on the conversion rate of *$SO_2$* using *$NaHCO_3$***

Although the model assumes that only one process step at a time controls the overall reaction rate, in practice, all of the process steps may play their roles simultaneously and the relative importance of each process step may vary with the extent of the reaction. Diffusion through the gas-film in the fixed-size particle case, for example, may control the early stages of the process, but it becomes less significant as the thickness of the product layer increases with time. Regarding this, Duo et al. (1995) suggested that the rate-determining step for the reaction of a calcium-based reagent with acidic gases is altered with extent of the reaction. They found that the chemical reaction controls the early stages of the reaction, which is followed by the combined control of chemical reaction and diffusion through product layer and then by a final stage, where the reaction becomes entirely controlled by diffusion through the product layer.

Therefore, the individual process steps reported in Figures 3.6-3.9 are summed to account for their simultaneous effects, as shown in Figure 3.10, thus obtaining the overall time required for the conversion of $HCl$ & $SO_2$ using $Ca(OH)_2$ and $NaHCO_3$. Note here that, for graphical presentation only, conversion times up to 500 s are shown, while the full conversion times are reported in Table 3.5. The results show that the conversion times for $HCl$ & $SO_2$ using $Ca(OH)_2$ are one order of magnitude greater than the conversion times using $NaHCO_3$. This clearly demonstrates the superior efficiency of $NaHCO_3$ in removing the acidic gases from the flue gas stream, compared to the conventional $Ca(OH)_2$.

Maximum sorption of $HCl$ & $SO_2$ does not occur in the venturi reactor in just one pass. The dry $Ca(OH)_2$ reagent is injected into the reactor in excess and some of the unreacted material is recycled back to the reactor for greater utilisation of the reagent, as shown in Figure 3.3. In this study, the theoretical number of recycle stages required for the sorption or neutralisation of 95% of the acidic gases and the time taken have been calculated for both $Ca(OH)_2$ and $NaHCO_3$. The results are shown in Table 3.5. The number of recycle stages is a function of the residence time, which in turn is dependent on the diameter of the venturi reactor and the flue gas flow rate. The larger the reactor diameter, the longer the residence time and the fewer the number of recycle stages. The results reported in Table 3.1 have been calculated based on a reactor diameter of 5 m and a flue gas flow rate of 108,000 $Nm^3/h$, with a residence time of approximately 7 s.

The results show that, for both types of reactions using $Ca(OH)_2$ and $NaHCO_3$, the sorption or removal of the acidic gases is far more efficient using $NaHCO_3$ and requires fewer recycle stages than $Ca(OH)_2$. Furthermore, it can also be observed that the conversion of $SO_2$ requires considerably longer times and many more recycle stages than $HCl$, because it has a greater tendency to cause pore blockage. This is in agreement with experimental studies reported by Chin et al. (2005), who attributed this behaviour to the physical properties of the reaction products. Product crystals formed by lime reaction with $HCl$, for example, are more soluble than those produced with $SO_2$.

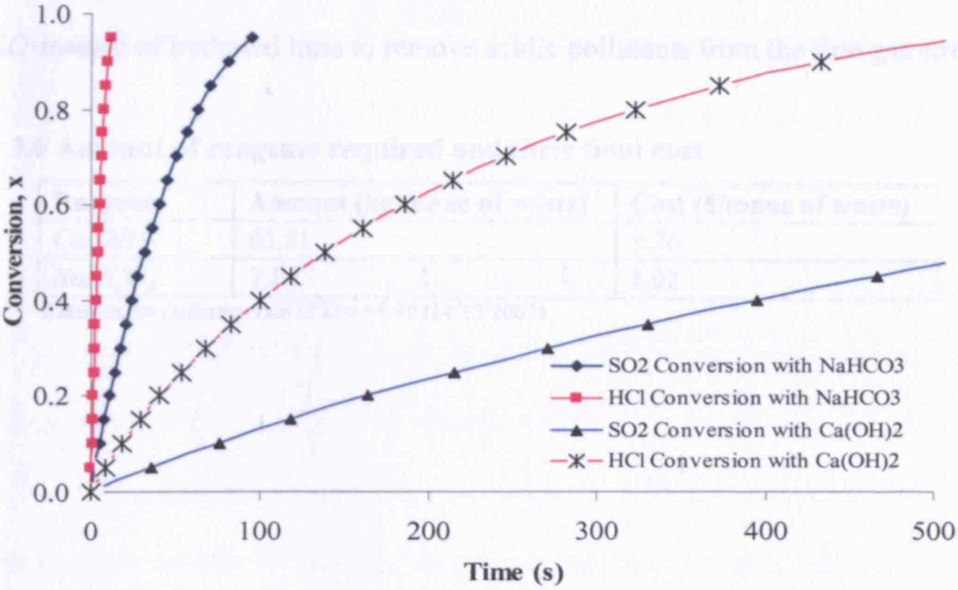


**Figure 3.10 Predicted overall conversion rate of $HCl$ and $SO_2$ using $NaHCO_3$ & $Ca(OH)_2$**

**Table 3.5 Conversion times and number of recycle stages**

| Reagent | Conversion times (s) | | Number of recycle stages | |
|---|---|---|---|---|
| | $HCl$ | $SO_2$ | $HCl$ | $SO_2$ |
| $Ca(OH)_2$ | 515 | 1960 | 78 | 296 |
| $NaHCO_3$ | 12 | 95 | 2 | 14 |

#### 3.1.2.4 Treatment costs

The economic feasibility of replacing $Ca(OH)_2$ with $NaHCO_3$ has been examined in this section. The evaluation was conducted using standard chemical engineering calculations (Sinnott et al., 1999), in which mass and energy balances of the plant were used. The amounts of reagents required for the neutralisation of the acidic pollutants were calculated with 10% excess to account for any material losses. The plant was assumed to be in operation for 312 working days per year.

The results are reported in Table 3.6 and show the amount of reagents required per tonne of MSW and their cost. It is observed that 7.14 kg of $NaHCO_3$ is required for the treatment of 1 tonne of waste and costs £1.0, whereas, 63.51 kg of $Ca(OH)_2$ is needed for the same treatment and costs £3.8. This demonstrates the attractive economic feasibility of using $NaHCO_3$ instead of hydrated lime to remove acidic pollutants from the flue gas stream.

**Table 3.6 Amount of reagents required and their final cost**

| Reagent | Amount (kg/tonne of waste) | Cost (£/tonne of waste) |
|---|---|---|
| $Ca(OH)_2$ | 63.51 | 3.76 |
| $NaHCO_3$ | 7.14 | 1.02 |

Based on an exchange rate of £1= €1.40 (14/12/2007)

## 3.2 Fluidized bed combustion & gasification processes

The suitability and effectiveness of a variety of fluidized bed combustion and gasification processes have been studied and presented in the previous chapter. The review highlighted that the commercial application of fluidized bed technologies has gained widespread acceptance, as they offer robust and scalable reactors, with better energy efficiencies and greater pollution controls. They are the most flexible technologies in coping with changes in waste quality and because they are easily started-up and shut-down, they can also manage longer term changes in waste quantity. These technologies require the pre-treatment of waste and hence, they are suitable for treating homogenous waste, such as RDF. This enables fluidized bed systems to be compatible with high levels of source segregation and promotes recycling/composting initiatives.

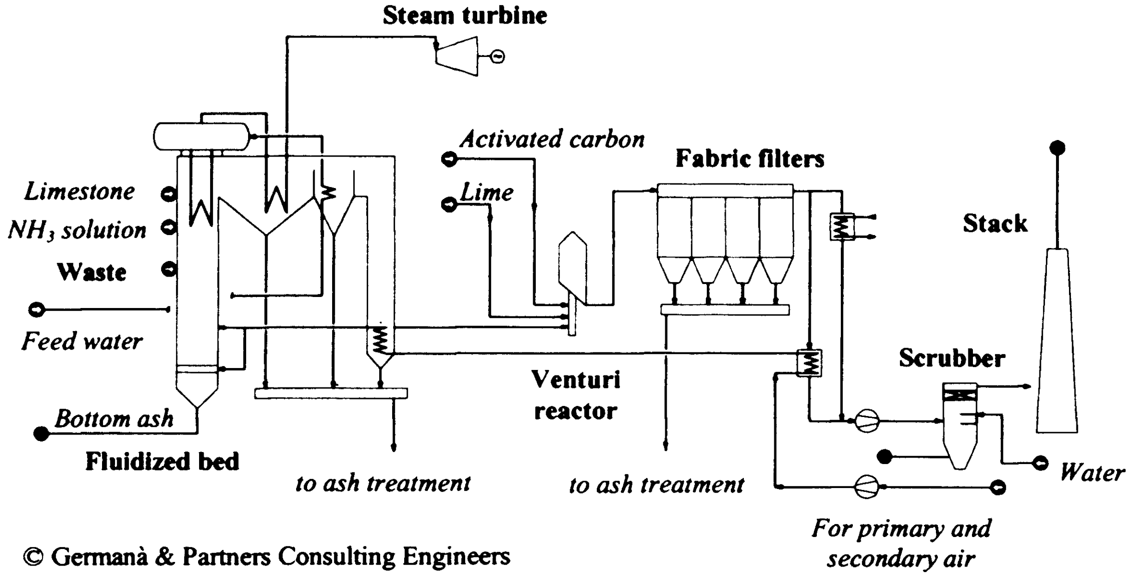
The aim of the following sections is to investigate the applicability of fluidized bed systems at different scales. Combustion processes are typically centralised operations, with plant capacities up to 600,000 tpa. Whereas gasification processes benefit from flexibility of scale, as they can be built efficiently and economically at smaller scales, unlike combustion processes, which are economically viable at larger scales.

Furthermore, it is essential to recognise the importance of choosing the appropriate energy conversion technologies, such as steam turbines and gas engines, as these technologies can play a major role in achieving efficient energy recovery from waste and determining the applicability of EfW processes at different scales. In the following sections, four case studies describing the process design of fluidized bed combustion and gasification processes coupled with different energy conversion technologies are presented. Steam turbine is considered for the combustion process, while gas engine, fuel cells and combined cycle gas turbine are considered for the gasification process. The chapter concludes with an overall discussion of the findings in section 3.3.

### 3.2.1 Fluidized bed combustion coupled with steam turbine (Case study 2)

The process design of a small-to-medium scale EfW plant treating 50,000 tpa of RDF and generating up to 7 MWe of electricity using a steam turbine has been examined. The plant, designed by Germanà & Partners, serves the municipality of the City of Ravenna in Italy and was commissioned in 1998. It employs a bubbling fluidized bed (BFB) supplied by EPI and is fitted with a SNCR system to control *NOx* emissions in the combustion chamber by the addition of aqueous ammonia (see section 2.3). Limestone is also added to the furnace to reduce sulphur formation and inhibit ash slagging.

Figure 3.11 depicts a schematic diagram of the Ravenna plant. The processing of waste into RDF that is suitable for feeding into the fluidized bed is carried out by material shredding, magnetic separation and compression through a roller mill. The flue gas cleaning system consists of a venturi reactor, fabric filters and a scrubber. Activated carbon is injected into the venturi reactor to capture dioxins/furans and residual mercury from the flue gas stream, while the acidic gases, such as $HCl$, $SO_2$ and $HF$, are neutralised and removed by the addition of hydrated lime.



© Germanà & Partners Consulting Engineers

**Figure 3.11 Schematic diagram of the Ravenna EfW combustion plant**

### 3.2.1.1 Mass and energy balances

The fluidized bed is designed to operate at 50% excess air and utilise RDF in varying quantities of 4 and 6 t/h and with LHV of 14.7 and 16.7 MJ/kg. The variation in the calorific value of the waste depends on the waste collection area and its composition, which is shown in Table 3.7. Therefore, the mass and energy balances were performed for four different design scenarios and the results are summarised in Table 3.8.

**Table 3.7 Waste composition of the Ravenna plant**

| **Component** | **% wt on dry basis** |
|---|---|
| C | 55.7 |
| *H* | 4.6 |
| *N* | 0.7 |
| *O* | 17.8 |
| *S* | 0.5 |
| *Cl* | 0.7 |
| *Ash* | 20.0 |
| *Moisture* | 15.8-25% |

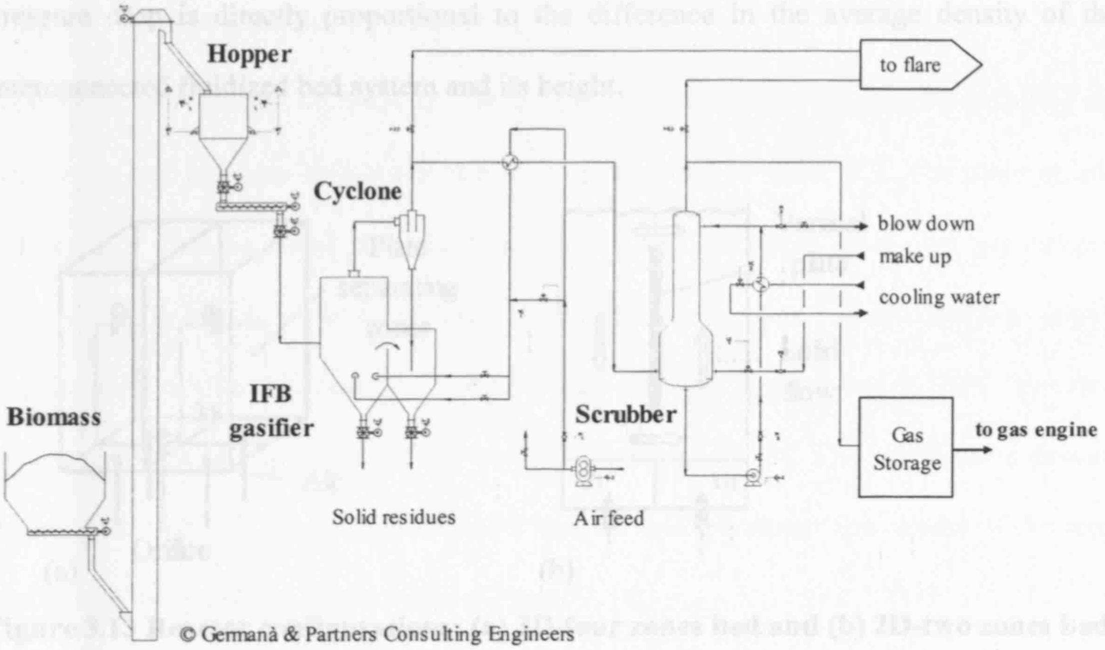
The results show that operating the plant at 6 t/h of RDF, with a calorific value of 16.7 MJ/kg, generates 7.3 MWe of electricity (using a steam turbine with a 30% electrical efficiency). This gives the highest overall system efficiency of 26.1%. The combustion process would require 55.5 t/h of air and generate 60.7 t/h and 1.4 t/h of exhaust gases and solid residues, respectively. Over 2% of the solid residues are recovered as bottom ash, while the rest are APC residues and are treated within the facility by solidification before final disposal.

**Table 3.8 Mass and energy balances of the Ravenna plant**

| **Design parameters** | **Design scenarios** | | | |
|---|---|---|---|---|
| | **1** | **2** | **3** | **4** |
| RDF feed (t/h) | 6 | 4 | 6 | 4 |
| LHV (MJ/kg) | 14.7 | 14.7 | 16.7 | 16.7 |
| RDF thermal capacity (MWth) | 24.4 | 16.3 | 27.9 | 18.6 |
| Power output (MWe) | 6.2 | 3.8 | 7.3 | 4.5 |
| System efficiency (%) | 25.5 | 23.2 | 26.1 | 24.1 |
| Air required (t/h) | 46.7 | 31.6 | 55.4 | 35.3 |
| Solid residues (t/h) | 1.2 | 0.8 | 1.4 | 0.9 |
| Exhaust gases (t/h) | 52.1 | 35.6 | 60.7 | 38.8 |

### 3.2.2 Fluidized bed gasification coupled with gas engine (Case study 3)

This study has investigated the process design of a simple air gasification system that generates 160 kWe of electricity from wood using a gas engine. A schematic representation of the plant is shown in Figure 3.12. The plant consists of an interconnected bubbling fluidized bed (IFB) gasifier, flue gas treatment and power generation system, which includes gas storage. The gas cleaning system comprises of a cyclone and scrubber. This is adequate to remove the solid particulates from the fuel gas stream, such as char and ash, as well as tar and gaseous pollutants. The gasifier has a novel design structure, in that it is divided by a baffle plate into two zones.



© Germanà & Partners Consulting Engineers

**Figure 3.12 A bubbling fluidized bed gasification process**

Biomass is introduced into the main, dense zone of the gasifier and material circulation takes place between the two zones. This circulation of solids between two beds has been first investigated by Kuramoto et al. (1985) and (1986) in two-dimensional (2D) and three-dimensional (3D) beds, as illustrated in Figure 3.13. For the 2D bed, the reactor was divided by a partition plate, with an opening to form two portions of fluidized beds with different gas velocities ($u_2 > u_1$). As a consequence, the more dense bed moves downwards, while the lighter bed moves upwards, thus inducing an anti-clockwise solid circulation.

For the 3D bed, the interior of the vessel was divided into four sections by intersecting two flat vertical plates at right angles. Two sections were used for the upwards-flowing bubbling fluidized beds and the other two sections were used for the downwards-flowing bubble-free fluidized beds. The particle circulation between the zones was attributed to the difference in the fluidizing gas velocities and the pressure drop across the orifice. This pressure drop is directly proportional to the difference in the average density of the interconnected fluidized bed system and its height.

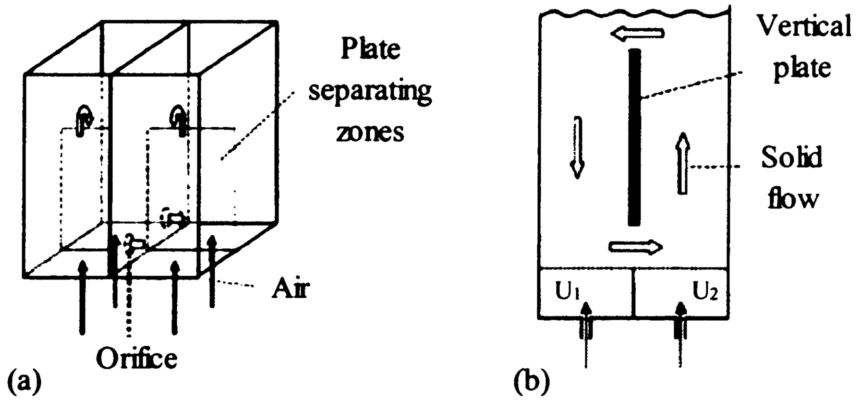


**Figure 3.13 Reactor configurations: (a) 3D-four zones bed and (b) 2D-two zones bed**

The circulating motion of solids between two beds has been used in the design of the IFB gasifier by Foscolo et al. (2007) and the gasification plant, shown in Figure 3.12, has been built and operated in China in collaboration with ENEA (Italian National Agency for New Technologies, Energy and the Environment) and LIER (the Chinese Liaoning Research Institute of Yingkou).

The design of the IFB gasifier addresses one of the main drawbacks in most biomass fluidized bed applications, which is the tendency of the biomass particles to segregate at the surface of the bed. This occurs because of the difference in size and density between the biomass and sand particles in the fluidized bed, thus leading to a variation in particle concentration over the bed height (Kehlenbeck et al., 2002). Particle circulation between zones in the IFB gasifier eliminates this drawback, as it enhances the gas-solid mixing and prevents segregation from taking place. In addition, elutriation of fine carbon particles is also reduced, minimising the solid load to the cyclone.

### 3.2.2.1 Mass and energy balances

The mass and energy balances of the gasification process were performed using the proximate and ultimate analysis of the biomass reported in Table 3.9. The plant utilises 280 kg/h of Chinese wood and generates 160 kWe of electricity using two gas engines, each with a nominal power of 80 kWe. The gasification process is calculated to have a thermal conversion efficiency of 56.1%[2] and the gas engine has a 20% electrical efficiency, thus giving an overall system efficiency of 11.1%. The gasification process requires 287 kg/h of air and generates 20 kg/h of solid residues. The results of the mass and energy balances are summarised in Figure 3.14.

**Table 3.9 Proximate and ultimate analysis of the biomass used**

| **Proximate analysis** | | | | | **Ultimate analysis (wt % daf)** | | | |
|---|---|---|---|---|---|---|---|---|
| *Fixed carbon (%)* | *Moisture (%)* | *Volatiles (%)* | *Inerts (%)* | *LHV (MJ/kg)* | *C (%)* | *H (%)* | *O (%)* | *N (%)* |
| 8.4 | 31.9 | 83.4 | 1.9 | 18.5 | 48.2 | 6.4 | 45.1 | 0.2 |

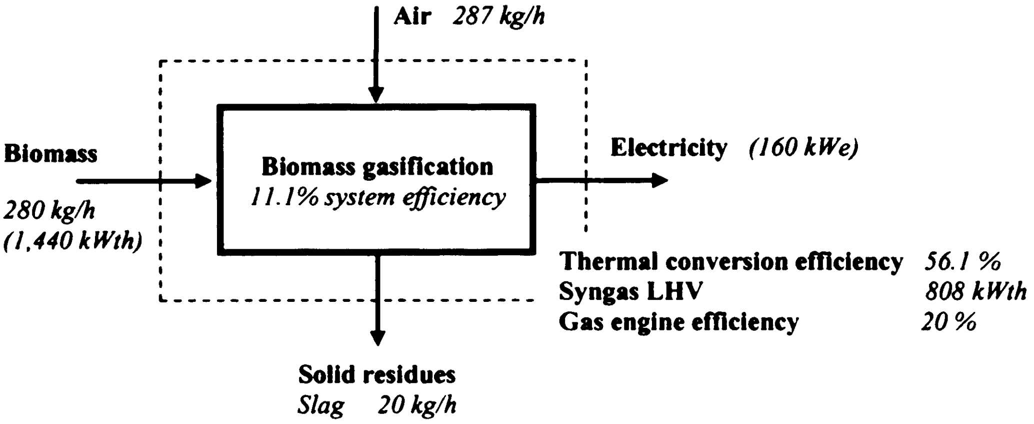


**Figure 3.14 Mass and energy balance of the gasification process using gas engine**

---

[2] In this work, the gasification thermal conversion efficiency also refers to the gasifier cold gas efficiency, which is defined as the ratio of the energy content of the syngas to the energy content of the feedstock.

### 3.2.3 Fluidized bed gasification coupled with fuel cell (Case study 4)

The process design of a biomass gasification plant integrated with Phosphoric Acid Fuel Cells (PAFC) is reported in this case study. The plant uses a circulating fluidized bed reactor to gasify clean biomass and generate 914 kWe of electricity using PAFC. A simplified schematic diagram of the plant is shown in Figure 3.15.

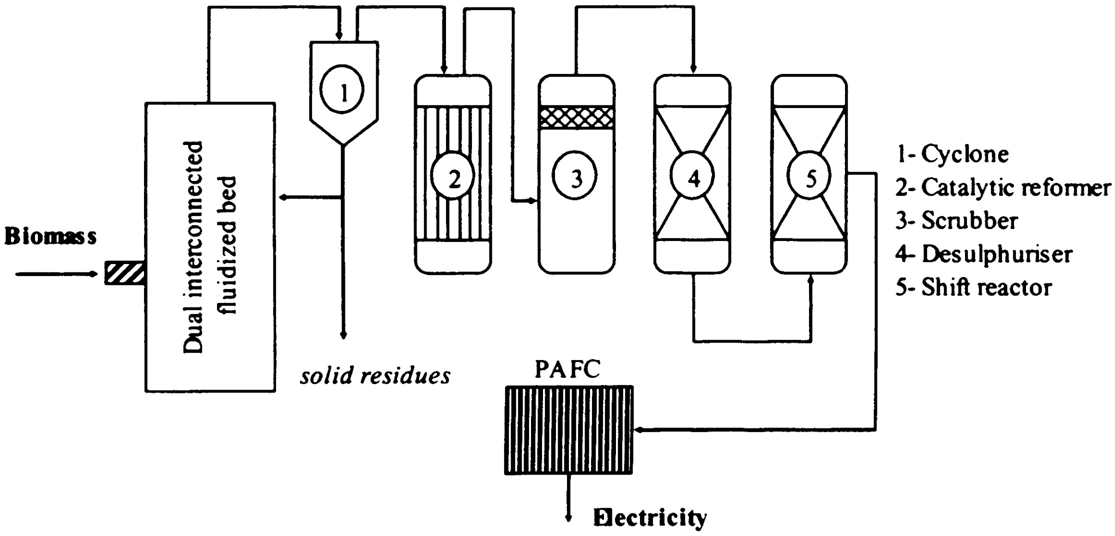


**Figure 3.15 Schematic diagram of the gasification plant using fuel cell**

The downstream gas clean-up system of the plant consists of the following:

- A cyclone to separate solid particles from the fuel gas;
- Catalytic reformers to enhance hydrogen content by reforming methane and tar;
- A scrubber to remove dust and acidic components, such as chlorides and fluorides;
- De-sulphurisers to remove any remaining sulphur-compounds, such as $H_2S$;
- A two-stage water-gas shift reactor system to convert $CO$ to $H_2$ and $CO_2$.

The gasifier, shown in Figure 3.16, is a fluidized bed that is connected to a second fluid bed, in which residual char from the first bed is combusted (Foscolo, 1997). Bed material is circulated between the two units so that the heat generated in the combustion zone is utilised to provide energy for the endothermic gasification process. The gasifier was developed by University College London (UK) in collaboration with University of L'Aquila (Italy) and the project was financed by the European Commission under the JOULE III programme (1995-97). The PAFC technology was chosen for the project because it was the only readily available fuel cell technology with proven track record.

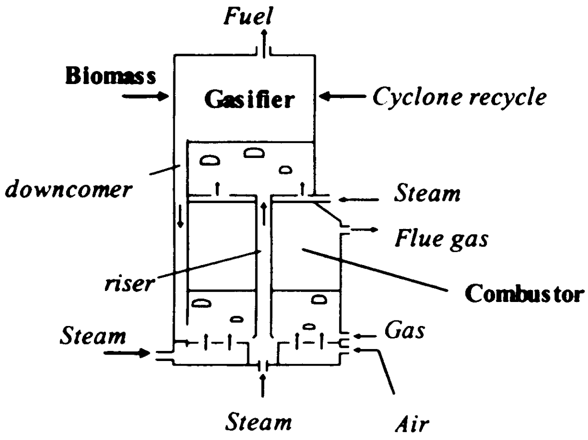


**Figure 3.16 A dual interconnected fluidized bed gasifier**

### 3.2.3.1 Mass and energy balances

The proximate and ultimate analysis of the biomass used by the plant is summarised in Table 3.10. Mass and energy balances of the gasification process were then carried out based on these compositions and the results are shown in Figure 3.17. The plant utilises 732 kg/h of clean biomass, mainly solid fuel crops, and produces a hydrogen-rich fuel gas comprising of over 66% hydrogen. Just over 80% of the hydrogen is consumed by the PAFC to generate 914 kWe of electricity. Therefore, the electrical conversion efficiency of the PAFC is 44.4%, giving an overall system efficiency of 30%. The gasification process requires 1.5 t/h of air and generates 37 kg/h of solid residues. The plant can also co-generate 744 kg/h of steam at 140°C and 3.7 bars, which is equivalent to about 122 kWth. However, this is not utilised by the plant, as it is wasted.

**Table 3.10 Proximate and ultimate analysis of the biomass used**

| **Proximate analysis** | | | | | **Ultimate analysis (wt % daf)** | | | |
|---|---|---|---|---|---|---|---|---|
| *Fixed carbon (%)* | *Moisture (%)* | *Volatiles (%)* | *Inerts (%)* | *LHV (MJ/kg)* | *C (%)* | *H (%)* | *O (%)* | *N (%)* |
| 18.0 | 20.0 | 56.0 | 6.0 | 17.5 | 48.7 | 5.4 | 44.6 | 1.2 |

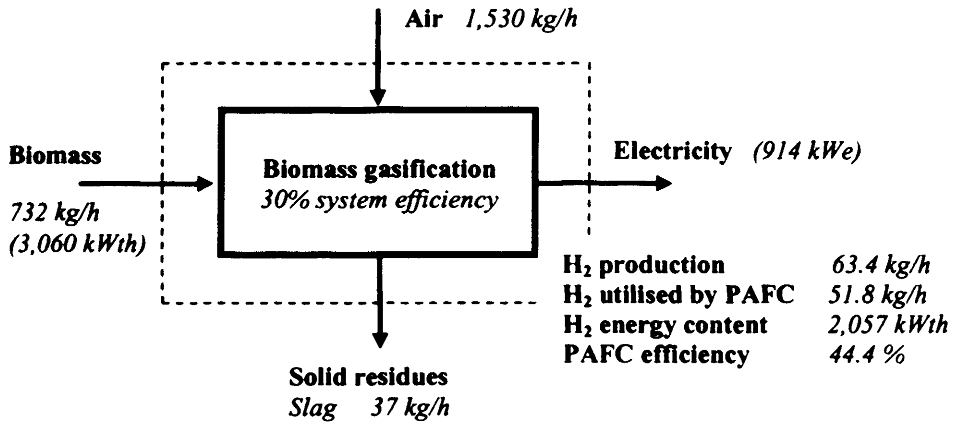


**Figure 3.17 Mass and energy balance of the gasification process using fuel cell**

## 3.2.4 Fluidized bed gasification coupled with CCGT (Case study 5)

This study reports the design of a BFB gasification plant to treat MSW in the form of RDF and generate electricity using a combined cycle gas turbine (CCGT) unit. The main objective of the study was to examine the technical performances of gasification systems that can efficiently treat urban waste from local municipality and thus enabling the diversion of waste from landfill and recovery of energy for heat and power applications.

A plant scale of 50,000 tpa was chosen for this analysis so the technical performance of the fluidized bed gasification system can be compared to Ravenna's fluidized bed combustion plant presented in section 3.2.1. Therefore, the gasification system will process RDF at a feed rate of 6 t/h and have a similar composition to that reported in Table 3.7. A schematic diagram of the gasification plant is illustrated in Figure 3.18.

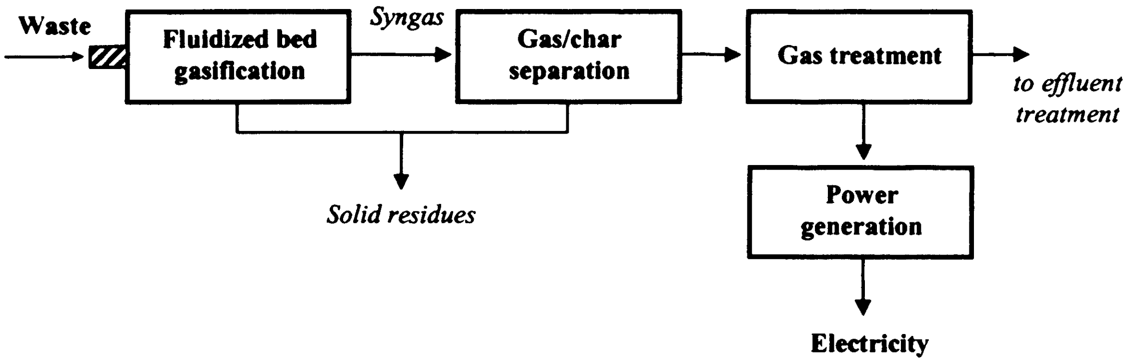


**Figure 3.18 Schematic diagram of the RDF gasification system using CCGT**

The downstream gas clean-up system of the plant consists of the following:

- A cyclone to separate solid particles from the fuel gas;
- A gas treatment system to produce a clean syngas. This includes gas quenching, venturi scrubber and a spry tower;
- An effluent treatment system to deal with the tar and solid materials in the wastewater.

### 3.2.4.1 Mass and energy balances

In this analysis, the RDF moisture content is taken to be 15.8%, which corresponds to a LHV for the RDF of 4000 kcal/kg or16.7 MJ/kg. The proximate and ultimate analysis of the waste are summarised in Table 3.11 and the results of the mass and energy balances are illustrated in Figure 3.19. The plant utilises RDF at 6 t/h and generates 8.0 MWe of electricity using a CCGT unit, with an electrical efficiency of 36.0%. This gives an overall system efficiency of 28.8%.

An average thermal conversion efficiency of 80% was used, as this value can range from 70-93% (Babu, 2006). The CCGT electrical efficiency was obtained from Bridgwater et al. (2002). The gasification process requires 7.6 t/h of air and generates 1.2 t/h of solid residues, of which one-third is bottom ash and the rest are APC residues.

**Table 3.11 Proximate and ultimate analysis of RDF**

| **Proximate analysis (wt %)** | | | | | **Ultimate analysis (wt % daf)** | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| *Fixed carbon (%)* | *Moisture (%)* | *Volatiles (%)* | *Inerts (%)* | *LHV (MJ/kg)* | *C (%)* | *H (%)* | *O (%)* | *N (%)* | *S (%)* | *Cl (%)* |
| 10.7 | 15.8 | 53.5 | 20.0 | 16.7 | 69.6 | 5.8 | 22.3 | 0.9 | 0.6 | 0.9 |

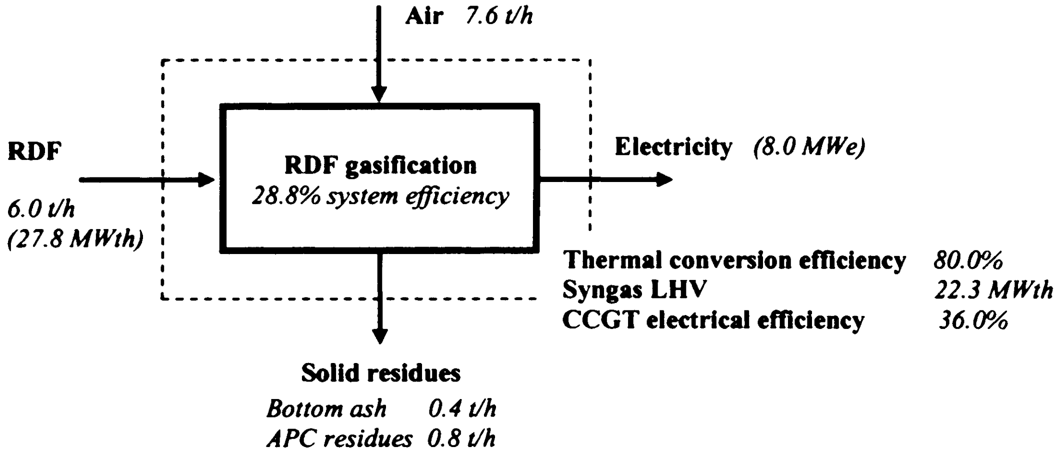


**Figure 3.19 Mass and energy balance of the gasification process using CCGT**

## 3.3 Discussion & conclusions

This chapter has investigated both the scales and technologies for recovering energy from biomass and waste. The process design of different combustion and gasification systems have been studied to examine their technical performances at different scales and using various reactor types and energy conversion technologies, namely steam turbines, gas engines, fuel cells and CCGT. The chapter also reported a study that contributed to the re-design of a large-scale combustion. The study investigated the efficiency and cost of replacing hydrated lime with sodium bicarbonate in the removal of acidic pollutants from the flue gas stream. A kinetic model was applied to simulate the reactions between the reagents and acidic pollutants, namely $HCl$ and $SO_2$. It was concluded that although sodium bicarbonate is a more expensive reagent, it is more efficient and it is economically a more attractive option for the removal of acidic pollutants than hydrated lime.

Combustion processes are centralised operations and are usually economically viable at large-scales. Most of these processes are based on moving-grate and fluidized bed reactors. However, fluidized bed systems are smaller than typical moving-grate systems and have been operated at small-to-medium scales, ranging from 50,000-150,000 tpa, as opposed to moving-grate systems, which have plant capacities of up to 600,000 tpa. Heat and power are usually generated using steam turbines, which can operate across a range of capacities and up to 500 MWe. Nonetheless, they are economically feasible only for capacities greater than 1.5 MWe because of their inherent low electricity generation efficiency and high capital costs. This is why large centralised combustion facilities are often preferred as they can benefit from economies of scale.

The first two case studies demonstrate this and enable us to report the technical performances of a 260,000 tpa moving-grate combustion system and a fluidized bed combustion plant at 50,000 tpa. Both systems are designed by Germanà & Partners and generate electricity using steam turbines. The overall system efficiencies are 28.3% and 26.1% for the moving-grate and fluidized bed systems, respectively. However, both processes assumed no heat losses from the boilers and the steam turbines were supplied with a 30% electrical conversion efficiency, irrespective of scale and steam conditions. Therefore, if the effect of boiler efficiency on the overall system performance is to be taken into account, then a 10% drop in boiler efficiency (i.e. to 90%) would correspond to a 3% decrease in the overall system efficiency. Similarly, a 1% decrease in steam turbine efficiency (i.e. to 29%) would correspond to a proportional 1% drop in the overall performance of the system.

In the third and fourth case studies, the process designs of two biomass gasification systems have been examined. Both projects were aimed at performing research and technical development of fluidized bed gasification, as well as the generation of heat and power from renewable sources. The research also addressed the perceived risks associated with the development of renewable energy technologies, as both projects proved their technical feasibility.

The projects were demonstrated at small-scales and thus are suitable for rural decentralised energy systems. Gas engines, as utilised by the first plant, are widely used in rural areas and present the most economical options for electricity generation. Fuel cells, on the other hand, have high efficiency and are seen as low carbon energy technologies. Gas engines and fuel cells are available in small modular units and can be easily integrated into small-to-medium scale energy systems. Small-scale biomass systems can also be fuelled by local resources, which can reduce the economic difficulties of transporting bulky fuels with low calorific values over large distances. The electricity generated can be sold locally or consumed internally, while the heat produced can be utilised within the process.

The gasification plant in case study 3 has the advantage of using an interconnected fluidized bed gasifier, which divides the vessel into two zones. This enhances the solid-gas mixing and eliminates biomass segregation at the bed surface, which is one of the main drawbacks in most biomass fluidized bed application. Particle circulation between the zones in the IFB gasifier also aids in reducing elutriation of fine carbon particles and thus minimising the solid load to the cyclone. This in turn reduces the amount of residues to be captured, treated or disposed of.

I believe that the next stage in the development of this project should be focused on the optimisation of the energy recovery process. This is because the existing overall system efficiency is only 11.1% and therefore, the potential advantages of the system are not realised. The gasification process has a thermal conversion efficiency of less than 60% and utilises the syngas in a gas engine, which can achieve higher efficiencies despite the scale limitation and low calorific value of the syngas. Therefore, the overall system performance can be doubled if the gasifier is operated with a thermal efficiency of 80% and the gas engine at a 25% efficiency, which are technically feasible.

Case study 4 reports the process design of a biomass gasification plant coupled with fuel cells for decentralised heat and power generation using hydrogen. Hydrogen is an energy-efficient, low-polluting fuel and is considered as one of the most promising energy carriers for the future. In fact, biofuels in general have recaptured the interests of governments and industry in recent years and it is seen as a long-term solution to reduce our carbon emissions and improve the security of energy supplies. National and regional legislative drivers, such as the EU Biofuels Directive, which sets a target for biofuels of 5.75% of market share for transport use by 2010, are also fuelling the booming biofuels market.

Technology-wise, fluidized bed gasification is the most common process for the production of syngas from biomass and coupling the process with fuel cells offers a high efficient system for heat and power generation. In addition, since the 'bio-syngas' resembles other syngas produced from the conventional fossil fuels, the cleaning and conditioning of these gases are available. Once cleaned and conditioned, the bio-syngas can be used for the synthesis of 'second-generation' biofuels, such as Fischer Tropsch products, methanol and hydrogen.

Fuel cells running on hydrogen have many advantages over traditional energy conversion technologies. These advantages include higher efficiencies and lower emissions. In this case study, the reported gasification plant using fuel cells was calculated to have a 30% overall system efficiency, which is higher than all other technologies examined in this chapter. Therefore, fuel cells have the potential as a low carbon energy technology, justifying its reputation as an 'enabler' for the hydrogen economy. However, they are very expensive when compared to other energy technologies and thus economically unattractive (see Table 2.1 in chapter 2).

Cost estimates for fuel cells by the UK's Performance and Innovation Unit suggested a range from £1,600 to £7,500 (€2,300-5,200) and noted that many designs are effectively prototypes, which are inherently expensive (PIU, 2002). Sustainable production and storage of hydrogen, as well as the development of a hydrogen infrastructure, are other key barriers for the development of the technology (Halliday et al., 2005). Nonetheless, improvement in the technology is expected to reduce costs and market penetration can be achieved by identifying and exploiting viable and favourable 'niche' application, such as small-scale CHP.

In case study 5, the design of a 50,000 tpa fluidized bed gasification plant utilising urban waste in the form of RDF was carried out. This was done in order to compare the technical performances of waste combustion and gasification systems using efficient energy technologies. A plant capacity of 50,000 tpa was found to be suitable for the treatment of urban waste from local municipalities, such as the city of Ravenna in Italy or one of the local authorise in London, for example, London Borough of Richmond, which landfills over 55,000 tpa of its urban waste. The plant employs a CCGT unit for the generation of 8.0 MWe of electricity and has an overall system efficiency of 28.8%, which is comparable to large-scale combustion processes. The overall system performance increases by 2% for every 5% increase in the thermal efficiency of the gasification process. Additionally, a 1% increase in the electrical efficiency of the CCGT unit increases the overall system performance by a similar 1%.

Table 3.12 summaries the technical performances of the different thermal treatment processes examined in this chapter. Note here that, for completeness, the performances of medium-scale fluidized bed combustion and gasification systems at 100,000 tpa have also been included (see the shaded area in Table 3.12). The mass and energy balances for the combustion and gasification processes at 50,000 tpa were used for the scale-up.

**Table 3.12 Technical performances of thermal treatment processes**

| | Combustion | | | Gasification | | | |
|---|---|---|---|---|---|---|---|
| Process | Moving-grate (case study 1) | Fluid Bed (case study 2) | Fluid bed | Fluid Bed (case study 3) | Fluid Bed (case study 4) | Fluid Bed (case study 5) | Fluid bed |
| Scale (tpa) | 260,000<br>Large | 50,000<br>Small-medium | 100,000<br>medium | 2,000*<br>Small | 5,100*<br>Small | 50,000<br>Small-medium | 100,000<br>Medium |
| Feed rate (t/h) | 34.48 | 6.00 | 12.00 | 0.28 | 0.73 | 6.00 | 12.00 |
| Fuel | MSW | MSW (RDF) | MSW (RDF) | Clean biomass | Clean biomass | MSW (RDF) | MSW (RDF) |
| Calorific value (MJ/kg) | 12.6 | 16.7 | 16.7 | 18.5 | 17.5 | 16.7 | 16.7 |
| Conversion technology | Steam turbine | Steam turbine | Steam turbine | Gas engine | Fuel Cell | CCGT | CCGT |
| Net power (MWe) | 34.1 | 7.3 | 14.8 | 0.2 | 0.9 | 8.0 | 18.2 |
| Overall system efficiency (%) | 28.3 | 26.1 | 26.6 | 11.1 | 30.0 | 28.8 | 32.6 |

* Based on the plants operating for 7000 hours a year, as original data for annual operation were not available

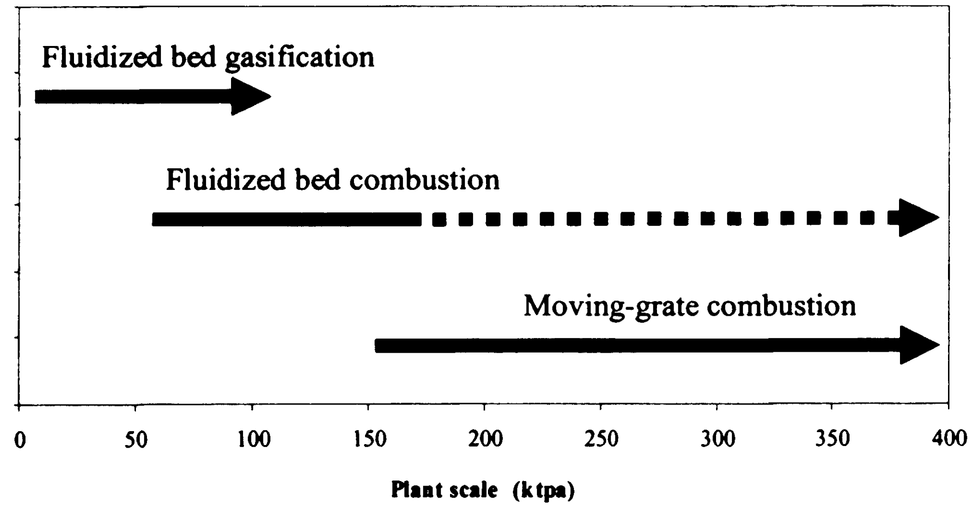


**Figure 3.20 Scales and technologies of thermal treatment processes**

In summary, Figure 3.20 outlines the scale and technologies for thermal treatment processes of waste. Moving-grate combustion systems are favourable at large-scale applications and, if the bottom ash is recycled, they would potentially divert the highest amounts of waste from landfills. Fluidized bed systems are suitable alternative technologies to moving-grate and capable of treating waste at a wider range of capacities.

The technology become favourable when integrated with reuse and recycling initiatives because of its compatibility with high levels of source separation. At small-to-medium scales, fluidized bed gasification systems are favourable because they can be built easily and economically. They also can utilise different energy conversion technologies with higher efficiencies.

Therefore, there is no 'one' solution for the thermal treatment of waste, as both scales and technologies have significant implications on the decision making of waste treatment options and policies. Suggestions for further developments of this work are presented later in Chapter 6, where ideas for future work are reported.

In addition, economic comparison between treatment options is an important part in the decision making process. However, it must be noted that direct comparison between different systems can be misleading as they are project-specific and costs are sensitive to local and regional factors, such as financial incentives and landfill costs. Hence, there is a need for a consistent approach to examine the technical and economic performances of these treatment options. The following chapter will address this issue and report the findings in a UK context.

# 4 Techno-economic analysis of EfW fluidized bed processes

## Summary

This chapter reports the technical and economic performances of small-to-medium scale EfW fluidized bed combustion and gasification processes, with the implications of different scales and technologies on costs and efficiencies. Two different scale scenarios of 50,000 tpa (tonne per annum) and 100,000 tpa plant capacities are considered for the generation of electricity-only, using a steam turbine for the combustion process and gas engine & combined cycle gas turbine (CCGT) for the gasification process. Mass and energy balances of the processes are performed and the economic viability and cost effectiveness of the different waste treatment options are assessed using a discounted cash flow (DCF) analysis. The comparisons of the different treatment options are also made by estimating their levelised costs and gate fees. Additionally, a sensitivity analysis is performed to take account of uncertainties in the model input parameters. The techno-economic analysis of moving-grate combustion, which are the traditional route for EfW in the UK, is also reported for comparison to fluidized bed combustion and gasification systems. In the next chapter, this analysis is extended for the generation of combined heat and power.

*Parts of this chapter have been submitted for publications in the following journals:*

Yassin, L., Lettieri, P., Simons, S.J.R., Germanà, A. (2008). Techno-Economic Performance of Energy-from-Waste Fluidized Bed Combustion & Gasification Processes. *Journal of Chemical Engineering.*

Yassin, L., Lettieri, P., Simons, S.J.R., Castillo-Castillo, A., Leach, M., Ryu, C., Swithenbank, J., Sharifi, V.N. (2008). From Traditional Incineration to More Advanced Fluidized Bed Gasification Technology for the Thermal Processing of Waste. *Waste and Resource Management.*

Castillo-Castillo, A., Leach, M., Yassin, L., Lettieri, P., Simons, S.J.R., Ryu, C., Swithenbank, J., Sherifi, V.N. (2008). The Potential Role of Different Scales of Incineration and Fluidised Bed Gasification Technologies in Future Waste Management Strategies. *Waste and Resource Management.*

# 4.1 Methodology

## 4.1.1 Setting the scenarios

The aim of this study is to evaluate the technical and economic performances of fluidized bed combustion and gasification systems and report the implications of different scales and technologies on costs and efficiencies. Two different scale scenarios of 50,000 tpa and 100,000 tpa were considered for the generation of electricity-only from urban waste, corresponding to small and medium-scale plant capacities, respectively. For each scale scenario, the different waste treatment options evaluated are as follows:

1. Fluidized bed gasification coupled with:
    - *Gas engine, (FBG+GE);*
    - *Combined cycle gas turbine, (FBG+CCGT);*

2. Fluidized bed combustion coupled with *steam turbine, (FBC+ST).*

Figure 4.1 illustrates the two thermal treatment processes studied for this evaluation. The steam generated from the combustion process is fed into an energy conversion system, which generates electricity using a steam turbine. Any contaminants in the flue gas, such as particulates and acidic pollutants, are removed by the flue gas treatment system before the gas is released to the atmosphere. For the gasification process, the syngas is cleaned from any contaminants before it is utilised by the energy conversion systems in either a gas engine or CCGT unit for electricity generation.

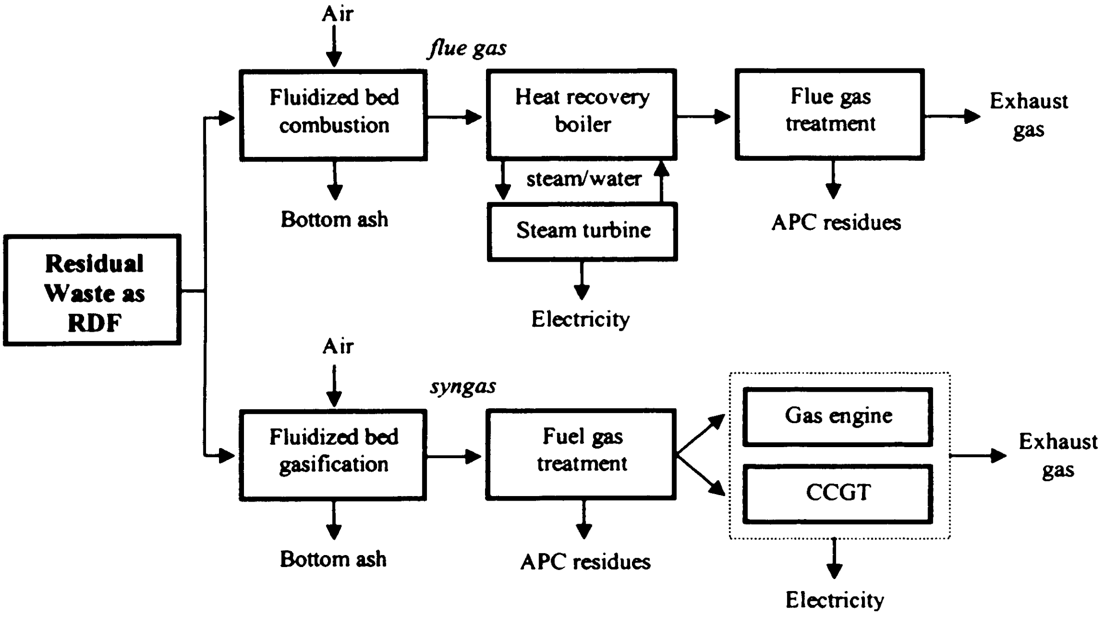


**Figure 4.1 Energy recovery from residual waste- Two process options**

Fluidized bed technologies require the pre-treatment of waste, thus they are suitable for treating homogenous waste, such as refuse-derived fuels (RDF) or solid recovered fuel (SRF). The RDF is usually produced from mechanical or mechanical biological treatment (MBT) processes, which also produce recyclables, compost-like materials and biogas.

The mechanical production of RDF are based on two different approaches: (i) production of wet floc-type RDF by shredding, screening, magnetic & eddy current separation and possibly air classification; and (ii) production of dry, high-density RDF by intensive processing of MSW followed by drying and compaction into a pellet (AiIE, 2003, Hernandez-Atonal et al., 2007).

RDF production from MBT processes involves size reduction and homogenisation, biological drying and material separation & recovery. Therefore, fluidized bed systems are compatible with high levels of source segregation and promote recycling and composting initiatives. The RDF in this analysis is assumed to be supplied by a third party contractor or an MBT process.

In this section, the mass and energy balances for the different waste treatment options are described and form the basis for the input parameters of the economic model. The background assumptions used in developing the rest of the model are presented in the following section, while the results are discussed in section 4.2 and a sensitivity analysis, which takes account of uncertainties in the model input parameters, is performed in section 4.3.

The properties of waste have huge variation depending on many factors, such as waste type and area of collection (rural, urban or commercial), seasonal variations and recycling levels. Other factors include ethnic grouping and type of household properties (Poll, 2004). Although information on the physical composition of waste is available, it is nevertheless difficult to derive sufficient information from these sources, as they lack the chemical and elemental compositions (Burnley, 2007).

Therefore, in this study, the waste characteristics used for developing the mass and energy balances for the combustion and gasification processes have been provided by Germanà & Partners Consulting Engineers. These data are summarised in Table 4.1 and report the proximate and ultimate analysis of the RDF used.

**Table 4.1 Proximate and Ultimate analysis of the RDF**

| **Proximate analysis (wt %)** | | | | | **Ultimate analysis (wt %)** | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| *Fixed carbon (%)* | *Moisture (%)* | *Volatiles (%)* | *Inerts (%)* | *LHV (MJ/kg)* | *C (%)* | *H (%)* | *O (%)* | *N (%)* | *S (%)* | *Cl (%)* |
| 10.7 | 15.8 | 53.5 | 20.0 | 16.7 | 69.6 | 5.8 | 22.3 | 0.9 | 0.6 | 0.9 |

Performing the mass and energy balances enable the comparison of the technical performances of the different waste treatment options by determining their overall system efficiencies. System efficiencies are defined as the ratio of the net generated electricity to the energy input to the system, as shown in Equation 4.1. However, to obtain these values, the combustion and gasification efficiencies, as well as the performances of the different prime moves, i.e. steam turbines, gas engines and CCGT units, need to be obtained.

$$\text{System efficiency } [\%] = \frac{\text{Net generated electricity } [MW]}{\text{Energy input to system } [MW]} * 100 \tag{4.1}$$

Gasifiers have thermal or cold gas efficiencies between 70-93%, with most operating at between 75% and 88% (C-Tech Innovation, 2003, Environment Agency, 2002, Rensfelt & Östman, 1996). Equation 4.2 describes the cold gas efficiency of a gasifier, which can be defined as the ratio of the energy content of the syngas to the energy content of the waste feedstock (Higman & van de Burgt, 2003). A cold gas efficiency of 70% was used in this analysis to reflect the unavailability of proven, commercial plants in the UK for MSW treatment by gasification. This is discussed further in section 4.3 as part of the sensitivity analysis, where the effects of changes in the cold gas efficiency on both the levelised costs of waste treatment and gate fees are evaluated. On the other hand, a thermal efficiency of 90% is assumed for the combustion processes, which are well-proven and have greater operational reliability than the gasification processes. Both systems are assumed to operate for 329 days a year, which is equivalent to 90% system availability (PFI Scotland, 1998).

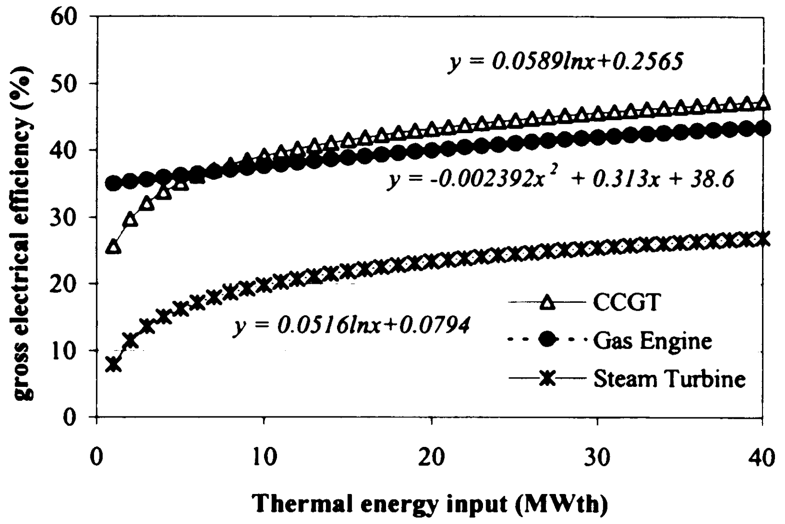


**Figure 4.2 Gross electricity generation efficiencies of the prime movers**

The performances of the prime movers were obtained using literature date published by Bridgwater et al. (2002), which are presented in Figure 4.2 for a range of thermal energy input of 1-40 MWth. Figure 4.2 illustrates the relationship between the thermal energy input to the prime movers and their corresponding gross electrical generation efficiencies. The net generated electricity was calculated by subtracting the internal energy consumption of the combustion and gasification processes from the gross generated electricity obtained using Figure 4.2 for a given thermal energy input. In this analysis, the electrical generation efficiency is defined as the ratio of power output to the energy supplied to the prime mover (see Equation 4.3).

$$\text{Cold gas efficiency } [\%] = \frac{\text{Heating value of product gas } [MW]}{\text{Heating value of feedstock } [MW]} * 100 \qquad (4.2)$$

$$\text{Electrical generation efficiency } [\%] = \frac{\text{Power output } [MW]}{\text{Energy input to prime mover } [MW]} * 100 \qquad (4.3)$$

For the fluidized bed combustion process, an average internal energy consumption or site power use of 1.2 MWe and 1.9 MWe were used for the scale scenarios of 50,000 tpa and 100,000 tpa, respectively. This is comparable with the Ravenna fluidized bed combustion plant reported in section 3.2.1 and the Dundee EfW facility (Thurgood, 1999), which have similar sizes. For the gasification processes, the internal energy consumption was calculated as 11% and 15% of the gross generated electricity by the FBG+GE and FBG+CCGT systems, respectively (Fichtner, 2004). These values are based on similar fluidized bed gasification processes employing gas engines and CCGT units.

### 4.1.2 Developing the model

It is important to note here that it is difficult to make direct cost comparisons between the different waste treatment technologies based on literature data for several reasons. Firstly, there is no 'real' cost data for emerging processes, such as gasification, in the UK. Secondly, there are differences in the accounting practices used by many suppliers (McLanaghan, 2002). Some suppliers in the UK may quote the costs of the gasification and combustion systems and exclude the costs of electricity generation or the residue management costs. Others may simply quote costs that are lower than the actual costs for equivalent plants in Europe, in order to look competitive in the UK market. Thirdly, gasification processes have different configurations and can employ various energy conversion systems, which are at various stages of commercialisation and hence, result in different quoted cost estimates.

In this study, an economic model was developed using a consistent methodology to allow for the comparison between the different process and technology options. The model consists of capital costs, operating costs and projected annual revenues. It uses a basic discounted cash flow analysis (DCF) (Gerrard, 2000, Peters & Timmerhaus, 1991, Sutherland, 2007), which relates the values of costs and revenues that occur over the economic life of the project in terms of present worth, i.e. the amount that a future sum of money is worth today given a specified rate of return. The comparison will also be made by estimating the levelised costs of waste treatment and predicted gate fees for the different waste treatment options. The levelised cost is a useful tool for comparing different technologies as it calculates the cost of producing a unit of output from the proposed systems. The gate fee estimates are typically paid by local authorities to contractors for the disposal and treatment of waste. Usually, the lower the gate fee, the more attractive is the waste treatment option.

Although this analysis compares mature and traditional combustion technologies, which has been 'down the learning curve' with 'unproven' gasification technologies in the UK, it aims to demonstrate the cost effectiveness of these technologies at current market state. Gasification costs will reduce as more plants are built and commercial operations achieved. Since the uptake of these technologies is difficult to predict, it is impractical to use estimates of future costs. Moreover, developers may get pushed away from technologies that fail to meet long term economic claims in early demonstration (Bridgwater, 2002).

The costs and revenues resulting from the economic evaluation are indicative values and can be used to compare the different treatment options since a consistent methodology has been adopted for this comparative analysis. However, such costs and revenues are not actual contract values and will depend on suppliers, plant scale, technology used and type of energy recovery system employed, as well as local area factors.

#### 4.1.2.1 Capital costs

The available data in the literature for the capital costs of advanced thermal treatment processes, such as gasification and pyrolysis, vary significantly from one plant to another (Eunomia, 2001, Wheeler & de Rome, 2002). McLanaghan (2002) reported capital costs of £8-93m for 32-360 ktpa gasification and pyrolysis plants in the UK, while in Defra's Waste Strategy for England (2007b), costs of £22-67m were estimated for plant scales of 30-150 ktpa. In Europe, capital costs range from £9-59m for 20-200 ktpa plants. The capital costs for combustion systems in the UK are summarised in Table 4.2 for plant scales ranging from 50-400 ktpa. Other cost estimates of £65-149m were also reported by Defra for plant scales of 100-400 ktpa (Defra, 2007b). These costs are usually for mass-burn incineration systems, which are largely moving-grate incinerators (refer to section 2.2.2).

Moving-grate systems are commercial and well-established worldwide and as a result, there is less uncertainty associated with their costs, compared to gasification systems. However, the public perception of combustion is less than favourable and this has a significant implication on the project development cost, which can be unexpectedly high due to the high planning risks associated with the process. The planning approval for the Belvedere EfW combustion plant in the London borough of Bexley in 2006, for example, came more than 15 years after the first planning application was submitted. The Riverside facility still faces a "massive task to win over the local community" and has survived an unsuccessful bid by the Mayor of London and Bexley council in early 2007 to overturn the planning approval (letsrecycle.com, 2007b). Therefore, capital costs of combustion systems will vary according to local circumstances and scales.

**Table 4.2 Capital costs of EfW incineration plants**

| Plant Scale (ktpa) | Capital Cost (£m) |
|---|---|
| 50 | 12.5-19 |
| 100 | 25-36 |
| 150 | 38-45 |
| 200 | 73-100 |
| 400 | 40-58 |

Source: McLanaghan (2002)

In this study, the capital cost of a Novera Energy-type facility (see section 2.2.3.2) has been adopted for the cost of the gasification system, since the facility uses a similar technology and plant configuration to that considered for this evaluation (AiIE, 2003, Defra, 2005b). The costs of a gas engine and CCGT unit were then added to obtain the overall system costs (EDUCOGEN, 2001). For the combustion process, the capital cost of the Dundee fluidized bed EfW facility has been adopted (PFI Scotland, 1998). All cost data were updated and reported in ($£_{2006}$), using appropriate indices from the Office for National Statistics (ONS). Where the cost data were unavailable, Equation 4.4 was used, which gives the general relationship between cost and scale.

$$\frac{Cost_1}{Cost_2} = \left(\frac{Scale_1}{Scale_2}\right)^n \qquad (4.4)$$

where $Cost_1$ is cost of the proposed plant in (£), which is at $Scale_1$ in (ktpa); $Cost_2$ is cost of reference plant in (£), which is at $Scale_2$ in (ktpa); and $n$ is the scale exponent. The scale exponent is derived from historical data for similar plants and is usually in the range of 0.6 to 0.8 (Gerrard, 2000, Peters & Timmerhaus, 1991).

### 4.1.2.2 Operating costs

The operating costs of combustion processes range from £35/t to £55/t for plant capacities of 50-400 ktpa, while operating costs of £20/t to £55/t were given for gasification and pyrolysis processes with plant capacities of 32-360 ktpa (McLanaghan, 2002). In this study, the operating costs of the different waste treatment options have been divided into maintenance and consumable costs, labour, ash disposal, running costs of the energy conversion systems and plant overheads. The different operating costs involved are described as follows:

- *Maintenance & consumables* – £10.2/t of input waste was used for the combustion process (Thurgood, 1999), while a maintenance & consumable cost of £20.0/t of input waste was used for the gasification processes (AiIE, 2003).
- *Labour* – An average salary of £31,000 was assumed, with the number of staff being process and system capacity dependent. For the combustion process, 15 & 24 staff was assumed to run and maintain the 50 ktpa and 100 ktpa plants in two daily shifts, respectively, whereas 15 & 23 staff was assumed for the gasification processes (Thurgood, 1999).
- *Ash disposal* – 20% of the input waste is ash, as reported in Table 4.1. One-third of the ash is generated as bottom ash and the other two-third is APC residues. The bottom ash was assumed to be recycled, while the APC residues including fly ash were sent to a hazardous landfill. The costs of landfill including transport and landfill tax are shown in Table 4.3 (Jacobs, 2005). The landfill tax was increased by £8 per year until it reached £48/t and then kept at that rate for the duration of the project life-time (Defra, 2007b).

- *Energy conversion systems* – The operating costs of the gas engine, CCGT and steam turbine are reported in Table 4.4 (EDUCOGEN, 2001).
- *Plant overheads* – This was assumed at 2% of the capital cost (Bridgwater, 2002).

**Table 4.3 Estimate landfill costs**

| | **Landfill type** | |
|---|---|---|
| **Cost (£/t)** | **Non-hazardous landfill** | **Hazardous landfill** |
| Landfill cost incl. transport | 24 | 80 |
| Landfill tax (rate for 2007/08) | 24 | 24 |
| Total cost | 48 | 104 |

**Table 4.4 Operating costs of energy conversion systems**

| **Energy conversion system** | **Cost range (£/MWhe)** | **Average used (£/MWhe)** |
|---|---|---|
| Gas engine | 4.1-6.6 | 5.4 (0.5 p/kWhe) |
| Combined cycle gas turbine | 3.3-3.9 | 3.6 (0.4 p/kWhe) |
| Steam turbine | 1.1-1.6 | 1.4 (0.1 p/kWhe) |

### 4.1.2.3 Projected revenues

Projected revenues from the different waste treatment options depend on gate fees, sales of electricity, Renewable Obligation Certificates (ROCs), Levy Exemption Certificates (LECs), Packaging Recovery Notes (PRNs) and sales of secondary aggregates. The different revenues considered are described as follows:

- *Gate fees* – This is the amounts paid by local authorities for the treatment and disposal of the waste. Gate fees are site, process and scale specific (see section 4.1.2.4 for further detail).
- *Sales of electricity* – An industry standard base electricity price of 2.50 p/kWh was assumed (Jacobs, 2005, Enviros, 2005).
- *Renewable Obligation Certificates (ROCs)* – A conservative value of 3.43 p/kWh was used, which is the ROCs buyout price for the 2007/2008 period (Ofgem, 2007a). Sixty

eight percent of the waste is regarded as biodegradable, which is then eligible for ROCs (Defra, 2006b).

- *Levy Exemption Certificates (LECs)* – This represents the value for being exempt from the climate change levy on electricity. The current rate for the 2007/2008 period is 0.44 p/kWh (Ofgem, 2007b).
- *Packaging Recovery Notes (PRNs)* – These are part of the UK producer responsibility requirement introduced to meet the EU Packaging and Packaging Waste Directive (94/62). The current market rate for the PRNs is £2/t and this is issued for 19% of the total weight of the waste treated (letsrecycle.com, 2007c, Environment Agency, 2007c).
- *Sales of secondary aggregates* – The price value for bottom ash as secondary aggregates range from £7/t to £10/t according to The Waste & Resources Action Programme (2006). A value of £7/t was used in this study.

#### 4.1.2.4 Gate fee calculations

The gate fee is levied on each tonne of MSW taken in for thermal treatment in order to offset the total operating costs of the facility. It also takes into account the capital costs of the facility and revenues generated. The gate fees for MSW plants in the UK using gasification and pyrolysis processes vary between £25/t to £100/t, while gate fees of £36/t to £55/t have been reported for new large-scale EfW combustion (McLanaghan, 2002, Juniper, 2003, House of Commons, 2007).

In this study, the gate fee was calculated using the DCF analysis to balance the net present values of costs and revenues, over the plant life-time of 30 years, and includes an operator profit of 20% (see Equation 4.5). The impact of ROCs on the gate fee for the gasification systems was also evaluated.

$$Gate\ fee = \sum_{n=1}^{30} \left[ PV(costs) - PV(income) \right] \quad (4.5)$$

where *PV* is present value and *n* is the plant life-time (see Appendix A.2 for further details)

### 4.1.2.5 Levelised cost of waste treatment calculations

Another way to perform comparisons between different technologies with different capital investment, operation and power output, is to calculate their levelised costs. This is the accepted method for the economic comparison of different power generation plants. It quantifies the unitary cost of electricity produced or waste treated during the plant life-time and is reported in p/kWh or £/t of input waste. The levelised cost was calculated as the ratio of the total plant life-time expenses against total expected outputs, expressed in terms of present worth (NEA & IEA, 2005).

In the following section, the results of the technical and economic evaluation of the different process and technology options are presented. A discount rate of 6% was used and all costs and revenues were assumed to be constant. Standardised financial tools, such as the net present value (NPV) and internal rate of return (IRR), were employed to assess the profitability of the different options.

An option is economically attractive if it has the highest IRR and the NPV is greater than zero. The NPV refers to the difference between the present values of all costs and associated revenues. This is shown in Equation 4.6, where $i$ is the discount rate, $CF_n$ is the annual cash flow (revenues-operating costs) at the *n*th year and *TPC* is the total plant cost. The IRR was calculated as the discount rate that makes the NPV equal to zero (Sutherland, 2007).

$$NPV = \sum_{n=1}^{30} \frac{CF_n}{(1+i)^n} - TPC \tag{4.6}$$

# 4.2 Results and Discussion

The results of the techno-economic analysis of EfW fluidized bed combustion and gasification systems are presented in this section. The analysis is performed for the generation of electricity-only from urban waste at two different scale scenarios of 50 ktpa and 100 ktpa. For the technical analysis, the performances different waste treatment options are compared by determining their overall system efficiencies. The capital and operating expenditures, as well as the projected revenues generated from the sales of recovered energy and materials are reported for the economic comparison. A sample calculation for the techno-economic analysis of a 50 ktpa FBG+CCGT is shown Appendix A.2.

## 4.2.1 Technical performance

The net electricity generated by the different treatment systems and their overall system efficiencies are reported in Table 4.7 & 4.6 for the two plant scales of 50 ktpa and 100 ktpa, respectively. The results demonstrate that the ability of gasification processes to employ more efficient energy conversion systems, such as gas engines and CCGT, enables them to have greater electrical generation efficiencies and, as a result, they can have better overall system performances than combustion processes, which use steam turbines. Fluidized bed gasification coupled with CCGT (FBG+CCGT), in particular, offers the most energy efficient treatment option, with overall system efficiencies of 26% and 28% for both scale scenarios of 50 ktpa and 100 ktpa, respectively. Fluidized bed gasification systems using gas engine (FBG+GE) have overall efficiencies of 24% and 26%, while efficiencies of 18% and 22% are reported for the combustion systems (FBC+ST).

**Table 4.5 Technical performances of treatment options at 50 ktpa scale scenario**

| | Waste treatment options | | |
|---|---|---|---|
| | **FBG+GE** | **FBG+CCGT** | **FBC+ST** |
| Thermal energy of waste | 29.4 (MWth) | | |
| Mass flow rate | 6.3 (t/h) | | |
| Gross electrical generation efficiency of prime movers | 38.4 (%) | 43.5 (%) | 24.9 (%) |
| Gross generated electricity | 7.9 (MWe) | 9.0 (MWe) | 6.6 (MWe) |
| *Site power use* | 0.9 (MWe) | 1.3 (MWe) | 1.2 (MWe) |
| *Net generated electricity* | 7.0 (MWe)<br>55,500 (MWhe) | 7.6 (MWe)<br>60,000 (MWhe) | 5.4 (MWe)<br>42,400 (MWhe) |
| Overall system efficiency | 23.9 (%) | 25.9 (%) | 18.3 (%) |

**Table 4.6 Technical performances of treatment options at 100 ktpa scale scenario**

| | Waste treatment options | | |
|---|---|---|---|
| | **FBG+GE** | **FBG+CCGT** | **FBC+ST** |
| Thermal energy of waste | 58.8 (MWth) | | |
| Mass flow rate | 12.7 (t/h) | | |
| Gross electrical generation efficiency of prime movers | 41.7 (%) | 47.6 (%) | 28.4 (%) |
| Gross generated electricity | 17.2 (MWe) | 19.6 (MWe) | 15.1 (MWe) |
| *Site power use* | 1.9 (MWe) | 2.9 (MWe) | 1.9 (MWe) |
| *Net generated electricity* | 15.3 (MWe)<br>120,600 (MWhe) | 16.7 (MWe)<br>131,200 (MWhe) | 13.2 (MWe)<br>103,700 (MWhe) |
| Overall system efficiency | 26.0 (%) | 28.3 (%) | 22.4 (%) |

The results also show the greater sensitivity of the technical performances of FBC+ST to scale. The combustion system efficiencies increased by over 22% with the doubling of the plant capacity, compared to an increase of 8-9% for the gasification systems. This highlights the nature of the combustion processes, which are centralised operations and technically more efficient at larger scales.

## 4.2.2 Economic performance

The economic performances of the fluidized bed combustion and gasification systems are summarised in Table 4.7 & 4.8 for the two plant scales of 50 ktpa and 100 ktpa. The capital and operating costs were reported for each system and the cost effectiveness of these waste treatment options were compared using NPV and IRR, as well as predicted gate fees and levelised costs of waste treatment.

**Table 4.7 Economic performances of treatment options at 50 ktpa scale scenario**

| | **Waste treatment options** | | |
|---|---|---|---|
| | **FBG+GE** | **FBG+CCGT** | **FBC+ST** |
| Capital costs | 16.0 (£m)<br>321 (£/t) | 16.8 (£m)<br>336 (£/t) | 29.7 (£m)<br>594 (£/t) |
| Operating costs | 2.8 (£m)<br>57 (£/t) | 2.8 (£m)<br>55 (£/t) | 2.3 (£m)<br>47 (£/t) |
| NPV @ 6% discount rate | 11.4 (£m)<br>228 (£/t) | 11.4 (£m)<br>227 (£/t) | 12.7 (£m)<br>255 (£/t) |
| IRR | 12.1 (%) | 11.8 (%) | 9.8 (%) |
| Gate fees | | | |
| *without ROCs* | 67 (£/t) | 65 (£/t) | 87 (£/t) |
| *with ROCs* | 42 (£/t) | 37 (£/t) | 87 (£/t) |
| Levelised costs | | | |
| *in terms of electricity generated* | 7.46 (p/kWh) | 6.87 (p/kWh) | 10.91 (p/kWh) |
| *in terms of waste treated* | 83 (£/t) | 82 (£/t) | 93 (£/t) |

**Table 4.8 Economic performances of treatment options at 100 ktpa scale scenario**

| | **Waste treatment options** | | |
|---|---|---|---|
| | **FBG+GE** | **FBG+CCGT** | **FBC+ST** |
| Capital cost | 27.0 (£m)<br>270 (£/t) | 27.3 (£m)<br>273 (£/t) | 48.1 (£m)<br>481 (£/t) |
| Operating cost | 5.4 (£m)<br>54 (£/t) | 5.2 (£m)<br>52 (£/t) | 4.3 (£m)<br>43 (£/t) |
| NPV @ 6% discount rate | 21.1 (£m)<br>211 (£/t) | 20.6 (£m)<br>206 (£/t) | 22.1 (£m)<br>221 (£/t) |
| IRR | 12.7 (%) | 12.5 (%) | 10.0 (%) |
| Gate fees | | | |
| *without ROCs* | 57 (£/t) | 52 (£/t) | 67 (£/t) |
| *with ROCs* | 29 (£/t) | 22 (£/t) | 67 (£/t) |
| Levelised costs | | | |
| *in terms of electricity generated* | 6.35 (p/kWh) | 5.71 (p/kWh) | 7.76 (p/kWh) |
| *in terms of waste treated* | 77 (£/t) | 75 (£/t) | 80 (£/t) |

The results show that gasification systems represent the cheapest option, with capital costs ranging from £16-27 million. However, FBG+CCGT systems have higher costs than FBG+GE systems, reflecting the higher capital investment for the more efficient CCGT system configuration. On the other hand, capital costs of £30-48 million are reported for the combustion systems.

Therefore, conventional combustion systems, in this case fluidized beds, are not as competitive at small-to-medium scales as the more compact gasification systems, which can be built economically as modular units at smaller scales. This is mainly because combustion systems need to have large boilers to recover heat and gas cleaning systems to clean the large volumes of flue gas generated.

However, the calculated operating costs of the different treatment options show that combustion systems have the lowest costs, with reported annual costs of £47/t and £43/t for the plant capacities of 50 ktpa and 100 ktpa. These costs also illustrate the greater sensitivity of the combustion systems to economies of scale, as doubling the plant capacity reduced the operating costs by 8%. This is compared to an average reduction of 5% for the FBG+GE and FBG+CCGT systems, as their operating costs fall to £54/t and £52/t, respectively. FBG+GE systems have higher operating costs than FBG+CCGT primarily because of the higher operating and maintenance costs of the gas engines, as reported in Table 4.4. This is also shown in Figure 4.3, which breaks down the operating costs for the different waste treatment options.

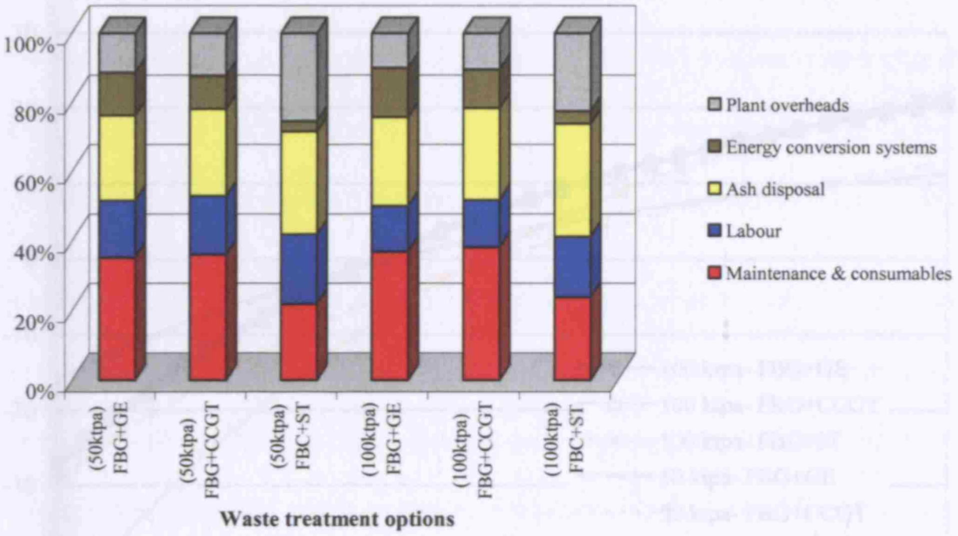


**Figure 4.3 Breakdown of operating costs for the different waste treatment options**

Maintenance & consumable costs make up the largest portion of the operating costs for the gasification systems. This is followed by ash disposal, labour, running costs of the energy conversion systems and plant overheads. For the combustion systems, ash disposal costs make up the largest portion of the operating costs, followed by maintenance & consumable costs, plant overheads, labour and running costs of the steam turbines.

The NPV of the different waste treatment options are positive, as shown in Table 4.7 & 4.8, thus indicating that they are all economically viable at both plant scale scenarios. However, although combustion systems seem to be the most attractive options, with higher NPV of £221/t and £255/t, compared to £206/t to £228/t for the gasification systems, the latter yields a better rate of return on investment. The average IRR for gasification is 12%, whilst it is 10% for combustion.

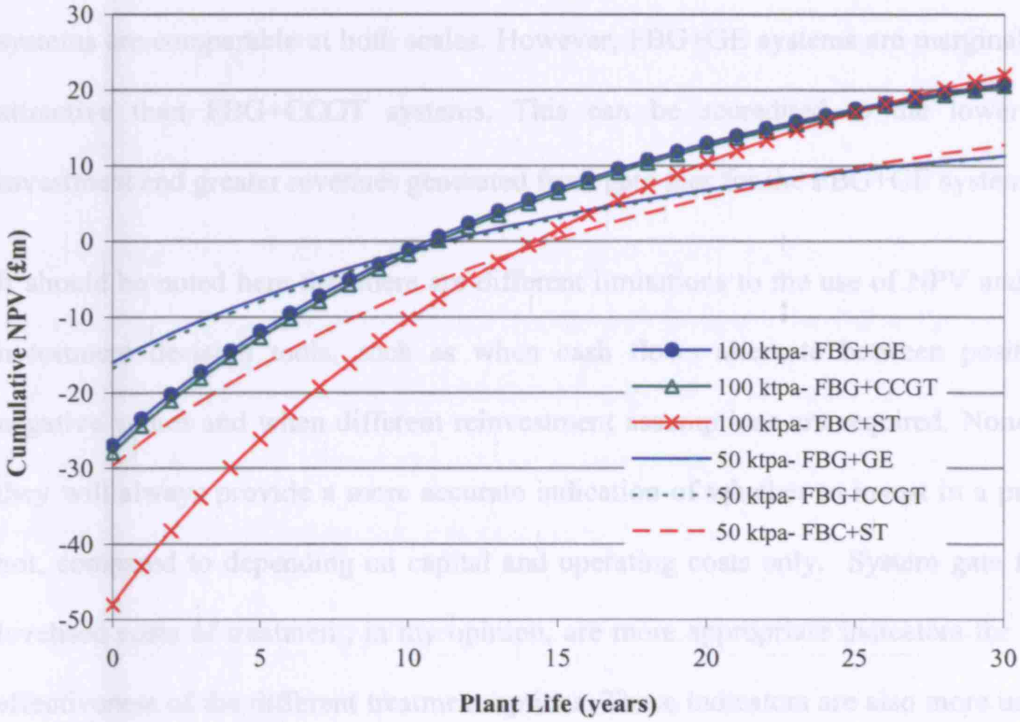


**Figure 4.4 Cumulative NPV for the different treatment options**

Figure 4.4 illustrates the cumulative NPV of the different treatment options for both scale scenarios. It shows that the combustion systems, despite their higher investment costs, achieve higher NPV than gasification. This can be largely attributed to the lower operation costs of combustion and greater revenues generated from gate fees. However, it is clear that the discounted payback periods for the combustion systems, i.e. the times required to recover the initial investment from the discounted future cash inflows, are on average 4 years longer than the gasification systems, which have average discounted payback periods of 11 years.

Figure 4.4 also shows that the economic performances of the different gasification systems are comparable at both scales. However, FBG+GE systems are marginally more attractive than FBG+CCGT systems. This can be accredited to the lower capital investment and greater revenues generated from gate fees for the FBG+GE systems.

It should be noted here that there are different limitations to the use of NPV and IRR as investment decision tools, such as when cash flows alternate between positive and negative values and when different reinvestment assumptions are required. Nonetheless, they will always provide a more accurate indication of whether to invest in a project or not, compared to depending on capital and operating costs only. System gate fees and levelised costs of treatment, in my opinion, are more appropriate indicators for the cost effectiveness of the different treatment options. These indicators are also more useful for the different stakeholders, such as the waste disposal authorities, who are cost-driven and simply would want to know how much the treatment of each tonne of waste will cost.

Therefore, when taking gate fees into account, gasification systems and, in particular, FBG+CCGT become the most attractive treatment option at both scale scenarios. For the 50 ktpa plant scale scenario, FBG+CCGT and FBG+GE have gate fees of £65/t and £67/t, respectively, while FBC+ST becomes the least attractive treatment option with a gate fee of £87/t. As the plant scale increases to 100 ktpa, all treatment options become cheaper and FBC+ST becomes more competitive at this larger scale scenario, with a 23% reduction in the gate fee to £67/t. The gate fee reduces by 15% to £57/t for FBG+GE and by 19% to £52/t for FBG+CCGT.

As explained earlier, in this evaluation, the gate fee was calculated to balance the costs and revenues over the plant life-time of each treatment option using the DCF analysis. Advanced thermal treatment processes including gasification are eligible for ROCs for the electricity generated from the biomass fraction of the waste, while combustion processes are only eligible when combined with good quality CHP. The effects of incorporating revenues from ROCs into the analysis are also reported in Table 4.7 & 4.8. The results show that the gate fees reduce by £26/t to £28/t and £28/t to £31/t for the gasification systems at 50 ktpa and 100 ktpa, thus enabling them to be a more attractive and cheaper treatment option than combustion by 55-62%.

In addition, it should be highlighted that in this study, the RDF was assumed to be supplied by a third party contractor or an MBT operator, who would usually send the RDF to landfills or supply it to cement kilns, if the market is viable. In the latter case, the MBT operator would pay for the RDF to be used in the cement kilns but for a "figure less then that of landfill" (letsrecycle.com, 2007d).

Therefore, utilising the RDF from MBT enables the gasification system to be part of an integrated waste management strategy that accommodates more than one waste treatment option, thus achieving the diversification of waste management approaches in order to meet the recycling, composting and recovery targets. It also enables fluidized bed processes to benefit from the use of homogenous and high calorific value RDF. The collaboration between Novera Energy, Shanks and East London Waste Authority (ELWA) is an example of this practice. Novera's gasification plant in East London will process 90-100 ktpa of RDF supplied from the nearby Shanks MBT facility at Frog Island, with ELWA benefiting through Landfill Allowance Trading Scheme (LATS).

Regarding this, the extra benefits, achieved from the reduction in gate fees because of the eligibility of the gasification systems to ROCs, will offer very competitive 'RDF disposal' costs for the MBT operators and establish a market for the RDF. Currently, the market size for RDF is limited and the gasification systems may face competition from the cement kiln and power generation sectors. Hence, it is essential that gasification system operators secure the supply of RDF, which in turn will aid in their planning application. For example, the successful planning application of Novera's East London plant was subject to the condition that it signed a contract with Shanks for the supply of RDF (LTGDC, 2006).

Another indicator for the cost effectiveness of the different treatment options is to calculate their levelised costs in terms of the annual amounts of electricity generated or quantity of waste treated. Levelised cost is a powerful analytical tool as it gives a constant annual cost value, which would have to be paid in order to repay the capital, operation and maintenance expenses over the life-time of the project. Table 4.7 & 4.8 report the levelised costs for the different treatment options in terms of p/kWhe and £/t.

The results show that the gasification systems are the least cost options for investment, with levelised costs in terms of annual electricity generated of 7.5 p/kWh for FBG+GE and 6.9 p/kWh for FBG+CCGT at the 50 ktpa plant scale capacity. FBC+ST is the highest cost option with level cost of 10.9 p/kWe. Similar trends to those reported for the gate fees are also observed here as the plant scale capacity increases to 100 ktpa. The unit costs of all treatment options become cheaper and the combustion system becomes more competitive at this larger scale scenario, with a 29% reduction in the levelised cost to 7.8 p/kWe. For the gasification systems, the levelised cost reduces instead by 15% for

FBG+GE to 6.3 p/kWe and by 17% to 5.7 p/kWe for FBG+CCGT, which is still the cheapest treatment option at both scales.

In summary, the technical and economic comparison of the different waste treatment options is presented in Table 4.9 for the plant scale scenarios of 50 ktpa and 100 ktpa.

**Table 4.9 Techno-economic performances of combustion & gasification systems**

| | Fluidized bed process type | |
|---|---|---|
| | **Gasification** | **Incineration** |
| **Technical performance** | | |
| Thermal energy of waste | 29-59 (MWth) | 29-59 (MWth) |
| Mass flow rate | 6-13 (t/h) | 6-13 (t/h) |
| Gross electrical conversion efficiency | 38-48 (%) | 25-28 (%) |
| Net generated electricity | 7-17 (MWe) | 5-13 (MWe) |
| Overall system efficiency | 24-28 (%) | 18-22 (%) |
| **Economic performance** | | |
| Capital costs | 270-336 (£/t) | 481-594 (£/t) |
| Operating costs | 52-57 (£/t) | 43-47 (£/t) |
| NPV @ 6% discount rate | 206-228 (£/t) | 221-255 (£/t) |
| IRR | 11.8-12.7 (%) | 9.8-10.0 (%) |
| Gate fees | | |
| *without ROCs* | 52-67 (£/t) | 87-67 (£/t) |
| *with ROCs* | 22-42 (£/t) | - |
| Levelised costs | | |
| *in terms of electricity generated* | 5-7 (p/kWe) | 7-11 (p/kWe) |
| *in terms of waste treated* | 75-83 (£/t) | 80-93 (£/t) |

## 4.3 Sensitivity analysis

In this section, the effects of changing model input parameters on the economic performances of the different waste treatment options are evaluated. The sensitivity analysis has been carried out on all waste treatment options, as each input parameter or system variable can affect the overall system performances to a different degree. Seventeen different system variables have been chosen for the sensitivity analysis and the effects of a ±10% change in these variables on the levelised costs and gate fees have been examined. In addition, variations in discount rates, as well as the performances of traditional moving-grate combustion plants at larger scales, were also assessed.

### 4.3.1 Effects of changes in model input parameters

The sensitivity analysis is a useful tool in evaluating the model structure and modelling assumptions by taking into account the uncertainties in the model input parameters. This can then direct us to where the impacts of the uncertainties are important, thus identifying the most influential parameters and testing the robustness of the assumptions made. The results of the sensitivity analysis are presented in Table 4.10 & 4.11, where the sensitivity of the model output, i.e. levelised cost or gate fee, to a parameter change is shown as the percentage difference of the model output with respect to its original value.

In Table 4.10, the sensitivity analysis shows that the calorific value of the waste, electricity generation efficiencies of the prime movers and gasifier efficiency have the greatest impact on the levelised cost. In addition, the gate fee is also shown to be mainly affected by the operating costs, ROCs and biomass fraction of the waste, as illustrated in Table 4.11. A graphical representation of the most sensitive system variables affecting the levelised cost and gate fee for a 100 ktpa FBG+CCGT scenario is shown as an example in Figure 4.5. The most influential model input parameters are further discussed in the following sections.

**Table 4.10 Effects of changes on levelised costs**

| Plant scale scenario | | 50 ktpa | | | 100 ktpa | | |
|---|---|---|---|---|---|---|---|
| Waste treatment options | | FBG+GE | FBG+CCGT | FBC+ST | FBG+GE | FBG+CCGT | FBC+ST |
| Base Scenario (p/kWh) | | 7.46 | 6.87 | 10.91 | 6.35 | 5.71 | 7.76 |
| | | | | | | | |
| Model input parameters | | Effects of changes on levelised costs | | | | | |
| Calorific value of waste | +10% | -8.7% | -9.6% | -12.6% | -8.5% | -9.4% | -11.7% |
| | -10% | 12.0% | 11.9% | 17.0% | 11.9% | 11.6% | 15.1% |
| Gasifier Efficiency | +10% | -8.7% | -9.6% | 0.0% | -8.6% | -9.4% | 0.0% |
| | -10% | 11.9% | 11.9% | 0.0% | 11.8% | 11.6% | 0.0% |
| Electricity generation efficiency | +10% | -8.3% | -8.5% | -10.8% | -8.2% | -8.4% | -10.1% |
| | -10% | 10.2% | 10.4% | 13.8% | 10.0% | 10.2% | 12.7% |
| Capital costs | +10% | 3.6% | 3.8% | 5.9% | 3.3% | 3.4% | 5.5% |
| | -10% | -3.6% | -3.8% | -5.9% | -3.3% | -3.4% | -5.5% |
| Discount rate | +10% | 1.8% | 1.9% | 3.0% | 1.6% | 1.7% | 2.8% |
| | -10% | -1.8% | -1.8% | -2.9% | -1.6% | -1.6% | -2.7% |
| Operator profit | +10% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| | -10% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| Plant life-time | +10% | -0.9% | -1.0% | -1.5% | -0.8% | -0.8% | -1.4% |
| | -10% | 1.2% | 1.2% | 1.9% | 1.1% | 1.1% | 1.8% |
| Landfill of BA | +10% | 5.5% | 5.6% | 5.0% | 6.0% | 6.1% | 5.7% |
| Operating costs | +10% | 7.2% | 7.0% | 5.3% | 7.4% | 7.4% | 5.7% |
| | -10% | -7.2% | -7.0% | -5.3% | -7.4% | -7.4% | -5.7% |
| Maintenance & consumable costs | +10% | 2.4% | 2.4% | 1.1% | 2.6% | 2.7% | 1.3% |
| | -10% | -2.4% | -2.4% | -1.1% | -2.6% | -2.7% | -1.3% |
| Labour costs | +10% | 1.1% | 1.1% | 1.0% | 0.9% | 1.0% | 0.9% |
| | -10% | -1.1% | -1.1% | -1.0% | -0.9% | -1.0% | -0.9% |
| Landfill of BA with 10% increase in disposal costs | | 8.1% | 8.1% | 7.3% | 8.8% | 9.0% | 8.4% |
| ROCs | +10% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| | -10% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| Biomass fraction | +10% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| | -10% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| PRNs | +10% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| | -10% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| If PRN is withdrawn | | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| Electricity price | +10% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| | -10% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| LECs | +10% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| | -10% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |

## Table 4.11 Effects of changes on gate fees

| Plant scale scenario | | 50 ktpa | | | 100 ktpa | | |
|---|---|---|---|---|---|---|---|
| Waste treatment options | | FBG+GE | FBG+CCGT | FBC+ST | FBG+GE | FBG+CCGT | FBC+ST |
| Base Scenario (£/t) | | 67.42 | 64.54 | 86.50 | 57.25 | 52.37 | 66.63 |
| | | | | | | | |
| Model input parameters | | Effects of changes on levelised costs | | | | | |
| Calorific value of waste | +10% | -3.5% | -4.8% | -3.8% | -4.5% | -6.4% | -5.6% |
| | -10% | 3.9% | 4.8% | 3.8% | 5.0% | 6.3% | 5.5% |
| Gasifier Efficiency | +10% | -3.5% | -4.8% | 0.0% | -4.5% | -6.4% | 0.0% |
| | -10% | 3.9% | 4.8% | 0.0% | 5.0% | 6.3% | 0.0% |
| Electricity generation efficiency | +10% | -3.3% | -4.2% | -3.2% | -4.3% | -5.7% | -4.7% |
| | -10% | 3.3% | 4.2% | 3.2% | 4.3% | 5.7% | 4.7% |
| Capital costs | +10% | 5.3% | 5.8% | 7.6% | 5.2% | 5.8% | 8.0% |
| | -10% | -5.3% | -5.8% | -7.6% | -5.2% | -5.8% | -8.0% |
| Discount rate | +10% | 2.7% | 2.9% | 3.9% | 2.6% | 2.9% | 4.0% |
| | -10% | -2.6% | -2.8% | -3.8% | -2.6% | -2.8% | -3.9% |
| Operator profit | +10% | 2.5% | 2.6% | 2.1% | 2.7% | 2.9% | 2.4% |
| | -10% | -2.5% | -2.6% | -2.1% | -2.7% | -2.9% | -2.4% |
| Plant life-time | +10% | -1.3% | -1.5% | -1.9% | -1.3% | -1.5% | -2.0% |
| | -10% | 1.7% | 1.9% | 2.5% | 1.7% | 1.9% | 2.6% |
| Landfill of BA | +10% | 8.9% | 9.3% | 6.9% | 10.4% | 11.4% | 9.0% |
| Operating costs | +10% | 10.6% | 10.8% | 6.9% | 11.9% | 12.6% | 8.2% |
| | -10% | -10.6% | -10.8% | -6.9% | -11.9% | -12.6% | -8.2% |
| Maintenance & consumable costs | +10% | 3.6% | 3.7% | 1.4% | 4.2% | 4.6% | 1.8% |
| | -10% | -3.6% | -3.7% | -1.4% | -4.2% | -4.6% | -1.8% |
| Labour costs | +10% | 1.7% | 1.7% | 1.3% | 1.5% | 1.6% | 1.3% |
| | -10% | -1.7% | -1.7% | -1.3% | -1.5% | -1.6% | -1.3% |
| Landfill of BA with 10% increase in disposal costs | | 12.6% | 13.2% | 9.9% | 14.9% | 16.3% | 12.8% |
| ROCs | +10% | -6.2% | -7.7% | 0.0% | -9.7% | -14.1% | 0.0% |
| | -10% | 6.2% | 7.7% | 0.0% | 9.7% | 14.1% | 0.0% |
| Biomass fraction | +10% | -7.0% | -8.6% | 0.0% | -10.9% | -15.9% | 0.0% |
| | -10% | 7.0% | 8.6% | 0.0% | 10.9% | 15.9% | 0.0% |
| PRNs | +10% | -0.1% | -0.1% | 0.0% | -0.1% | -0.1% | -0.1% |
| | -10% | 0.0% | 0.1% | 0.1% | 0.0% | 0.1% | 0.1% |
| | If PRN is withdrawn | 0.6% | 0.6% | 0.4% | 0.7% | 0.7% | 0.6% |
| Electricity price | +10% | -4.1% | -4.6% | -2.5% | -5.3% | -6.3% | -3.9% |
| | -10% | 4.1% | 4.6% | 2.5% | 5.3% | 6.3% | 3.9% |
| LECs | +10% | -0.5% | -0.6% | -0.3% | -0.6% | -0.8% | -0.5% |
| | -10% | 0.5% | 0.6% | 0.3% | 0.6% | 0.8% | 0.5% |

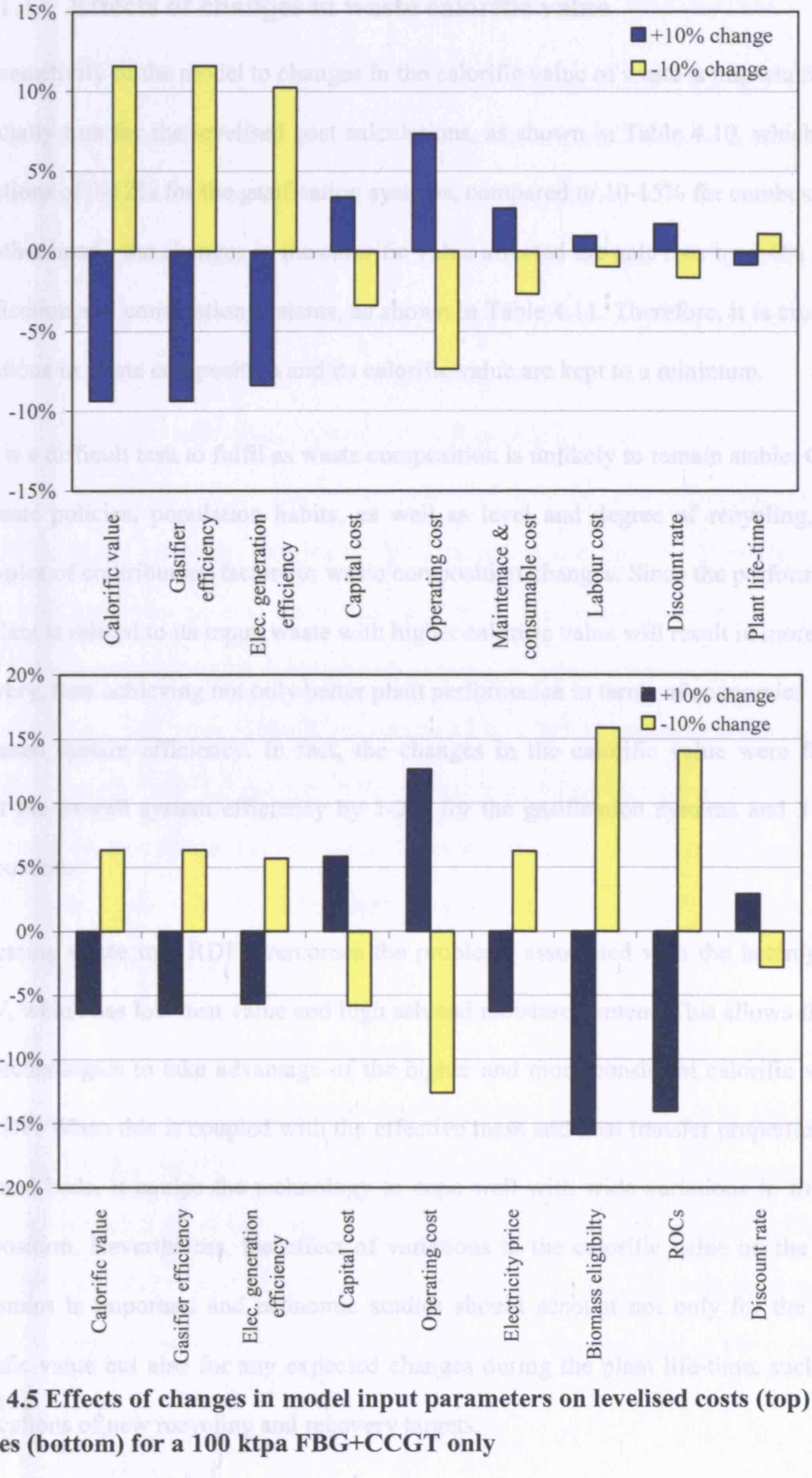


**Figure 4.5 Effects of changes in model input parameters on levelised costs (top) and gate fees (bottom) for a 100 ktpa FBG+CCGT only**

#### 4.3.1.1 Effects of changes in waste calorific value

The sensitivity of the model to changes in the calorific value of waste is important. This is especially true for the levelised cost calculations, as shown in Table 4.10, which reports variations of 9-12% for the gasification systems, compared to 10-15% for combustion. On the other hand, the changes in the calorific value affected the gate fees by 4-6% for both gasification and combustion systems, as shown in Table 4.11. Therefore, it is crucial that variations in waste composition and its calorific value are kept to a minimum.

This is a difficult task to fulfil as waste composition is unlikely to remain stable. Changes in waste policies, population habits, as well as level and degree of recycling, are all examples of contributory factors to waste composition changes. Since the performance of the plant is related to its input, waste with higher calorific value will result in more energy recovery, thus achieving not only better plant performance in terms of economics but also increased system efficiency. In fact, the changes in the calorific value were found to affect the overall system efficiency by 1-2% for the gasification systems and 3-5% for combustion.

Processing waste into RDF overcomes the problems associated with the heterogeneous MSW, which has low heat value and high ash and moisture content. This allows fluidized bed technologies to take advantage of the higher and more consistent calorific value of the RDF. When this is coupled with the effective mass and heat transfer properties of the fluidized beds, it equips the technology to cope well with wide variations in the waste composition. Nevertheless, the effect of variations in the calorific value on the system economics is important and economic studies should account not only for the current calorific value but also for any expected changes during the plant life-time, such as the implications of new recycling and recovery targets.

#### 4.3.1.2 Effects of changes in combustion and gasification thermal efficiency

The cold gas or gasifier efficiency was used as a measure of the transformation of chemical energy in the waste into syngas and directly affects the electrical generation performances of the gasification systems. As stated earlier, a value of 70% has been used in the model to reflect the unavailability of proven, commercial gasification plants in the UK for MSW treatment. This value represents the lower efficiency range for most gasifiers and as the technology matures, it will gain greater operational reliability and improved system efficiency, which in turn will lead to further cost reductions. Therefore, the 70% cold gas efficiency is a reasonable assumption and further improvement in this value will make the process more competitive in the marketplace. It is also worth mentioning here that the first fluidized bed gasification plant by Novera Energy for MSW treatment in the UK, which should be operational by 2008, is expected to achieve a cold gas efficiency of 70-75% (Howson, 2007). Changes in the gasifier efficiency affected the level costs and gate fees at the two scales investigated by 9-12% and 4-6%, respectively, as shown in Table 4.10 & 4.11. This corresponded to an 11-12% variation in the gasification system efficiencies.

Similarly, the combustion thermal efficiency is another important system variable, which is usually overlooked in the techno-economic analysis as it is assumed to be 100%, i.e. no heat losses (see section 3.3). In this study, a combustion efficiency of 90% was assumed to take account of heat losses in the boilers. An increase in this efficiency to 95% gives a 6-7% increase in the overall system performance and vice versa. This also corresponds to a 6-7% increase in the level costs and 2-3% increase in the gate fees of the combustion systems.

#### 4.3.1.3 Effects of changes in electrical generation efficiency

The electrical generation efficiencies of the gas engines, CCGT and steam turbines have great impact on the economic performances of the different waste treatment options. The sensitivity of the levelised costs to these system variables is greater when compared to their impact on the gate fees. For the levelised costs, sensitivities of 8-10% for gasification and 10-14% for combustion were reported. This is compared to sensitivities of 3-6% for the gate fees of both processes.

The electrical generation efficiencies used in this evaluation are reasonable and within the range of most published data (EDUCOGEN, 2001). However, one has to recognise that the applications of gas engines and turbines in EfW processes are not common in the UK at present, as opposed to steam turbines. This is despite the fact that they are widely used for power generating applications using fossil fuels. CCGT units, in particular, achieve the highest thermal-to-electricity efficiency of any commercial power generation technology. They also have the lowest specific investment costs in terms of p/kWe (EDUCOGEN, 2001). However, because of the lack of proven track record for gasification systems in the UK and perceived project implementation risks, the technology is not 'bankable' in current market state.

Therefore, in order to be competitive in the UK market, some technology developers are quoting low indicative costs to gain attention (Juniper, 2003). Others, like Novera Energy, are reconfiguring their processes to incorporate more conventional and proven technologies, such as steam turbines. In this arrangement, instead of using a gas engine or turbine, the syngas gas is combusted in a boiler and the energy is recovered using a steam turbine. This has lower electrical generation efficiencies, as shown in Figure 4.2, and leads to an increase in the plant footprint in order to deal with the high flue gas volumes generated. In fact, the reported overall efficiency of gasification with syngas combustion is between 10-20% (Defra, 2007e), which is comparable, if not lower, with burning the waste directly in traditional moving-grate combustion systems without any pre-treatment (see section 4.3.3 for further details).

The main issues with the use of syngas produced from waste in a gas engine or turbine are the degree of cleanliness of the gas and its calorific heat value. Hence, a 10% provision for greater cleaning of syngas was added to their operating costs. Future advances in the syngas cleanup processes and the use of high calorific value RDF, coupled with further development in the performance and cost of gas engines & turbines, will however render applications in EfW projects increasingly more attractive.

Therefore, these developments are important in helping to bring forward gasification and ATT process technologies to replace fossil fuels for heat and power generation in the medium to long term. However, this will only be fully achieved through supportive policies and incentives, such as ROCs, and through active R&D by major industry players and research institutions.

#### 4.3.1.4 Effects of changes in electricity and ROCs prices

Revenues generated from the sale of electricity and ROCs are essential, particularly for the economic viability of the gasification systems. In this study, conservative values have been used for both parameters to take into account the regular changes in their values, which are linked to the supply and demand in the energy markets.

Although ROCs were sold for an average price of 4.93 p/kWh in a recent auction in October 2007, a value of 3.43 p/kWh has been used in the calculations, which is the ROCs buyout price for the 2007/2008 period. This is because it is unlikely that supply will meet demand for greener electricity and therefore, the ROC prices will be determined by the buy-out price. Therefore, the actual price for ROCs will remain above the buy-out price and choosing a default value for ROCs at the buy-out price is a reasonable and conservative assumption. If supply is to exceed demand, ROC prices will drop and both the revenues to renewable generators and future development of renewable technologies will be hampered.

Similarly, electricity prices fluctuate, depending on the supply and demand of gas, which is a substantial component of the UK fuel mix in electricity generation. The default value used for the electricity price was 2.50 p/kWh, which is taken as an industry standard base electricity price. The risk involved in price fluctuations can be mitigated by securing forward contracts, for example, to supply renewable electricity to major electricity retailers.

Another model input parameter, which has an even greater significance than ROCs prices, is the fraction of waste that is eligible as biomass. A ±10% change in this parameter affects the gasification gate fees by 7-16% at the 50 ktpa and 100 ktpa plant capacities. This again calls for the economic evaluation of future projects to not only account for the current waste compositions but also for any expected changes during the project life-time, thus maximising the potential revenues from ROCs.

#### 4.3.1.5 Effects of changes in capital and operating costs

The economic performances of the different waste treatment options are sensitive to their capital and operating costs, as expected. Changes in the capital costs affected the levelised costs by 3-6%, while variations of 5-8% were reported for the gate fees. On the other hand, sensitivities of 5-7% were reported for the levelised costs because of the changes in the operating costs, while variations of 7-13% were reported for the gate fees.

The costs reported in this evaluation are indicative costs and are not actual contract values. In reality, these costs will depend on suppliers, plant scale, technology used and type of energy recovery system employed, as well as local area logistics. Therefore, there is some inevitable and inherent uncertainty associated with the calculated values, which have uncertainties of ±10%. This is attributed to using the lower and upper values for the scale exponent of 0.6 and 0.8 in the general relationship between cost and scale, which is given by Equation 4.4. Nonetheless, uncertainties or errors of up to ±30% are typical in study estimates of this type (Bridgwater, 2002).

**Table 4.12 Effect of a 20% increase in capital costs of the gasification systems**

| **Plant scale scenario** | **50 ktpa** | | **100 ktpa** | |
|---|---|---|---|---|
| **Waste treatment options** | **FBG+GE** | **FBG+CCGT** | **FBG+GE** | **FBG+CCGT** |
| Capital cost | 19.2 (£m)<br>385 (£/t) | 20.0 (£m)<br>400 (£/t) | 32.2 (£m)<br>322 (£/t) | 32.5 (£m)<br>325 (£/t) |
| Operating cost | 2.9 (£m)<br>58 (£/t) | 2.8 (£m)<br>57 (£/t) | 5.5 (£m)<br>55 (£/t) | 5.3 (£m)<br>53 (£/t) |
| NPV @ 6% discount rate | 12.2 (£m)<br>244 (£/t) | 12.2 (£m)<br>243 (£/t) | 22.4 (£m)<br>224 (£/t) | 22.0 (£m)<br>220 (£/t) |
| IRR | 11.5 (%) | 11.3 (%) | 12.0 (%) | 11.8 (%) |
| Gate fees | | | | |
| *without ROCs* | 75 (£/t) | 72 (£/t) | 63 (£/t) | 58 (£/t) |
| *with ROCs* | 49 (£/t) | 44 (£/t) | 35 (£/t) | 27 (£/t) |
| Levelised costs | | | | |
| *in terms of electricity generated* | 8.00 (p/kWh) | 7.37 (p/kWh) | 6.74 (p/kWh) | 6.08 (p/kWh) |
| *in terms of waste treated* | 89 (£/t) | 88 (£/t) | 81 (£/t) | 80 (£/t) |

Table 4.12, as an example, reports the economic performances of the gasification systems based on a 20% increase in the capital costs. This case scenario takes into account the recent cost data reported for the Novera's East London gasification plant (letsrecycle.com, 2007e). The results show that only FBG+CCGT is cost competitive at the smaller plant scale of 50 ktpa, as it can offer a gate fee, which includes the income from ROCs, for the RDF below the estimated landfill cost of £48/t (see Table 4.3). At the

medium scale of 100 ktpa, both gasification systems are costs competitive, with FBG+CCGT still being the most attractive option.

As shown in Figure 4.3, maintenance and consumables coupled with the costs of ash disposal make up the largest portion of the operating costs for the different waste treatment options. A ±10% change in the maintenance costs affects the levelised costs of all treatment options by 1-3% and gate fees by 1-5%. The bottom ash, which was assumed to be recycled, generates annual revenues of £23,000 and £47,000 for the 50 ktpa and 100 ktpa plant scales, respectively. These values have been calculated using a price value of £7/t (WRAP, 2006) for the bottom ash (see section 4.1.2.3).

However, if markets for the recycled ash were unavailable, then it has to be disposed off to a landfill, costing between £160,000 and £320,000 per annum, with the landfill tax rising by £8/t till 2010. This would increase the levelised costs of all treatment options by 5-6% and gate fees by 7-11%. In the case scenario where the disposal costs rise by 10%, then this would increase the levelised costs by 7-9% and gate fees by 10-16%.

### 4.3.2 Variations in discount rates

For this analysis, the economic performance of FBG+CCGT at 100 ktpa is taken as the base case condition as it represents the most attractive waste treatment option. The economic viability of the process was then tested using higher discount rates, to reflect greater conservatism and compare different outcomes, as well as providing objectivity to the analysis. Discount rates of 8% and 10% were used, as well as 3.5%, which is the Treasury rate for public sector projects.

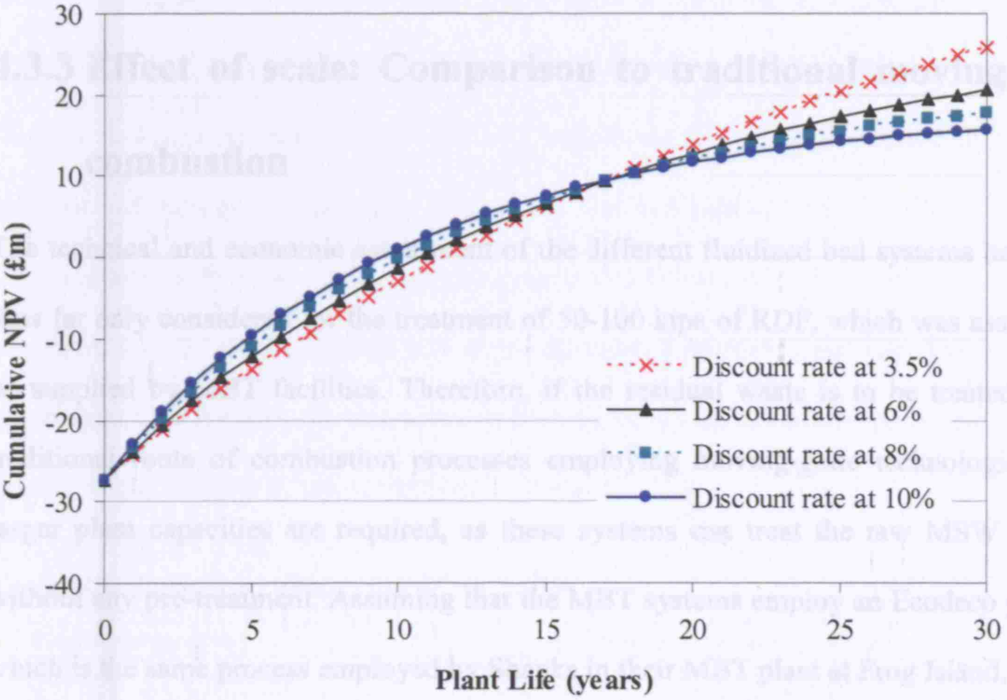


**Figure 4.6 Effect of discount rates on the NPV for FBG+CCGT at 100 ktpa only**

Figure 4.6 demonstrates that at the higher discount rates of 8% and 10%, the NPV falls because future earnings are worth less in today's values. Nonetheless, the NPV are still all positive, thus proving the economic viability of the system at these elevated rates. The figure also illustrates the higher economic performances resulting from using lower discount rates. HM Treasury recommends using a discount rate of 3.5% in all public sector analysis and so by discounting at higher rates, the risk associated with the private investment is accounted for. The effects of different discount rates on the levelised costs and gate fees are presented in Table 4.13.

**Table 4.13 Effect of discount rates on levelised costs and gate fees**

| | Discount Rate | | | |
|---|---|---|---|---|
| | 3.5 (%) | 6.0 (%) | 8.0 (%) | 10.0 (%) |
| Gate fees without ROCs | 47 (£/t) | 52 (£/t) | 58 (£/t) | 63 (£/t) |
| Levelised costs | 5.34 (p/kWhe) | 5.71 (p/kWhe) | 6.04 (p/kWhe) | 6.40 (p/kWhe) |

## 4.3.3 Effect of scale: Comparison to traditional moving-grate combustion

The technical and economic assessment of the different fluidized bed systems have been thus far only considered for the treatment of 50-100 ktpa of RDF, which was assumed to be supplied by MBT facilities. Therefore, if the residual waste is to be treated by the traditional route of combustion processes employing moving-grate technologies, then larger plant capacities are required, as these systems can treat the raw MSW directly without any pre-treatment. Assuming that the MBT systems employ an Ecodeco process, which is the same process employed by Shanks in their MBT plant at Frog Island, 50% of the input raw MSW will be converted into RDF or solid recovered fuel (Shanks, 2007). As a result, the moving-grate combustion systems will need to treat100-200 ktpa of raw MSW.

In the following sections, the technical and economic performances of moving-grate combustion for the treatment of 100-200 ktpa of MSW are considered. The overall system efficiencies and capital investment will also be compared to fluidized bed combustion and gasification systems co-located with MBT facilities.

### 4.3.3.1 Technical performance

In order to carry out the techno-economic analysis of the moving-grate combustion systems, an average composition of the MSW was needed. Data from Porteous (2005) has been used for the combustible fraction of MSW, which was calculated to be $C_6H_{9.600}O_{2.981}N_{0.150}S_{0.009}Cl_{0.059}$ and was in good agreement with other data available in the literature (C-Tech Innovation, 2003). The moisture content was assumed to be 30%, while the ash content was taken from recent data of the Sheffield EfW plant by Garrod (2006) at 27%. The calorific value was then calculated from the elemental composition of the waste using correlations proposed by Channiwala & Parikh (2002) and the resultant estimated properties are shown in Table 4.14. The moving-grate combustion process was designed with a thermal efficiency and system availability of 90%. The gross electricity generated by the steam turbine was obtained using Figure 4.2 and the internal energy consumption of the process was taken at 14% of the gross electricity generated, which is similar to the site power use of the Sheffield plant.

**Table 4.14 Estimated properties of the MSW**

| **Proximate analysis** | | | | **Ultimate analysis (wt % daf)** | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Moisture (%) | Combustibles (%) | Inerts (%) | LHV (MJ/kg) | C (%) | H (%) | O (%) | N (%) | S (%) | Cl (%) |
| 30.0 | 43.0 | 27 | 8.15 | 53.81 | 7.17 | 35.65 | 1.57 | 0.22 | 1.57 |

The results of the technical performances of the moving-grate systems at 100 ktpa and 200 ktpa are reported in Table 4.15. One of the main advantages of these systems is their ability to utilise raw MSW directly. However, the low calorific value of the waste (8.15 MJ/kg compared to 16.7 MJ/kg for RDF), coupled with the low efficiency of steam turbines limit the amount of energy that can be generated using these systems. Therefore, they have lower system performances than fluidized bed gasification, which can achieve up to 28% overall system efficiencies at 100 ktpa, compared to efficiencies of up to 22% for moving-grate combustion at the larger plant scales of 200 ktpa.

**Table 4.15 Technical performances of moving-grate combustion systems**

| **Waste treatment option** | **Moving-grate combustion** | |
|---|---|---|
| **Plant scale scenario** | **100 ktpa** | **200 ktpa** |
| Thermal energy of waste | 28.7 (MWth) | 56.8 (MWth) |
| Mass flow rate | 12.7 (t/h) | 25.1 (t/h) |
| Gross electrical generation efficiency of steam turbine | 24.7 (%) | 28.2 (%) |
| Gross generated electricity | 6.4 (MWe) | 14.4 (MWe) |
| *Site power use* | 0.9 (MWe) | 2.0 (MWe) |
| *Net generated electricity* | 5.5 (MWe)<br>43,300 (MWhe) | 12.4 (MWe)<br>99,000 (MWhe) |
| Overall system efficiency | 19.1 (%) | 21.9 (%) |

Moving-grate systems also have lower system efficiencies than fluidized bed combustion, which has efficiencies of 18% and 22% at the smaller plant scales of 50 ktpa and 100 ktpa, respectively, as reported in Table 4.5 & 4.6. However, one can argue that the fluidized bed systems utilise higher calorific value RDF and the energy used in its production has not been taken into consideration in the analysis of the case scenarios presented so far. Therefore, the energy requirement for the conversion of raw MSW into RDF for an Ecodeco MBT process was added to the overall site power use for the fluidized bed systems. The value for the energy requirement for the MBT process were reported at 30-32 kWh per tonne of input waste (Paiola, 2007), corresponding to a 16-20% increase in the site power use or internal energy consumption of the fluidized bed combustion systems. However, this in turn would only reduce their system efficiencies by 2-3% to 17.6% and 21.7%.

Figure 4.7 & 4.8 compare the technical performances of traditional moving-grate combustion systems with fluidized bed combustion and gasification systems co-located with MBT facilities, for the treatment of 100 ktpa and 200 ktpa of residual waste, respectively. The comparisons reveal once again the better technical performances of the gasification systems and, in particular, the higher efficiency and electricity generation when the fluidized bed gasification is combined with CCGT.

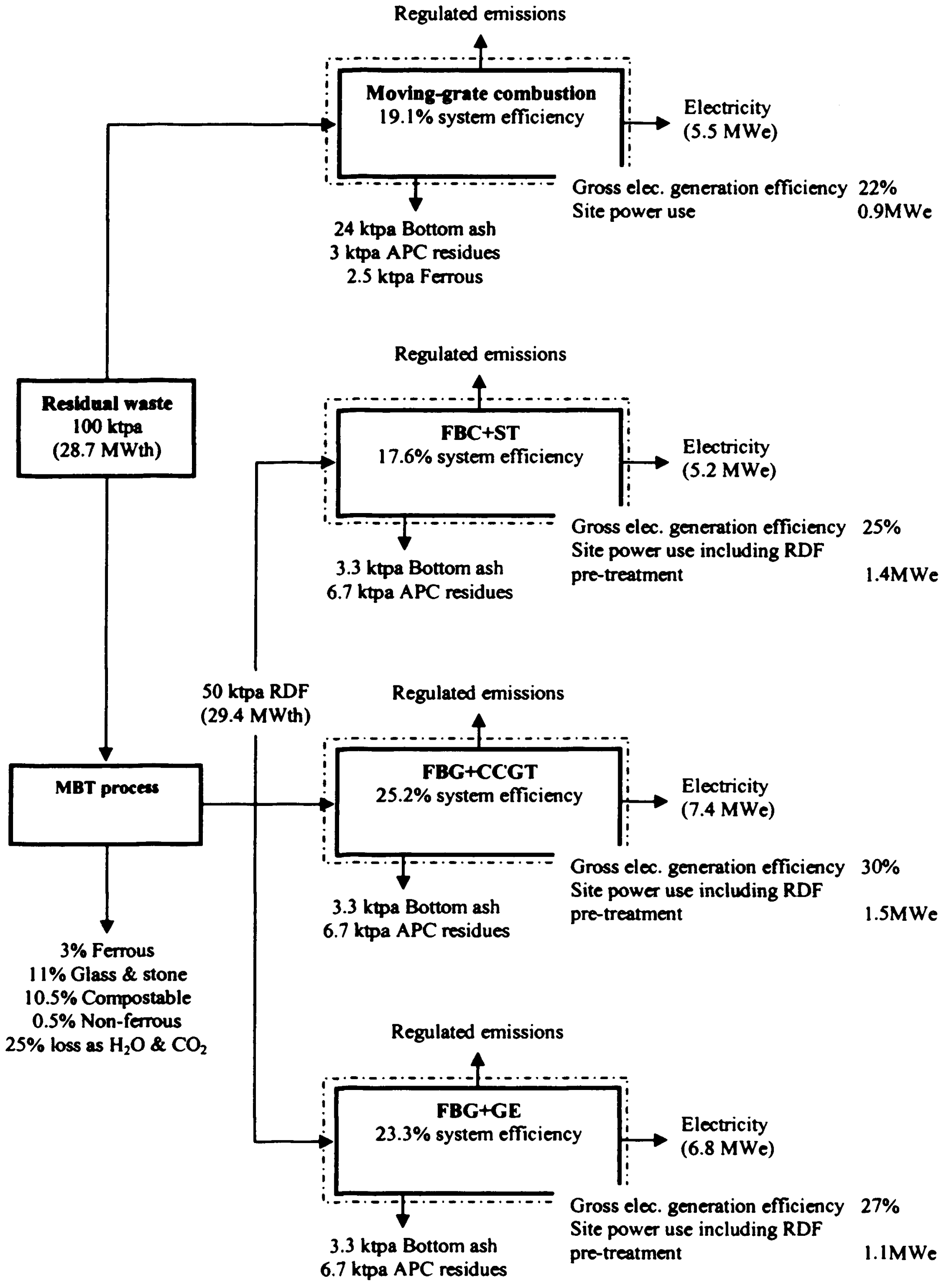


**Figure 4.7 Simplified mass and energy balance for the treatment of 100 ktpa of residual waste**

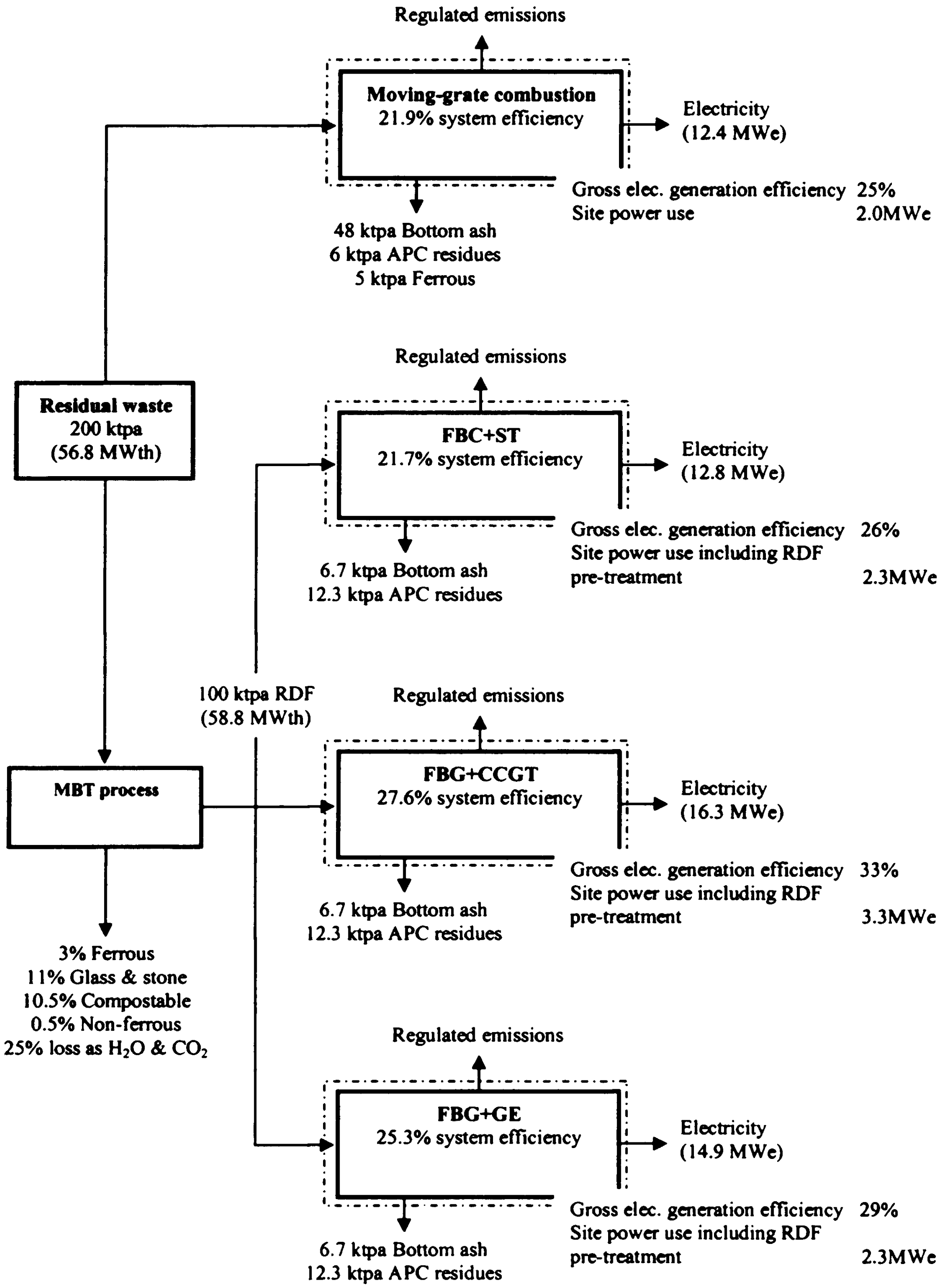


**Figure 4.8 Simplified mass and energy balance for the treatment of 200 ktpa of residual waste**

#### 4.3.3.2 Economic performance

For the cost competitiveness of the moving-grate combustion systems, the economic model developed in section 4.1.2 has been used. As discussed earlier, the costs of the moving-grate systems are well-established in the UK as 17 out of the UK's 19 waste combustion facilities employ these technologies. These technologies are also available from credible suppliers who have proven track record and therefore, have the lowest risk of implementation relative to any other technologies.

However, the project development costs of combustion systems can be unexpectedly high due to the high planning risks associated with the process (Juniper, 2003). As a result, capital costs of moving grate systems vary from one plant to another, according to local circumstances and scales. Differences in accounting practices used by suppliers coupled with the availability of different economic modelling approaches have also contributed to the variation in published capital costs.

In this analysis, existing data for the capital costs of different EfW moving-grate facilities in the UK have been obtained, together with published data from Defra (2007b) and Ilex (2005a) report to the Department of Trade & Industry. All cost data were updated and then plotted against their respective plant scales, as shown in Figure 4.9. The best regression curve was found (see Equation 4.7) and the capital cost was calculated from this.

$$Capital\ cost = 34.136e^{0.0033x} \tag{4.7}$$

where capital cost is in (£million) and $x$ is the plant capacity in (ktpa).

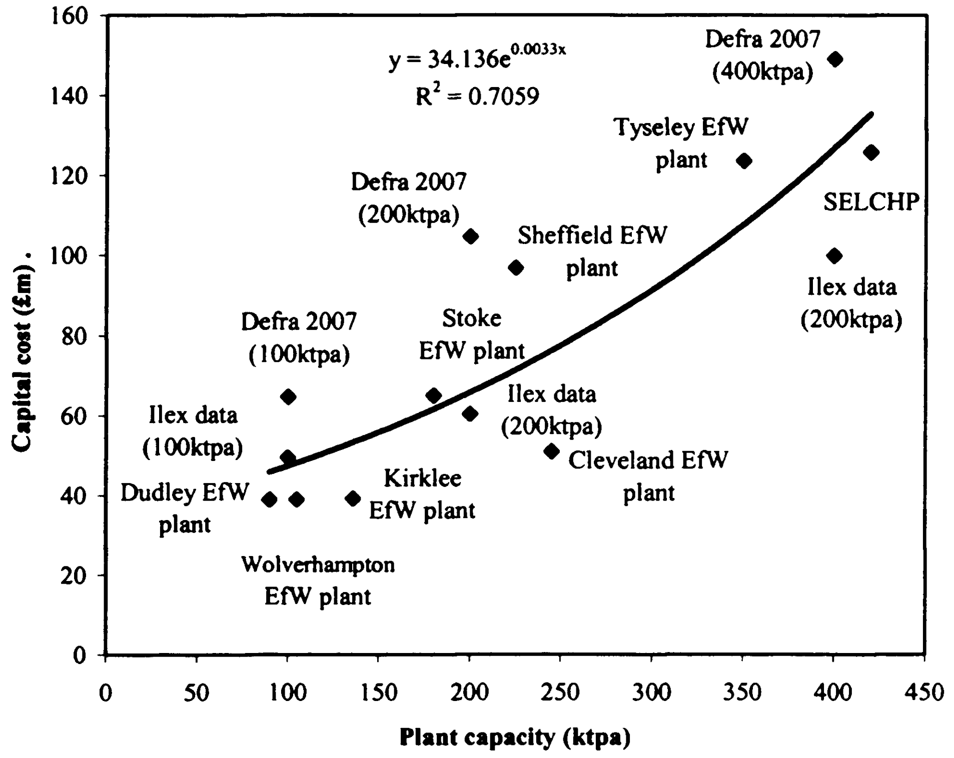


**Figure 4.9 Capital costs for EfW incineration facilities**

For the operating costs, Table 4.16 summaries the input model parameters used in the evaluation, while the different revenues considered are the same as that reported in section 4.1.2.3. Note here that fluidized bed technologies have better carbon burnout and hence generate less bottom ash than moving-grate systems. However, they produce more APC residues, as shown in Figure 4.7 & 4.8, which need to be landfilled as hazardous materials and as a consequence, incur higher ash disposal costs.

**Table 4.16 Model parameters used for the operating cost calculations**

| Parameter | Value |
|---|---|
| Maintenance | 3% of capital cost. This includes consumable costs and maintenance of the steam turbines. (Ilex, 2005a, RPS-MCOS, 2005) |
| Labour | 24 employees, each with an average salary of £31,000 (Environment Agency, 2007b) |
| Ash disposal | 27% of input waste, of which 89% is bottom and 11% is air pollution control residues (Garrod, 2006) |
| Plant overheads | 2% of capital costs (Bridgwater, 2002) |

The results of the economic performances of the moving-grate combustion systems are shown in Table 4.17 for the 100 ktpa and 200 ktpa plant scales. The results demonstrate that these systems are capital-intensive options, with capital costs of £330/t and £475/t, compared to the gasification systems of £270/t to £336/t, as summarised in Table 4.9.

However, moving-grate systems are marginally cheaper than fluidized bed combustion, when both technologies are compared at the 100 ktpa plant scale. Nevertheless, fluid bed combustion benefits from the use of high calorific value RDF, which enables it to recover more energy from the waste and increase its projected revenues from the sales of electricity. As a result, the fluid bed system has higher NPV and IRR and can offer lower gate fee and levelised cost per electricity generated than the moving-grate system.

**Table 4.17 Economic performances of moving-grate combustion systems**

| **Waste treatment option** | **Moving-grate combustion** | |
|---|---|---|
| **Plant scale scenario** | **100 ktpa** | **200 ktpa** |
| Capital cost | 47.5 (£m)<br>475 (£/t) | 66.0 (£m)<br>330 (£/t) |
| Operating cost | 3.4 (£m)<br>34.3 (£/t) | 4.7 (£m)<br>23 (£/t) |
| NPV @ 6% discount rate | 19.1 (£m)<br>191 (£/t) | 26.4 (£m)<br>132 (£/t) |
| IRR | 9.5 (%) | 9.5 (%) |
| Gate fees | 69 (£/t) | 42 (£/t) |
| Levelised costs | | |
| *in terms of electricity generated* | 16.0 (p/kWh) | 9.7 (p/kWh) |
| *in terms of waste treated* | 69 (£/t) | 48 (£/t) |

Figure 4.10 shows the capital costs of the different waste treatment options presented in Figure 4.7 & 4.8 for the treatment of 100 ktpa and 200 ktpa of residual waste. It demonstrates the overall competitive costs of fluidized bed gasification systems co-located with MBT processes, compared to moving-grate combustion systems. On the other hand, fluidized bed combustion combined with MBT is only cost competitive for

the treatment of 100 ktpa. The capital costs of the MBT systems were calculated based on an Ecodeco MBT process (AIIE, 2003).

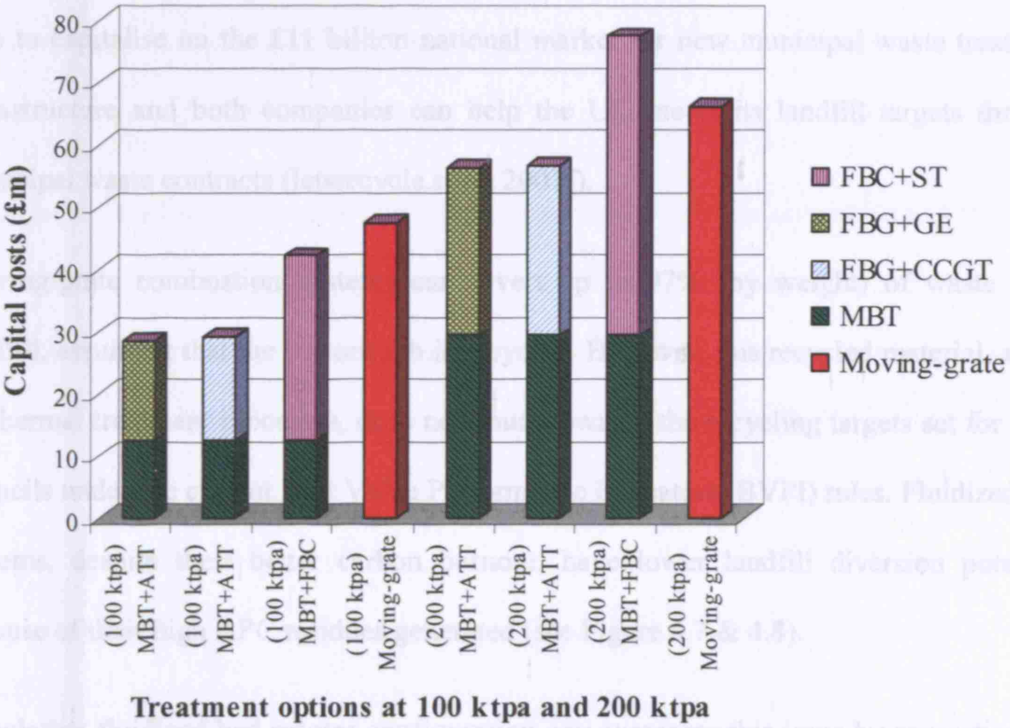


**Figure 4.10 Costs of fluidized bed systems with MBT compared to moving-grate combustion**

Therefore, fluidized bed gasification systems co-located with MBT facilities have greater technical and economic performances than the direct municipal waste combustion using grate-moving systems. They can also play an important role in an integrated waste management strategy that follows the waste hierarchy and ensures used products are recycled with energy recovery from the residual waste, while the remaining waste for which there is no further beneficial use is landfilled.

As emphasised earlier, both gasification and MBT processes are unproven technologies in the UK, and unless Novera and Shanks demonstrate their technical and economic viability, then the future uptake of these technologies could be seriously jeopardised.

Nevertheless, they are the only companies in the UK that are strategically positioned to commercialise these systems and establish 'first-mover' advantage, as they will be able to capture market share more easily due to a lack of competition. In addition, they will be able to capitalise on the £11 billion national market for new municipal waste treatment infrastructure and both companies can help the UK meets its landfill targets through municipal waste contracts (letsrecycle.com, 2007f).

Moving-grate combustion systems can divert up to 97% (by weight) of waste from landfill, assuming that the bottom ash is recycled. However, this recycled material, as for all thermal treatment processes, does not count towards the recycling targets set for local councils under the current Best Value Performance Indicators (BVPI) rules. Fluidized bed systems, despite their better carbon burnout, have lower landfill diversion potential because of their high APC residues generated (see Figure 4.7 & 4.8).

Circulating fluidized bed reactor configuration can overcome this issue by separating the char and ash particles from the syngas and recycling them back to the bottom part of the fluidized bed. Nonetheless, fluidized bed systems are compatible with recycling and composting initiatives and they produce solid residues that are more suitable for re-use than the residues from moving-grate combustion systems.

In addition, there are higher levels of recycling involved in the production of RDF from MBT processes, as illustrated in Figure 4.7 & 4.8. The recyclates from these processes qualify for BVPI and thus contribute significantly to achieving the national recycling targets for household waste.

The compostable fraction generated from the MBT processes can also contribute towards the BVPI for composting. However, the potential applications of these products, known as compost-like outputs or CLO, are dependent upon their quality, as well as the legislative and market conditions (Defra, 2007g). The CLO can be used as a soil improver for Brownfield and landfill restorations.

However, not all products meet the appropriate criteria for their utilisation and currently, the 10.5% of the compostables produced by the Shanks MBT facility in East London are landfilled because of this. Further treatment options for the compostable fraction is under investigation by Ecodeco, such as composting and anaerobic digestion.

## 4.4 Conclusions

This chapter has reported the technical and economic performances of EfW fluidized bed combustion and gasification systems, with the implications of different scales and technologies on their costs and efficiencies. Two different scale scenarios of 50 ktpa and 100 ktpa plant capacities were considered for the generation of electric power using a steam turbine for the combustion process and a gas engine & CCGT for the gasification process. Mass and energy balances of the processes were performed and the economic viability and cost effectiveness of the different waste treatment options were assessed using a discounted cash flow analysis. Additionally, a sensitivity analysis was performed to identify the most influential model input parameters and test the robustness of the assumptions made. The techno-economic analysis of traditional moving-grate combustions systems was also reported and compared against the different fluidized bed systems co-located with MBT facilities.

For the different fluidized bed waste treatment options, the analysis has shown that the ability of gasification processes to employ more efficient energy conversion systems, enables them to have greater electrical generation efficiencies and, as a result, they have better overall system performances of 24-28%, compared to 18-22% for combustion processes. Fluidized bed gasification coupled with CCGT, in particular, offers the most energy efficient treatment option.

In terms of economic performances, capital costs of £270/t to £336/t were reported for the gasification options, compared to £481/t to £594/t for combustion. Fluidized bed gasification coupled with gas engine has the cheapest capital cost option and the highest rate of return on investment. However, this is offset by its higher operating cost and the lower system efficiency, compared to fluidized bed gasification coupled with CCGT, which is the most attractive treatment option in terms of gate fee and levelised cost of waste treatment.

Although fluidized bed gasification systems have an unproven track record in the UK, they are compatible with high levels of source segregation and therefore, have the potential to contribute towards integrated waste management practices. In addition, the operational reliability of the systems will be further improved, as more facilities are commissioned and operated at commercial scales. Furthermore, financial incentives, such as ROCs, securing long-term contractual agreements for the supply of RDF, as well as supportive policies and active R&D by major industry players and research institutions are important factors for the full commercialisation of these processes, especially for plant scales larger than 50 ktpa.

The sensitivity analysis has demonstrated that the calorific value of the waste, electricity generation efficiencies of the prime movers and gasifier efficiency had the greatest impact on the levelised cost, while the gate fee was mainly affected by the operating costs, as well as electricity & ROC prices and biodegradable fraction of the waste.

Finally, although traditional moving-grate combustion systems have been shown to have lower technical and economic performances, compared to fluidized bed gasification systems co-located with MBT facilities, they had the highest landfill diversion potential, assuming the bottom ash was recycled. This said, gasification systems co-located with MBT facilities can achieve higher levels of recycling; however, market availability for their outputs will have a significant influence on the environmental impacts of these processes.

# 5 Potential for EfW with combined heat and power

## Summary

The first part of this chapter highlights the potential of distributed energy and, in particular, combined heat and power as an important technology contributing to meeting the UK's energy policy and emission targets. Obstacles and barriers for the uptake of CHP are identified and different plant configurations for the simultaneous generation of heat and power are also presented. The second part of the chapter reports the technical and costs effectiveness of utilising the waste heat from EfW facilities. The study focuses on the additional capital and operating costs involved in incorporating CHP into these facilities, as well as the projected revenues from heat sales and eligibility for ROCs. Mass and energy balances are carried out and the cost effectiveness of the different waste treatment options with CHP is assessed using a discounted cash flow analysis. The comparison is also made by estimating the levelised costs of waste treatment and predicted gate fees. Furthermore, the environmental benefits associated with combined heat and power from EfW facilities are evaluated and the $CO_2$ savings achieved from displacing fossil fuels in the separate generation of heat and power are also reported.

# 5.1 Introduction

## 5.1.1 Distributed energy

Most of our energy is supplied through a nationwide network. For example, in the current UK system, electricity is produced in a small number of large power stations and then transported to distribution companies, as shown in Figure 5.1. This centralised generation involves feeding into a high-voltage transmission system, which provides connection for 85% of the total generating capacity and is operated by National Grid Electricity Transmission plc (NGET). Although this centralised model offers economies of scale and high reliability, we have existing and emerging technologies that can efficiently generate heat and power near where they are consumed. This gives rise to distributed energy, which is also referred to as decentralised energy or embedded generation.

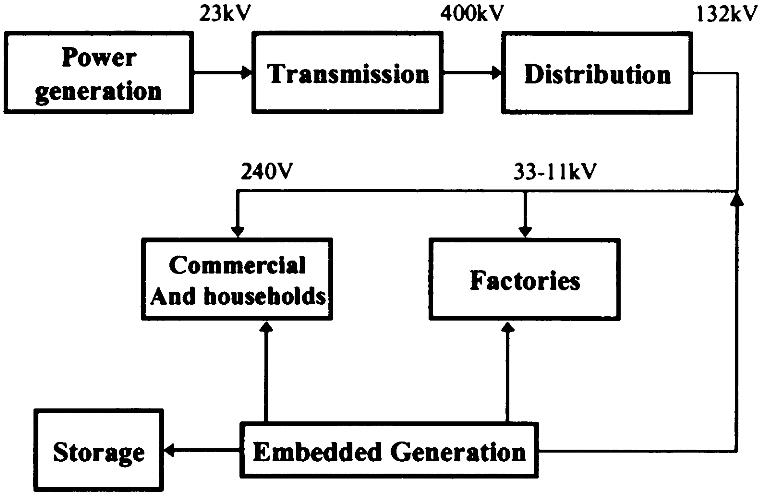


**Figure 5.1 Embedded generation**

Distributed energy involves feeding electricity into the supply system at the lower voltage level of the distribution networks, which are owned and operated by the Distribution

Network Operators (DNOs). Excess electricity can be stored or fed back to the distribution system (DTI, 2006b). Generally, distributed energy refers to a wide range of technologies that do not rely on the high-voltage electricity transmission or the main gas networks. These include:

- Plants connected to a distribution network rather than the transmission network or supply electricity directly to customers, as shown in Figure 5.1. It also includes small installations of solar panels, wind turbines or biomass/waste burners (micro-generation);
- All combined heat and power (CHP) plants of any scale;
- Non-gas heat sources, such as biomass, wood, solar thermal panels, geothermal energy or heat pumps, where the heat is used in just one household or piped to a number of users in the residential, commercial and industrial sectors.

The Proximity Principle has been described in the UK Waste Strategy 2000 as a tool for planning authorities and businesses when considering the requirements and location of waste management facilities and regional self-sufficiency (Sustainable Development, 2000b). The principle states that waste should be managed as close as possible to where it arises. This reduces transport impacts and enables local communities to deal with their waste more sustainably. It also encourages behavioural change through increased awareness of energy consumption. Furthermore, heat and power generated from EfW facilities can be utilised locally, relieving some of the increased energy demands on larger power stations and gas networks.

## 5.1.2 Drivers for uptake of distributed energy

In the recent Energy White Paper (DTI, 2007a), the threat posed by climate change and the need for secure, clean and reliable energy are recognised as the two major long-term energy challenges for the UK. Local energy supply from renewable sources can play an important part in meeting our energy policy goals by reducing carbon emissions and providing indigenous and reliable fuels. Other drivers for the uptake of distributed energy include:

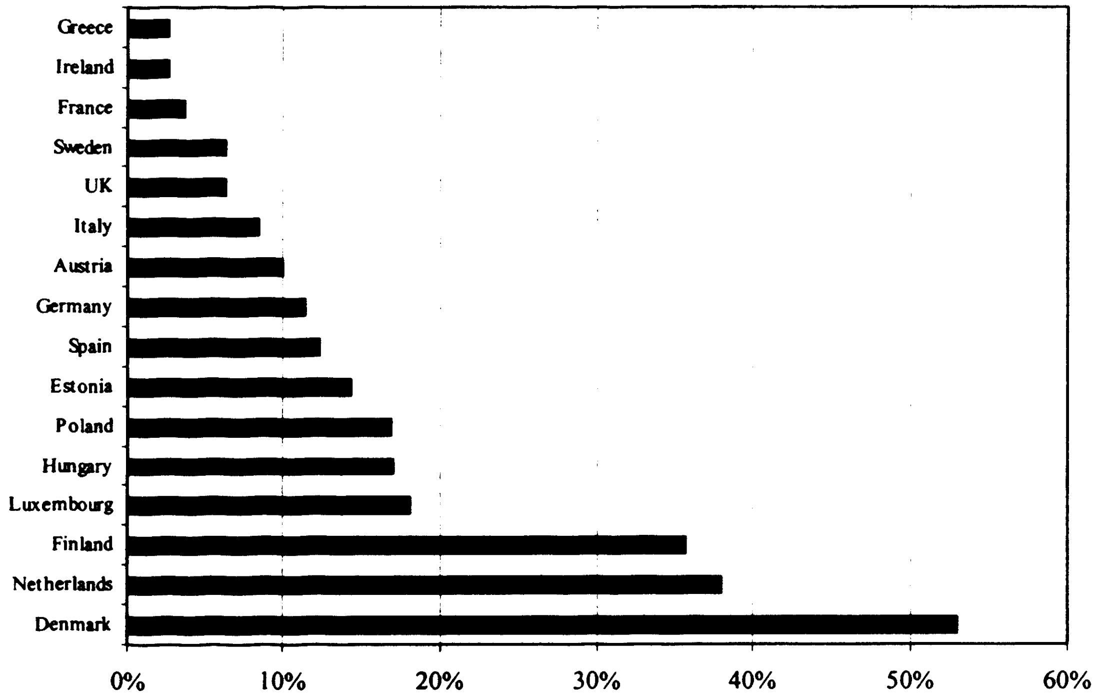
- *More efficient use of fossil fuels* – Using CHP to capture the heat generated from burning fuels and utilising it locally reduces carbon emissions and the demand for imported gas. CHP also offers energy savings when compared to the separate supply of electricity and heat (see Section 5.1.5). Further efficiencies are achieved through the avoided transmission and distribution losses, which have been estimated to account for 9% of the electricity delivered or about 30% of the delivery cost (IEA, 2002). These reduced losses would consequently translate into lower carbon emissions.
- *Greater awareness of energy issues* – A community-based energy system can help raise awareness of the supply and demand of energy and promote its efficient use. Community or district heating, in particular, can be utilised in residential and commercial developments, shopping centres and business parks. This in turn may provide additional opportunities for the commercial exploitation of CHP (Defra, 2004). Furthermore, distributed energy can potentially play a role in addressing fuel poverty issues. For example, it can provide low cost heating to social housing through community heating, as currently practised in Aberdeen (Ofgem, 2007c).

- *Greater fuel diversity* – A decentralised system utilising renewable sources increases the diversity and security of supply, while reducing our reliance on fossil fuels.
- *Improved flexibility* – A modular system allows additional capacity be installed as it is needed. Therefore, the decentralised system can run at maximum efficiency, as the risk of demand fluctuations is reduced. In addition, the distributed generation enhances network reliability because of the reduced transmission power flows and ability to secure local demand at times of system stress (DTI, 2006b).

### 5.1.3 UK potential for CHP

The UK Government recognises CHP as an important technology contributing to meeting its energy policy and emission targets. The Combined Heat and Power Quality Assurance (CHPQA) programme was established in 2000 in order to assess the quality of installed CHP plants and introduce the concept of 'Good Quality CHP' (AEA Technology, 2004). As part of the UK strategy to meet its 12.5% reduction of greenhouse gas emissions by 2008/12 under the Kyoto Protocol, the UK Government has set itself two further targets: 10% of the electricity supplied in the UK should come from renewable sources by 2010; and installation of 10 GWe of Combined Heat and Power by 2010. These targets aim to encourage the deployment of low carbon distributed energy sources and set the UK on the path to achieving a 60% reduction in carbon dioxide emissions by 2050. The renewables target was extended to 15.4% of electricity supply by 2015/16.

In October 2007, two reports illustrating the UK potential for high efficiency CHP and progress to meeting that potential were published by the Government as part of the EC Cogeneration Directive. The Directive promotes high efficiency (Good Quality) CHP, where there is an economically justifiable use of heat to save energy and reduce carbon emissions. It includes provisions obliging Member States to analyse national potentials for high efficiency CHP and barriers to their realisation. The reports estimate that just over 10% of the UK's electricity will come from CHP generation by the end of 2010, while the economic potential exists to provide 17% of our total energy requirement from CHP (Defra, 2007h, Defra, 2007i). Currently, the UK's CHP generation is at 8.6% of total electricity supplied, which compares poorly with other European countries who have achieved levels as high as 50%, as shown in Figure 5.2.



Source: Piddington (2006)

**Figure 5.2 Share of co-generated electricity across Europe**

According to the Biomass Task Force Report (2005), heat accounts for over a third of primary energy consumption in the UK. However, only 1% of the heat market is currently sourced from renewable fuels, such as EfW. Furthermore, recent reports by Ernst & Young (2007a and 2007b) have highlighted that whilst the use of renewables for electricity generation is supported by the Renewable Obligation (RO) and Renewable

Transport Fuel Obligation (RTFO), there are no targets or incentives for the generation of heat from renewable sources. These reports were commissioned by Defra and BERR (formerly DTI) to evaluate whether there is a need for support for the UK renewable heat sector and the level of support required.

Table 5.1 presents the market share of renewable heat in Europe and its key drivers. The high levels of deployment of renewable heat are mainly attributed to policy support, which combines financial and non-financial measures that are particularly focused on the residential district heating (DH) sector. Obligatory connections to heat infrastructure has also proved successful in overcoming difficulties in the development of large DH schemes. In the UK, the market for renewable and waste heat have been estimated to be between 37,000 GWh and 87,000 GWh by 2020, corresponding to 5% and 12% of the current UK heat requirements, respectively (Ernst & Young, 2007b).

**Table 5.1 Renewable heat market share in Europe**

| Country | Market share | Key drivers |
|---|---|---|
| Sweden | 26% | • Extensive deployment of DH from biomass-fuelled CHP;<br>• Capital grants for extending heat transmission network, reduced VAT and supportive planning for DH; |
| Denmark | 13% | • Use of DH to supply residential and commercial sectors;<br>• Planning legislation to install heat transmission network; obligatory connection of CHP to heat network and a ban on electric heating; |
| Germany | 5% | • Generous electricity tariffs for biomass;<br>• Public support; supportive planning and grants for smaller applications; |
| Belgium | 2% | • Green certificate mechanism similar to RO but based on carbon savings to incentivise the use of renewable CHP. |

Source: Ernst & Young (2007b)

Therefore, there is a huge potential for improving the energy efficiency of residential, as well as the commercial and industrial sectors in the UK, which remains to be exploited. In addition, support mechanisms, similar to those practised elsewhere in Europe, should be adopted in order to promote the use of appropriate technology mix and maximise the contribution from renewable heat and power.

### 5.1.4 Obstacles and barriers for CHP

The economic potential for the CHP identified in the previous section may not be realised, as there are significant obstacles and barriers affecting their installation in the UK. Table 5.2 shows the installed CHP capacity in the UK from 2003 to 2005. During that period, there were 1,502 CHP schemes installed at the end of 2005 and the electricity generation from CHP increased by about 19% to 27,235 GWh. However, Defra (2007h) has reported that between 2000 and 2003, growth in installed capacity was hampered due to unfavourable gas and electricity prices coupled with the volatility and uncertainty of future fuel prices at that period. As a result, investments were driven away to conventional heat generating plants, which have lower capital costs and are less risky investments.

**Table 5.2 Installed CHP capacity in the UK (2003-2005)**

| **Year** | **2003** | **2004** | **2005** |
|---|---:|---:|---:|
| Number of schemes | 1,443 | 1,518 | 1,502 |
| Total installed capacity | 10,797 (MWe) | 9,105 (MWe) | 9,088 (MWe) |
| Good Quality CHP | 4,848 (MWe) | 5,653 (MWe) | 5,440 (MWe) |
| Heat capacity | 7,025 (MWth) | 9,721 (MWth) | 6,789 (MWth) |
| Total electricity generation | 48,729 (GWh) | 51,634 (GWh) | 53,122 (GWh) |
| High efficiency CHP electricity | 22,950 (GWh) | 26,337 (GWh) | 27,237 (GWh) |
| Heat generation | 52,718 (GWh) | 55,329 (GWh) | 51,454 (GWh) |

Source: Defra (2007h)

While these obstacles can not be changed or influenced directly, there are other practical barriers that can be resolved through regulatory framework (Defra, 2007h). These include technical and financial difficulties in connecting to the distribution network; licensing; and the need to capture the full environmental benefits from the EU Emissions Trading

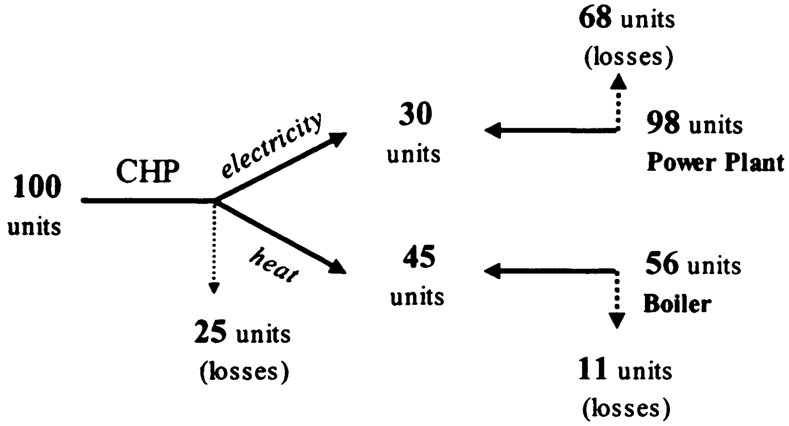
Scheme (EU ETS). Therefore, the Government has recognised the difficult market for CHP and now offers incentives for Good Quality CHP through:

- *Taxation* – This include exemption from the Climate Change Levy for all Good Quality CHP fuel inputs and electricity outputs; eligibility for Enhanced Capital Allowances; Business Rates exemption and reduction in VAT on domestic micro-CHP;
- *Market mechanisms* – These comprise of eligibility for ROCs for biomass-fuelled/EfW with CHP and favourable allocations that reward the carbon saved by CHP schemes under phase II of the EU Emissions Trading Scheme;
- *Positive policy framework* – This include encouraging the uptake of CHP through planning policy and Building Regulations, as well as updated guidance for power station developers to ensure full consideration of CHP.

### 5.1.5 CHP plant configurations

The simultaneous or sequential heat and power generation using CHP is a well-established type of distributed generation. CHP is a fuel-efficient energy system that can achieve between 15-40% reduction in the primary energy usage compared to the separate supply of electricity and heat, as illustrated in Figure 5.3. Here, the equivalent amounts of 30 units of electricity and 45 units of heat are produced using CHP and separate production schemes.

The CHP plant achieves an overall energy efficiency of 75%, while for the same amounts of heat and power, the separate production schemes achieve 49% overall energy efficiency and consume 154 units of fuel, compared to only 100 units for the CHP plant. Therefore, in this example, the CHP configuration saves 35% of primary energy.

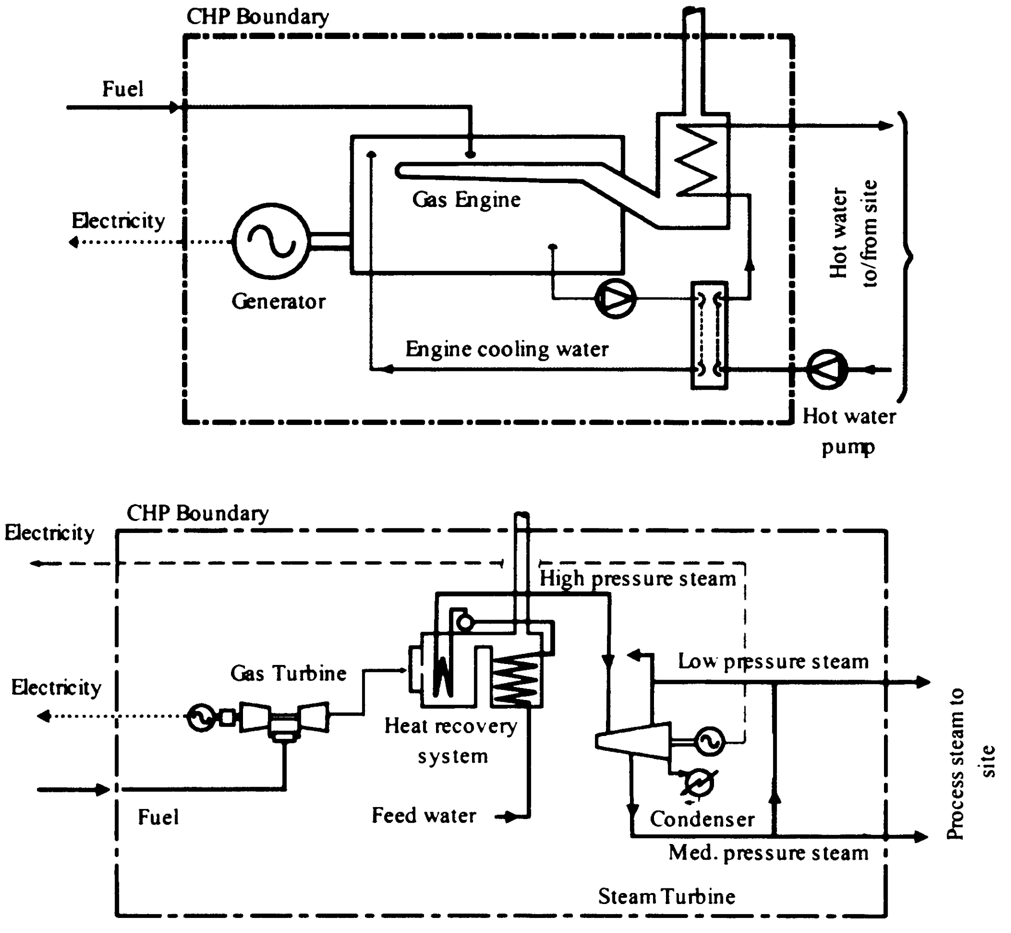


$\eta_{CHP} = 75\%$ $\eta_{separate\ heat\ and\ power} = 49\%$

**Figure 5.3 CHP and separate heat & power generation efficiencies**

CHP systems range from micro-CHP (3-200 kWe), through to small-scale (200kWe-2MWe) to large-scale (>2MWe). They consist of three principal components: prime movers; electrical generators; and heat recovery systems. The prime movers are the energy conversion technologies, which include gas engines, turbines, fuels cells and micro-turbines. These prime movers drive the electricity generator and the waste heat from the exhaust gas stream is recovered using a heat recovery boiler. In Chapter 2, Table 2.2 shows a comparison between the different conversion technologies for heat and power applications in terms of efficiencies, heat to power ratio and investment costs. The choice of prime movers depends on a number of factors including the heat to power ratio of site demand and the quality of heat required by the customer (ICHPA, 2008). Therefore, CHP schemes are site and project specific, as they have different exhaust gas flows and require heat output with different temperature and pressure characteristics.

Figure 5.4 illustrates two CHP configurations that incorporate a gas engine and combined cycle gas turbine (CCGT). The fuels are combusted in the gas engine and gas turbine producing heat, which is usually wasted in an electricity-only scheme. The waste heat is then fed into a heat exchanger to produce steam for industrial processes and hot water for district heating. The CHP scheme with CCGT, shown in Figure 5.4, combines the use of a gas turbine with a condensing steam turbine, which is usually employed when the process steam demand is small compared with the electrical demand. Back-pressure steam turbines are otherwise used for district heating applications and provide maximum economy with simplest installations (Mobley, 2001). A schematic diagram of a simple back-pressure steam turbine CHP installation is shown in Figure 5.5.



Adapted from CHPQA (2007)

**Figure 5.4 Schematic diagram of gas engine (top) and CCGT (bottom) CHP schemes**

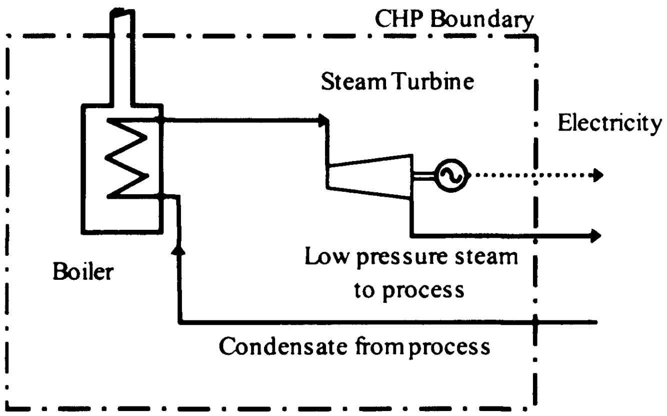


**Figure 5.5 Schematic diagram of a simple back-pressure steam turbine in CHP application**

## 5.2 Methodology

### 5.2.1 Setting the scenarios

In the previous sections, CHP was recognised as an important technology that can contribute to meeting the UK's energy policy and emission targets. Utilising the waste heat from renewable generators, such as EfW, allows for greater carbon reductions through the displacement of energy otherwise used for heat or steam production, the carbon avoided from conventional power generation, and avoided transmission and distribution losses.

The heat generated by EfW facilities can be sold to commercial or industrial users with large and uniform heat demand. Alternatively, the heat can be supplied to DH networks, which can cover both domestic and non-domestic users. Heat from dedicated CHP and EfW facilities are the most common resources in DH systems. In a DH network, the heat is distributed to consumers through a network of pipes buried under the pavements and just as consumers can tap into electricity and gas mains, they can do so for hot water. Heat exchangers connect the consumer heating system to the DH network.

District heating, which is also known as Community heating (CH) in the UK, is a popular concept in many European cities where heat off-take from EfW facilities is common (Ilex, 2005b). For example, the SYSAV plant in Malmö (Sweden) has supplied 20-25% of the total annual heat demand of 2,300 GWh for the city's DH system since the 1970s (BRE, 2008). Other examples where EfW plants are integrated into DH schemes include Budapest (Hungry), Copenhagen (Denmark), Munich (Germany), Paris (France) and Prague (Czech Republic). In the UK, EfW with CHP schemes operate in Sheffield and Nottingham (DH supply), Grimsby and Coventry (industrial energy supply), while the Lerwick plant in the Shetland Isles operates as heat-only (see Table 2.4 in Chapter 2). The Sheffield plant recovers heat from the combustion of waste and produces steam, which is used to generate up to 19 MWe of electricity to the National Grid and up to 60 MWth to the city's DH network. In 2006, the DH network supplied nearly 140 buildings including hotels, a hospital, leisure facilities and 2 universities. It sold 117,081 MWh of thermal energy, of which 75.3% was supplied by the EfW combustion plant (Garrod, 2006).

In this study, the technical and cost effectiveness of generating both heat and power from EfW facilities were evaluated. This study builds on earlier work in Chapter 4, which reported the techno-economic analysis of EfW fluidized bed combustion and gasification processes for electricity-only generation. The evaluation focuses on the additional capital and operating costs involved in incorporating CHP into EfW facilities. Therefore, the costs of delivering heat to market are assessed alongside the additional revenues from the sales of heat and eligibility for ROCs.

The same two scale scenarios of 50 ktpa and 100 ktpa used in Chapter 4 are considered, corresponding to small and medium scale EfW plant capacities, respectively. For each scale scenario, the different waste treatment options evaluated to incorporate CHP are as follows:

1. Fluidized bed gasification coupled with:
    - *Gas engine, (FBG+GE);*
    - *Combined cycle gas turbine, (FBG+CCGT);*
2. Fluidized bed combustion coupled with *steam turbine, (FBC+ST).*

For the technical performances of the different waste treatment options incorporating CHP, the mass and energy balances were performed as outlined in the previous chapter. Simple installations of the heat recovery systems for the different prime movers are shown in Figure 5.4 & 5.5. The heat output from each system was obtained by using typical heat to power ratios of 1.45, 1.5 and 3.0 for the FBG+GE, FBG+CCGT and FBC+ST systems, respectively (Obernberger & Thek, 2004b, Bullard et al., 2004).

Generally, in order for the conventional EfW facilities to qualify for ROCs, a market for the heat must be secured first. EfW with CHP facilities are required to be sized for local waste management objectives, whereas dedicated CHP technologies, using natural gas for example, are sized to meet large and constant heat loads. Although, the heat from EfW with CHP facilities can be supplied directly to large industrial users with high load factor, such as paper mills, the probability of EfW facilities being located next one is low (Ilex, 2005b). Additionally, the high temperature and pressure requirements from the industrial users may not be feasible. As a consequence, EfW with CHP facilities may face difficulties in establishing a suitable demand for the heat.

Therefore, in this analysis, the heat from the EfW with CHP facilities was assumed to supply newly-built DH schemes, which provide the most effective option for heat off-take from EfW facilities in the absence of industrial heat loads. These installations can be incorporated in the design phase, thus reducing capital investments, as it is cheaper to install pipes in less congested areas than in city centres. The newly-built DH schemes were assumed to have a mix of customers including domestic and non-domestic users, in order to guarantee a consistent year-round heat demands. The environmental benefits of using EfW with CHP were also assessed and compared to electricity-only EfW and separate supply of heat and power.

### 5.2.2 Developing the model

The cost effectiveness of the different waste treatment options with CHP was compared using a discounted cash flow analysis, as detailed in Chapter 4. A market discount rate of 9% (Defra, 2007h) was used to reflect the higher risk involved in CHP applications compared to 6% for electricity-only processes. The comparison was also made by estimating the levelised costs of waste treatment and predicted gate fees.

The input parameters forming the basis of the economic model, such as waste feed and system characteristics, were kept the same along with the model assumptions for the two scenarios considered in Chapter 4. This enables a consistent methodology to be adopted for the analysis. In the following sections, the additional costs and revenues involved in incorporating CHP into the different waste treatment options are described.

#### 5.2.2.1 Capital & operating costs

The capital costs involved in generating combined heat and power by the different waste treatment options consist of the EfW plant costs and the investment required for providing the district heating scheme. The costs of the EfW plants are reported in section 4.2 and include the costs of waste treatment, gas cleaning and electricity generation. The costs of providing the heat infrastructure include the installations of heat exchangers, heat networks and customer connections (Ilex, 2005b). Figure 5.6 illustrates the additional capital costs estimates for EfW facilities to incorporate CHP.

On the other hand, the operating costs of the EfW facilities are detailed in section 4.1.2.2 and include maintenance & consumables, labour, ash disposal, electricity generation systems and plant overheads. The additional operating costs involved in the provision of CHP are the running costs of the heat recovery systems and pumps, as well as the maintenance of heat networks and customer connections. These costs were obtained from Ilex's report to DTI (2005b) and are presented in Figure 5.7.

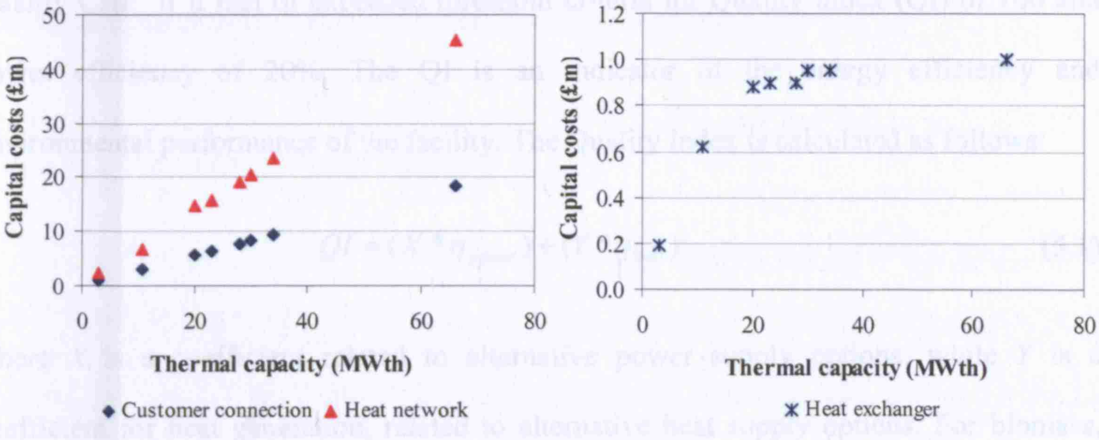


**Figure 5.6 Additional capital costs for the different EfW with CHP facilities**

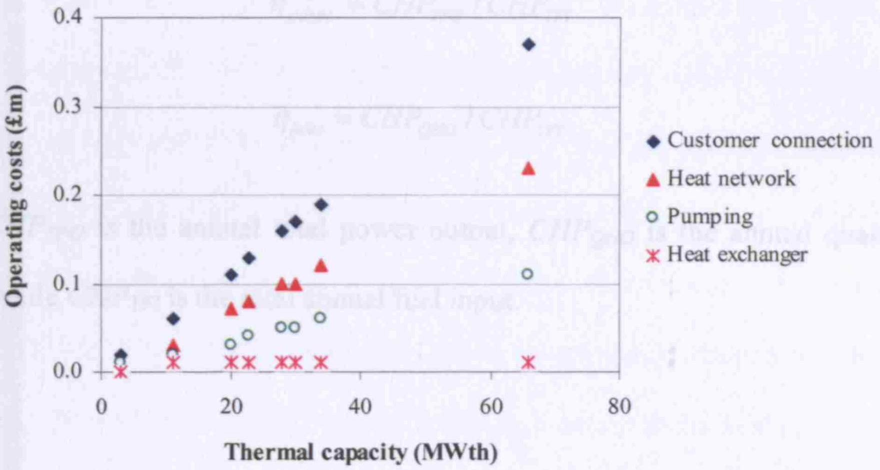


**Figure 5.7 Additional annual operating costs for the EfW with CHP facilities**

### 5.2.2.2 Projected revenues

Generating heat alongside electricity through CHP enables EfW facilities to benefit from the sales of heat. This in turn allows conventional and traditional technologies, such as combustion, to be eligible for ROC supports, provided they are approved as 'Good Quality CHP' by CHPQA. However, as mentioned earlier, a suitable demand for the heat must be established and secured first. An EfW facility with CHP can qualify as 'Good Quality CHP' if it met or exceeded threshold criteria for Quality Index (QI) of 100 and power efficiency of 20%. The QI is an indicator of the energy efficiency and environmental performance of the facility. The Quality Index is calculated as follows:

$$QI = (X * \eta_{power}) + (Y * \eta_{heat}) \tag{5.1}$$

where $X$ is a coefficient related to alternative power supply options, while $Y$ is a coefficient for heat generation, related to alternative heat supply options. For biomass, solid or liquid waste, $X$ and $Y$ are 400 and 140, respectively. $\eta_{power}$ and $\eta_{heat}$ are the power and heat efficiencies of the CHP, which are defined as follows:

$$\eta_{power} = CHP_{TPO} / CHP_{TFI} \tag{5.2}$$

$$\eta_{heat} = CHP_{QHO} / CHP_{TFI} \tag{5.3}$$

where $CHP_{TPO}$ is the annual total power output, $CHP_{QHO}$ is the annual qualifying heat output, while $CHP_{TFI}$ is the total annual fuel input.

## 5.3 Results and Discussion

The results of the techno-economic analysis of EfW fluidized bed combustion and gasification systems are presented in this section. The analysis is performed for the generation of combined heat and power from urban waste at two different scale scenarios of 50 ktpa and 100 ktpa. For the technical analysis, the performances of the different waste treatment options integrated with CHP are compared by determining their overall system efficiencies and environmental performances. The capital and operating expenditures, as well as the projected revenues generated from the sales of recovered energy and materials are reported for the economic comparison.

### 5.3.1 Technical performance

The net electricity and heat generated by the different treatment options and their overall system efficiencies are reported in Table 5.3 & 5.4 for the two plant scale scenarios of 50 ktpa and 100 ktpa, respectively. The results demonstrate that higher technical performances are achieved when heat and power are simultaneously recovered by the EfW facilities. Furthermore, combustion systems employing steam turbines have higher usable heat to power ratio and therefore, generate more heat than the other technologies.

This is reflected in their higher overall system efficiencies of 65% and 79% for the plant scale scenarios of 50 ktpa and 100 ktpa, respectively. Gasification systems have efficiencies of 55% and 58% for FBG+GE and FBG+CCGT, which increases by 6% and 9%, respectively, as the plant scale doubles to 100 ktpa. Table 5.3 & 5.4 also prove the eligibility of all waste treatment options for ROCs as the QI values are greater than 100. However, FBC+ST at 50 ktpa does not achieve the power efficiency threshold of 20% and as a result would not benefit from the additional income from ROCs.

**Table 5.3 Technical performances of treatment options at 50 ktpa scale scenario**

| | **Waste treatment options** | | |
|---|---|---|---|
| | **FBG+GE** | **FBG+CCGT** | **FBC+ST** |
| Thermal energy of waste | 29.4 (MWth) | | |
| Net generated electricity<br>*Amount available for export* | 7.0 (MWe)<br>55,500 (MWhe) | 7.6 (MWe)<br>60,000 (MWhe) | 5.4 (MWe)<br>42,400 (MWhe) |
| Net heat output<br>*Amount available for export* | 9.1 (MWth)<br>71,600 (MWth) | 9.7 (MWth)<br>76,500 (MWth) | 13.7 (MWth)<br>108,155 (MWth) |
| Electrical efficiency | 23.9 (%) | 25.9 (%) | 18.3 (%) |
| Thermal efficiency | 30.9 (%) | 33.0 (%) | 46.6 (%) |
| Overall system efficiency | 54.8 (%) | 58.9 (%) | 64.9 (%) |
| QI | 135 | 145 | 132 |

**Table 5.4 Technical performances of treatment options at 100 ktpa scale scenario**

| | **Waste treatment options** | | |
|---|---|---|---|
| | **FBG+GE** | **FBG+CCGT** | **FBC+ST** |
| Thermal energy of waste | 58.8 (MWth) | | |
| Net generated electricity<br>*Amount available for export* | 14.9 (MWe)<br>117,500 (MWhe) | 16.7 (MWe)<br>131,200 (MWhe) | 13.2 (MWe)<br>103,700 (MWhe) |
| Net heat output<br>*Amount available for export* | 19.2 (MWth)<br>151,600 (MWth) | 21.2 (MWth)<br>167,300 (MWth) | 33.5 (MWth)<br>264,400 (MWth) |
| Electrical efficiency | 25.3 (%) | 28.3 (%) | 22.4 (%) |
| Thermal efficiency | 32.7 (%) | 36.1 (%) | 57.0 (%) |
| Overall system efficiency | 58.0 (%) | 64.4 (%) | 79.4 (%) |
| QI | 143 | 159 | 161 |

In order to assess the environmental benefits of EfW with CHP compared to electricity-only EfW, the $CO_2$ production by both types of facilities was calculated. These calculations were based on the stoichiometric relationship that 1 mole of $C$ would give 1 mole of $CO_2$ (Murphy & McKeogh, 2004). Hence, the amounts of $CO_2$ produced were obtained by taking into account the technical performances of the different waste treatment options, presented in Table 5.3 & 5.4, as well as the carbon and biodegradable contents of the waste. The results are shown in Table 5.5, which also report the $CO_2$ savings by EfW with CHP facilities from displacing fossil fuels in the separate generation of heat and power. For this analysis, the EfW with CHP were assumed to replace heat provided by gas boilers with $CO_2$ emission factors of 242 g$CO_2$/kWh (Defra, 2004) and electricity imported from the grid with an emission factor of 523 g$CO_2$/kWh (Defra, 2007j). A sample calculation for a 50 ktpa FBG+CCGT with CHP is shown in Appendix A.3.

**Table 5.5 Environmental benefits of EfW with CHP facilities**

| Treatment options with CHP | $CO_2$ production (g$CO_2$/kWh) | | CHP $CO_2$ savings |
|---|---|---|---|
| | Electricity-only EfW | EfW with CHP | (t$CO_2$ per annum) |
| 50 ktpa FBG+GE | 421 | 184 | 25,868 |
| 50 ktpa FBG+CCGT | 372 | 163 | 32,465 |
| 50 ktpa FBC+ST | 506 | 146 | 31,699 |
| 100 ktpa FBG+GE | 387 | 171 | 59,653 |
| 100 ktpa FBG+CCGT | 340 | 149 | 75,948 |
| 100 ktpa FBC+ST | 442 | 122 | 84,875 |

The results in Table 5.5 indicate that if the waste heat from EfW facilities was utilised fully, then these facilities can achieve, on average, 72% and 56% reduction in $CO_2$ emissions per unit kWh using the combustion and gasification processes, respectively. Furthermore, EfW with CHP benefits from increased carbon reductions through the displacement of energy that would otherwise be used for heat, as well as the carbon emissions avoided from fossil fuel electricity generation, including transmission and distribution losses. Up to 84,875 tonnes of $CO_2$ can be avoided by using FBC+ST systems at 100 ktpa plant capacities. FBC+ST systems have better environmental performances than gasification when both heat and power are generated simultaneously.

They can achieve greater system efficiencies, thus reducing energy usage and lowering $CO_2$ emissions.

It should be noted here that a range of values have been given in the literature for the $CO_2$ emissions from EfW facilities. For example, Murphy & McKeogh (2004) gave a value of 220 $gCO_2$/kWh for electricity-only EfW incineration facilities and 58 $gCO_2$/kWh for facilities incorporating CHP. Porteous (2005) gave a value of 264 $gCO_2$/kWh, while IEA (2003) reported emissions of 367 $gCO_2$/kWh. The reasons for these variations are due to the scale of the facilities and varying characteristics of the residual waste. The emission estimates by Porteous (2005), for instance, were based on EfW incineration plants producing 500 kWhe per tonne of waste, which has average carbon and biodegradable contents of 22.6% (based on proximate analysis) and 85%, respectively. In comparison, the RDF considered in this study has average carbon and biodegradable contents of 44.7% and 68%. Therefore, the $CO_2$ emissions reported in Table 5.5 are predictably greater than the published values in the literature. That said, these values however give more accurate indications of the environmental performances of the different waste treatment options as they are based on the type and characteristics of the waste treated, scales and technologies used. Similarly, the CHP emission savings compared to the separate generation of heat and power are dependent on the mix of technologies and fuel displaced, which in turn vary from one country to another. For example, in 1996, the average $CO_2$ emission factors for electricity were 477 $gCO_2$/kWh in the UK, 40 $gCO_2$/kWh in France, 155 $gCO_2$/kWh in Austria and 716 $gCO_2$/kWh in Ireland (Thomas et al., 2000).

## 5.3.2 Economic performance

The economic performances of the different waste treatment options integrated with CHP are summarised in Table 5.6 & 5.7 for the two plant scale scenarios of 50 ktpa and 100 ktpa. The capital and operating costs are reported and the cost effectiveness of these options are assessed using NPV and IRR, as well as predicted gate fees and levelised costs of waste treatment.

**Table 5.6 Economic performances of treatment options at 50 ktpa scale scenario**

| | **Waste treatment options** | | |
|---|---|---|---|
| | **FBG+GE** | **FBG+CCGT** | **FBC+ST** |
| Capital costs | 26.9 (£m)<br>538 (£/t) | 28.9 (£m)<br>578 (£/t) | 44.0 (£m)<br>881 (£/t) |
| Operating costs | 3.2 (£m)<br>64 (£/t) | 3.1 (£m)<br>63 (£/t) | 2.8 (£m)<br>56 (£/t) |
| NPV @ 9% discount rate | 11.9 (£m)<br>239 (£/t) | 12.2 (£m)<br>245 (£/t) | 14.5 (£m)<br>289 (£/t) |
| IRR | 13.8 (%) | 13.6 (%) | 12.6 (%) |
| Gate fees | | | |
| *without ROCs* | 82 (£/t) | 81 (£/t) | 105 (£/t) |
| *with ROCs* | 56 (£/t) | 53 (£/t) | 105 (£/t)* |
| Levelised costs | | | |
| *in terms of electricity generated* | 10.46 (p/kWh) | 9.92 (p/kWh) | 16.60 (p/kWh) |
| *in terms of waste treated* | 116 (£/t) | 119 (£/t) | 141 (£/t) |

* Not eligible for ROCs

**Table 5.7 Economic performances of treatment options at 100 ktpa scale scenario**

| | **Waste treatment options** | | |
|---|---|---|---|
| | **FBG+GE** | **FBG+CCGT** | **FBC+ST** |
| Capital costs | 49.0 (£m)<br>490 (£/t) | 52.5 (£m)<br>525 (£/t) | 81.3 (£m)<br>813 (£/t) |
| Operating costs | 6.1 (£m)<br>61 (£/t) | 6.0 (£m)<br>60 (£/t) | 5.3 (£m)<br>53 (£/t) |
| NPV @ 9% discount rate | 22.4 (£m)<br>224 (£/t) | 22.8 (£m)<br>228 (£/t) | 27.0 (£m)<br>270 (£/t) |
| IRR | 13.9 (%) | 13.7 (%) | 12.6 (%) |
| Gate fees | | | |
| *without ROCs* | 70 (£/t) | 66 (£/t) | 80 (£/t) |
| *with ROCs* | 42 (£/t) | 35 (£/t) | 56 (£/t) |
| Levelised costs | | | |
| *in terms of electricity generated* | 9.27 (p/kWh) | 8.47 (p/kWh) | 12.65 (p/kWh) |
| *in terms of waste treated* | 109 (£/t) | 111 (£/t) | 131 (£/t) |

The results indicate that gasification systems with CHP offer the cheapest option, with capital costs of £27-53 million, compared to £44-81 million for the combustion systems. However, as reported in Table 5.3 & 5.4, the combustion systems have higher capital costs because they have larger thermal capacities than the gasification systems and can supply up to 72% more heat to the DH networks. This is further illustrated in Figure 5.8, which breaks down the capital costs of the different waste treatment options with CHP. In addition, if all the thermal capacities of the combustion systems are utilised fully, then they will gain greater income form heat sales and improve their cost effectiveness.

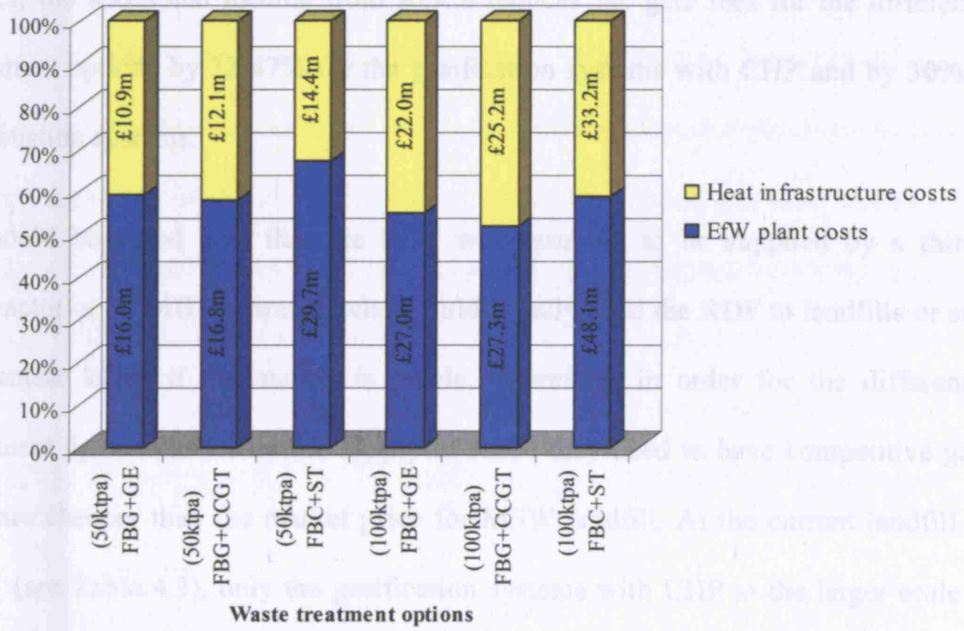


**Figure 5.8 Breakdown of capital costs for the different waste treatment options with CHP**

Utilising the waste heat available from the EfW facilities does not only increase their technical and environmental performances but also improves their economic viability. Table 5.6 & 5.7 show that all EfW with CHP facilities have better NPV and IRR performances when compared to electricity-only EfW (see Table 4.7 and 4.8). For the gasification systems with CHP, the NPV is 5-11% higher and the IRR is higher by 9-

15%. On the other hand, the NPV for the combustion systems with CHP is higher by 13-22% and the IRR by 26-29%.

In terms of gate fees and levelised costs of waste treatment, EfW with CHP facilities incur higher costs for utilising the waste heat, providing the heat infrastructure and connecting to the end users. When compared to electricity-only EfW, the gate fees for the gasification systems with CHP increase by 22-27% and the levelised costs by 40-48%. While for the combustion systems with CHP, the gate fees increase by 19-22% and levelised costs by 52-63%. Apart from FBC+ST at 50 ktpa, which does not qualify for ROCs, the additional income from ROCs reduces the gate fees for the different waste treatment options by 32-47% for the gasification systems with CHP and by 30% for the combustion systems.

It should be noted here that the RDF was assumed to be supplied by a third party contractor or an MBT operator, who would usually send the RDF to landfills or supply it to cement kilns, if the market is viable. Therefore, in order for the different waste treatment options to secure the supply of RDF, they need to have competitive gate fees that are cheaper than the market price for MSW landfill. At the current landfill cost of £48/t (see Table 4.3), only the gasification systems with CHP at the larger scale of 100 ktpa are able to offer reasonable gate fees for the supply of RDF. That said, as the landfill tax escalates (and consequently the landfill cost) by £8/t per annum, the rest of the waste treatment options will be able to offer favourable gate fees.

It has been established so far that the technical and economic performances of EfW with CHP facilities are site and project specific. Regarding the technical analysis, the overall system efficiencies of these facilities can be further improved by plant-wide heat recovery optimisation. For example, the steam turbines in the CCGT units can supply more heat if a duct burner is added to the system, while, different types of heat recovery boilers can be employed, which can give a range of heat rates. However, it is important to remember that the most optimal plant configuration is not necessarily the cheapest option, as there is a trade-off between efficiency and capital costs.

For the economic analysis, it was assumed that the waste heat from the EfW with CHP facilities supplies newly-built DH schemes, which have a mix of customers, including domestic and non-domestic users. All the waste heat was assumed to be exported to the DH network, with 10% allowance for distribution heat losses. These assumptions were made to recognise the important contribution from the mix of end user and heat density to the financial viability of the facilities. This is because the energy demands from the residential or domestic users-only are highly seasonable and depend on the types of the properties served. For example, purpose-built flats consume less energy than terraced or detached properties. In addition, the longer the heating season, the better the economic returns for the EfW with CHP facilities.

**Table 5.8 Number of potential residential, commercial and industrial users of CHP***

| Treatment options with CHP | No. of CHP electricity users | | No. of CHP heat users | |
|---|---|---|---|---|
| | Residential | Commercial/ industrial | Residential | Commercial/ industrial |
| 50 ktpa FBG+GE | 11,913 | 712 | 3,699 | 144 |
| 50 ktpa FBG+CCGT | 12,877 | 770 | 3,950 | 154 |
| 50 ktpa FBC+ST | 9,104 | 544 | 5,586 | 218 |
| 100 ktpa FBG+GE | 25,221 | 1,508 | 7,831 | 305 |
| 100 ktpa FBG+CCGT | 28,171 | 1,684 | 8,642 | 337 |
| 100 ktpa FBC+ST | 22,253 | 1,330 | 13,654 | 532 |

* 10% allowance was given for electricity transmission and heat distribution losses

Furthermore, public sector properties, such hospitals and schools, as well as universities, leisure centres and commercial developments have longer heating seasons and may provide year-round heat demands. Table 5.8 presents the number of potential users of combined heat and power from the EfW with CHP facilities. The results are based on the values reported in Table 5.3 & 5.4 for the electricity and heat generated from these facilities and the 2006 average electricity and gas consumption in London (BERR, 2008) for the residential, commercial and industrial sectors (see Appendix A.4 for further details).

The other main contributors to the financial viability of the EfW with CHP facilities are the scale of the DH schemes, their capital costs and market penetration. The first two contributors have been already addressed in this analysis, while the latter relates to the amounts of heat exported and number of buildings connected to the DH scheme (BRE, 2003). In this analysis, all the waste heat was initially assumed to be exported to the DH networks, corresponding to a 100% market penetration. Therefore, in order to assess the impact of heat demand on the economic viability, the NPV for the EfW with CHP facilities was calculated for a range of market penetration levels and the results are reported in Figure 5.9.

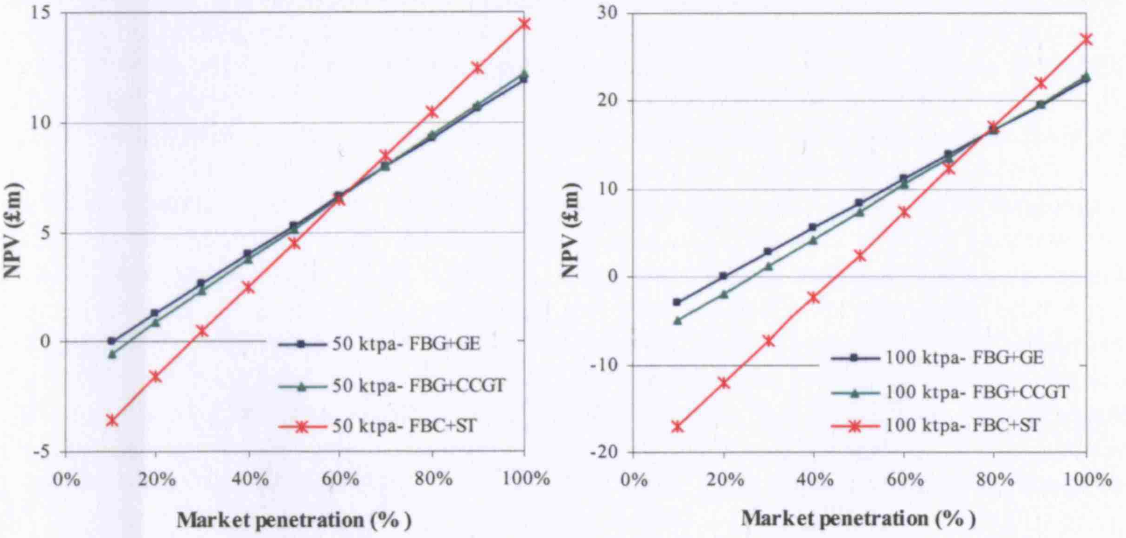


**Figure 5.9 Effect of different market penetration levels on the NPV of EfW with CHP facilities at 50 ktpa (left) and 100 ktpa (right) scale capacities**

The results show how the profitability of the EfW with CHP facilities varies with market penetration for both plant scale scenarios of 50 ktpa and 100 ktpa. The greater the amounts of heat exported and number of buildings connected to the DH scheme, the more profitable the investment. The results also reveal the level of market penetration required to break even and recoup the additional investments for the provision of CHP and DH networks. The profitability of the combustion systems with CHP are most affected by the amounts of heat exported. These systems require between 28-45% market penetration levels in order to recover their substantial investments. This is compared to only 10-26% for the gasification systems to break even, as shown in Table 5.9.

**Table 5.9 Required market penetration for break-even point**

| Treatment options with CHP | Market penetration for break-even point | |
|---|---|---|
| | 50 ktpa | 100 ktpa |
| FBG+GE | 9.9% | 20.2% |
| FBG+CCGT | 13.6% | 26.2% |
| FBC+ST | 27.7% | 44.9% |

## 5.4 Conclusions

This chapter has reported the technical and cost effectiveness of the simultaneous generation of heat and power from EfW facilities. The study builds on the earlier work reported in Chapter 4 and focuses on the additional capital and operating costs involved in incorporating CHP into EfW facilities. These costs include the installations and maintenance of heat exchangers, heat networks and customer connections. The projected revenues from heat sales and eligibility for ROCs were also evaluated for a range of market penetration levels. Furthermore, the environmental benefits associated with combined heat and power from EfW facilities were assessed and the $CO_2$ savings achieved from displacing fossil fuels in the separate generation of heat and power were also reported.

The technical analysis has shown that utilising the waste heat from the EfW facilities improves their system efficiencies. Combustion systems, in particular, have higher usable heat to power ratio and generate more heat than any of the other technologies. Therefore, they can achieve greater system efficiencies, thus reducing energy usage and lowering $CO_2$ emissions. In addition, the full utilisation of waste heat enables EfW facilities to reduce $CO_2$ emissions by 72% and 65% using combustion and gasification processes, respectively. Furthermore, EfW with CHP benefits from increased carbon reductions through the displacement of energy that would otherwise be used for heat, as well as the carbon emissions avoided from fossil fuel electricity generation, including transmission and distribution losses. However, the carbon savings are only applicable to the technologies, scales and waste characteristics considered in this analysis. They are also dependent on the mix of technologies and fuel displaced, which in turn vary from one country to another.

The economic viability of EfW with CHP facilities depends on their scale, capital costs, mix of customers using the DH network and the level of market penetration. The heat from these facilities was assumed to supply newly-built DH schemes, with a mix of customers including domestic and non-domestic users, in order to guarantee a consistent year-round heat demand. Capital costs of £490/t to £578/t were reported for the gasification systems with CHP, compared to £813/t and £881/t for the combustion systems.

Although all the waste heat was initially assumed to be exported to the DH networks, corresponding to a 100% market penetration, the profitability of the different options were tested against a range of market penetration levels. The results have shown that the profitability of the combustion systems with CHP are affected by the market penetration levels more than the other systems. These systems also require between 28-45% market penetration levels in order to recover their substantial investments in the DH schemes, as compared to only 10-26% for the gasification systems.

# 6 Conclusions and future work

In the developed world, over 75% of the population live in urban areas, a figure projected to rise to nearly 83% by 2030, while this rate of urbanisation is even faster in the developing world. Along with urbanisation came increased demands for energy and natural resources, fuelled by increasing consumption levels per capita in rich countries and rapid rise in consumption in developing ones, namely China and India. This has provided the setting for increased human activities, which have major economic and environmental impacts. As we burn fossil fuels and change land use, we are increasing the concentration of greenhouse gases, thus changing the nature of the earth surface and contributing to climate change.

The way we manage and dispose of our waste has a direct influence on greenhouse gas emissions. Therefore, if we are to satisfy our basic needs and enjoy a better quality of life without compromising the quality of life of future generations, we must improve our resource efficiency and reduce climate impact. Waste that is not created in the first place does not need to be re-used, recycled or disposed of and is, ultimately, the most environmentally desirable option.

The use of MSW to produce energy or fuel plays an important role in the UK's waste strategy, when integrated with recycling and re-use initiatives, as it reduces our reliance on landfill. It is also a low carbon, low cost fuel, which by displacing fossil fuels can help the Government in meeting its energy policy and emission targets. Moreover, EfW contributes to energy security through diversification of supply, as up to 17% of the total UK electricity consumption can be supplied by EfW in 2020.

The main objective of this research, which was defined as part of the Sustainable Urban Environment (SUE) waste management consortium, was to investigate the appropriate scales and technologies for the production of energy from waste in the urban environment. The research focused on the suitability and effectiveness of fluidized bed combustion and gasification processes, together with gas clean-up systems. The most appropriate scales for each of these approaches in relation to technical and economic performances were evaluated, so that a sound judgement can be made as to which processes should be used in the urban context.

Within this framework, the thesis began with a comprehensive assessment of fluidized bed reactor types and operational process conditions. The study focused on advanced thermal treatment processes, namely gasification, and reported the present and future status of these technologies, as well as the non-technical drivers affecting their commercial development. The assessment concluded with a review of the different emissions and residues generated from the thermal treatment processes, their management, practices and costs.

The scales and technologies for EfW and clean biomass were investigated during my five-month placement programme at Germanà & Partners Consulting Engineers in Rome (Italy). The main aim of the collaboration was to gain an in-depth understanding of design methodologies and engineering principles applied in the detailed design of real industrial energy recovery plants. The work enabled the study of mass and energy balances of a more traditional moving-grate combustion plant and identified key issues regarding the treatment of the output gas stream. This led to the subsequent consideration of more advanced technologies, such as fluidized bed combustion and gasification systems coupled with different energy conversion technologies. Furthermore, the study has identified the need for a consistent approach to examine the technical and economic performances of the different waste treatment options.

In addressing the problem posed earlier, a consistent methodology was adopted to compare the technical and economic performances of EfW fluidized bed combustion and gasification systems. Two different scale scenarios of 50 ktpa and 100 ktpa plant capacities were considered for the generation of electric power using a steam turbine for the combustion process and gas engine & CCGT for the gasification process. Mass and energy balances of the processes were performed and the cost effectiveness of the different waste treatment options was assessed using a discounted cash flow analysis. Additionally, a sensitivity analysis was performed to identify the most influential model input parameters and test the robustness of the assumptions made. The techno-economic analysis of traditional moving-grate combustions systems was also reported and compared against the different fluidized bed systems co-located with MBT facilities.

Finally, the technical and cost effectiveness of the simultaneous generation of heat and power from EfW facilities were reported. The study focused on the additional capital and operating costs involved in incorporating CHP into EfW facilities. These costs include the installations and maintenance of heat exchangers, heat networks and customer connections. The projected revenues from heat sales and eligibility for ROCs were also evaluated for a range of market penetration levels. Additionally, the environmental benefits associated with combined heat and power from EfW facilities were assessed and the $CO_2$ savings achieved from displacing fossil fuels in the separate generation of heat and power were also reported.

## 6.1 Main conclusions

The main conclusions from this research are summarised below:

- The literature review of traditional EfW combustion and more advanced waste thermal treatment processes, including gasification and pyrolysis, reveals that combustion processes are the most established, followed by gasification, while pyrolysis is at an early stage of commercialisation. For this reason, EfW technologies in the UK are predominately combustion processes employing moving-grate systems. These systems are well proven worldwide and are available from credible suppliers with a proven track record. However, the thesis highlights that fluidized bed combustion technologies offer alternative and reliable options to moving-grate because of their ability to handle waste of widely varied properties and the many advantages in controlling emissions. This is demonstrated by the fact that, although the technology has a limited track record in the UK for MSW treatment, there are over 150 plants in commercial operation in Europe and Japan.

- The thesis presented a review of various leading biomass and waste fluidized bed gasification technologies and demonstrated their technical feasibility, while employing different reactor types and operational conditions. The non-technical barrier that are currently preventing the full development and implementation of these technologies are also identified and discussed. Amongst these barriers, the work has revealed that the unavailability of commercial plants for MSW gasification in the UK is rendering this process non bankable in the current market state.

- The public perception, especially of incineration, is less than favourable and has to some extent hindered the development of EfW technologies in the UK. The appalling emission performances of the earlier generation of incinerators are the culprits and have clouted the public opinions for many years. However, the increased publicity of climate change has helped sustainable waste practices to move up the political agenda and the public are starting to embrace the need for waste reduction, recycling and energy recovery initiatives. In addition, the review showed that modern EfW plants have efficient energy recovery systems with sophisticated gas clean-up processes, produce energy and reduce waste to inert residues. Emissions are tightly controlled by the Environment Agency, who makes sure that they are kept well below stringent levels set by UK and EU legislations.

- The main residues from the thermal treatment processes are bottom ash and APC residues. The bottom ash is widely used throughout Europe as a secondary aggregate in road construction and building industry, while the APC residues including fly ash are treated and disposed of safely. The thesis stresses the importance of moving the treatment of these residues up the waste hierarchy, with more emphasis on recycling and recovery. However, this would require the establishment of consistent regulations and specification standards for residue re-use applications. The negative public opinion that recycled products from waste are of inferior quality and economic barriers, such as the low costs of natural minerals compared to ash residues, should be also addressed.

- Although there is no obvious "best" technology, fluidized beds offer robust and scalable reactors, with better energy efficiencies and greater pollution controls. The thesis highlights the need for the diversification of waste management approaches in order to meet the recycling, composting and recovery targets. This in turn, necessitates the establishment of facilities and sites that accommodate more than one waste management option. Since fluidized beds can be incorporated into such systems, they have the potential to contribute towards sustainable waste management practices across the UK.

- Five case studies describing the process design of combustion and gasification systems have been presented. The study examined their technical performances at different scales, ranging from 2,000 tpa to 260,000 tpa of waste, and using various reactor types and energy conversion technologies, namely steam turbines, gas engines, fuel cells and CCGT. The study also identified key issues regarding the removal of acidic pollutants from the flue gas stream. The efficiency and cost of replacing hydrated lime with sodium bicarbonate was investigated by applying a kinetic model in order to simulate the reactions between the reagents and acidic pollutants, namely $HCl$ and $SO_2$. It was concluded that although sodium bicarbonate is a more expensive reagent, it is more efficient and it is economically a more attractive option for the removal of acidic pollutants than hydrated lime. In this study, the theoretical numbers of recycle stages required for the sorption or neutralisation of 95% of the acidic gases and the time taken have been calculated for both reagents. The results obtained showed that sodium bicarbonate requires 95 s and 14 recycle stages for the removal of $HCl$ and $SO_2$ from the flue gas stream, compared to 1960 s and 296 recycle stages for hydrated lime. The study contributed to the re-design of a 34.1 MWe commercial-scale, moving-grate combustion plant that can process up to 260,000 tpa of waste.

- Regarding the technical performances of the five case studies, the analysis demonstrated that moving-grate combustion systems are favourable at large-scale applications and, if the bottom ash is recycled, they would potentially divert the highest amounts of waste from landfills. Fluidized bed systems are presented as suitable alternative technologies to moving-grate and are capable of treating waste of widely varied properties. These technologies become even more favourable when integrated with re-use and recycling initiatives because of their compatibility with high levels of source separation. Furthermore, at small-to-medium scales, fluidized bed gasification systems are shown to be favourable because they can be built efficiently and economically as modular units. They also can utilise different energy conversion technologies with higher efficiencies.

- Selecting the appropriate energy conversion technologies has a significant impact in the efficient recovery of heat and power from waste and determining the applicability of EfW processes at different scales. For combustion processes, heat and power are usually generated using steam turbines, which can operate across a range of capacities and up to 500 MWe. However, they are economically feasible only for capacities greater than 1.5 MWe because of their inherent low electricity generation efficiency and high capital costs. This is why large centralised combustion facilities are often preferred, as they can benefit from economies of scale. The first two case studies demonstrated this and reported the technical performances of a 34.1 MWe moving-grate combustion system processing 260,000 tpa and 7.3 MWe fluidized bed combustion plant at 50,000 tpa.

- In the third and fourth case studies, the use of gas engines and fuel cells were demonstrated, at the smaller scales of 2,000 tpa and 5,100 tpa respectively, for the generation of 160 kWe and 914 kWe from renewable sources using fluidized bed gasification systems. Gas engines are widely used in rural areas and present the most economical options for electricity generation. Fuel cells, on the other hand, have high efficiencies and are seen as low carbon energy technologies. Both technologies are available in small modular units and can be easily integrated into small-to-medium scale energy systems. Small-scale biomass systems can also be fuelled by local resources, which can reduce the economic difficulties of transporting bulky fuels with low calorific values over large distances. The electricity generated can be sold locally or consumed internally, while the heat produced can be utilised within the process.

- In case study 5, the design of a 50,000 tpa fluidized bed gasification plant employing CCGT and generating 8.0 MWe was carried out. This was done in order to compare the technical performances of waste combustion and gasification systems using efficient energy conversion technologies. CCGT is the most efficient way to generate electricity and the results of the process design have shown system efficiencies comparable to large-scale combustion processes.

- The study was further developed by analysing the technical and economic performances of EfW fluidized bed combustion and gasification systems at 50,000 tpa and 100,000 tpa. For the different fluidized bed waste treatment options, the analysis showed that the ability of gasification processes to employ more efficient energy conversion systems, enables them to have greater electrical generation efficiencies. As a result, they have better overall system performances of 24% to 28%, compared to 18% and 22% for combustion processes. Fluidized bed gasification coupled with CCGT, in particular, offers the most energy efficient treatment option.

- In terms of economic performances, capital costs of £270/t to £336/t were reported for the gasification options, compared to £481/t and £594/t for combustion. Fluidized bed gasification coupled with gas engine has the cheapest capital cost option and the highest rate of return on investment. However, this is offset by its higher operating cost and the lower system efficiency, compared to fluidized bed gasification coupled with CCGT, which is the most attractive treatment option in terms of gate fee and levelised cost of waste treatment. For the gasification options, gate fees of £52/t to £67/t were reported for both scale scenarios of 50,000 tpa and 100,000 tpa, compared to £67/t and £87/t for combustion. For the levelised costs, the gasification options cost between 5.7 p/kWh and 7.5 p/kWh, compared to 7.8 p/kWh and 10.9 p/kWh for combustion.

- Fluidized bed gasification systems have unproven track record in the UK. However, they are compatible with high levels of source segregation and therefore, have the potential to contribute towards integrated waste management practices. In addition, the operational reliability of the systems will be further improved, as more facilities are commissioned and operated at commercial scales. Moreover, financial incentives, such as ROCs, securing long-term contractual agreements for the supply of RDF, as well as supportive policies and active R&D by major industry players and research institutions, are important factors for the full commercialisation of these processes, especially for plant scales larger than 50 ktpa.

- The sensitivity analysis was carried out to evaluate the effects of changing system variables on the economic performances of the different waste treatment options. Seventeen system variables have been chosen and the effects of a ±10% change in these variables on the levelised costs and gate fees were examined. The sensitivity analysis demonstrated that the calorific value of the waste, electricity generation efficiencies of the prime movers and gasifier efficiency had the greatest impact on the levelised costs, while the gate fees were affected by the operating costs, ROCs and biodegradable fraction of the waste.

- Although traditional moving-grate combustion systems showed to have lower technical and economic performances, compared to fluidized bed gasification systems co-located with MBT facilities, they had the highest landfill diversion potential, assuming the bottom ash was recycled. This said, gasification systems co-located with MBT facilities can achieve higher levels of recycling. However, market availability for their outputs will have a significant influence on the environmental impacts of these processes.

- Finally, the technical and cost effectiveness of the simultaneous generation of heat and power from EfW facilities were reported. The technical analysis revealed that utilising the waste heat from the EfW facilities improves their system efficiencies. Combustion systems, in particular, have higher usable heat to power ratio and generate more heat than any of the other technologies. Therefore, they can achieve greater system efficiencies, thus reducing energy usage and lowering $CO_2$ emissions. In fact, the full utilisation of waste heat enables EfW facilities to reduce $CO_2$ emissions by 72% and 65% using combustion and gasification processes, respectively. Furthermore, EfW with CHP benefits from increased carbon reductions through the displacement of energy that would otherwise be used for heat, as well as the carbon emissions avoided from fossil fuel electricity generation, including transmission and distribution losses. Up to 84,875 tonnes of $CO_2$ can be avoided by using FBC+ST systems at 100 ktpa plant capacities. However, the carbon savings are only applicable to the technologies, scales and waste characteristics considered in this analysis. They are also dependent on the mix of technologies and fuel displaced, which in turn vary from one country to another.

- The economic viability of EfW with CHP facilities depends on their scale, capital costs, mix of customers using the DH network and the level of market penetration. The heat from these facilities was assumed to supply newly-built DH schemes, with a mix of customers including domestic and non-domestic users, in order to guarantee a consistent year-round heat demands. In this study, combustion and gasification systems with CHP showed the potential to supply up to 13,700 residents with heat and 28,000 others with power. Alternatively, they can supply to over 500 commercial & industrial users with heat and 1,700 others with power. In terms of economic performances, capital costs of £490/t to £578/t were reported for the gasification systems with CHP, compared to £813/t and £881/t for the combustion systems.
- Initially, all the waste heat was assumed to be exported to the DH networks, corresponding to a 100% market penetration. Therefore, the profitability of the different options was tested against a range of market penetration levels and the results have shown that the combustion systems with CHP were affected by the market penetration levels more than the other systems. These systems also require between 28% and 45% market penetration levels in order to recover their substantial investments in the DH schemes. This is compared to only between 10% and 26% for the gasification systems.

In conclusion, this thesis has addressed the technical and economic viability of EfW fluidized bed combustion and gasification processes, employing different energy conversion technologies. The thesis also highlighted the potential environmental benefits of these processes in offsetting significant amounts of fossil fuel-based generation and reducing carbon emissions. However, although the right technologies exist to efficiently and cost effectively reduce our reliance on landfill; increase resource efficiency; and reduce climate change impacts, these potentials can not be delivered without enabling and supportive policies. Therefore, one question remains:

*'Is the political will available?!'*

One would hope the answer is *'YES!'* and that this thesis has not been carried out in vain!

The UK Government has often been criticised for lack of direction and leadership, which have created uncertainty for the waste management industry. Moreover, only recently it has acknowledged the role that EfW can play as part of an integrated waste management solution. Nevertheless, the Government is making progress and trying to catch up with those European countries that have been successful in developing infrastructure for the diversion of waste from landfill.

That said, in order for the UK to emulate the performances achieved by these successful European countries, it needs to learn from their experiences, as they have had relevant policy, planning and financial mechanisms in place for a relatively long time.

## 6.2 Future work

This research project has focused on the suitability and effectiveness of fluidized bed combustion and gasification for the thermal treatment of urban waste. Therefore, it would be useful for future work to consider the technical and economic viability of pyrolysis processes (see section 2.2.4) for different process outputs (i.e. production of liquid fuel, solid char or syngas) and using different energy conversion technologies. Similarly, the production of chemicals and synthesis fuels from biomass and waste, such methanol or higher hydrocarbons, can be investigated for both pyrolysis and gasification processes in terms of system efficiencies and costs.

The technical and economic analysis performed throughout this research project can be followed-up by a comprehensive life cycle assessment (LCA), as part of a wider sustainability appraisal, which takes account of environmental, socio-economic and implementation issues. The sustainability objectives regarding the environment & health may include, for example, the reduction of greenhouse gas emissions and minimisation of adverse effects on water quality. Minimisation of local transport impacts and provision of employment opportunities can be included for the socio-economic objectives, while ensuring reliability of delivery and conforming to the waste hierarchy should be considered for the implementation and public framework objectives (Environment Agency, 2006b).

It was concluded in Chapter 4 that gasification systems co-located with MBT facilities can achieve high levels of recycling. However, this dependent on market availability for their products, which in turn is site and project specific. Therefore, the LCA should also consider the final destination of the recycled materials, as this will determine the overall landfill diversion potential of these processes and their environmental credentials.

In Chapter 5, the technical and economic performances, as well as the environmental benefits of EfW with CHP facilities have been evaluated. The potential for improving the energy efficiency of residential, as well as the commercial and industrial sectors in the UK were also highlighted. Beside district and community heating schemes, local heat and power can be supplied using CHP to individual buildings with high and consistent energy demand, such as universities, hospitals and prisons. Therefore, as a case study, the methodology developed in this thesis can be applied to investigate the suitability of providing heat and power to the residential and faculty buildings at University College London (UCL) using CHP. Detailed energy demand profiles for both electricity and heat consumption by the university can be performed in order to accurately size the CHP. In addition, the use of different fuel alternatives, such as biomass, waste and natural gas can be evaluated along with different energy conversion technologies, such as micro-turbines, gas engines and fuel cells.

The techno-economic analysis detailed in Chapter 4 & 5 can be also used to determine the potential of incorporating CHP into the EfW facilities in London, such as Edmonton & SELCHP. Moreover, the potential viability for supplying process steam from Novera's East London Sustainable Energy Facility (ELSEF) to the near by industrial plants can also be investigated. The ELSEF is currently planned to only generate electricity.

# Nomenclature

## Abbreviations

| | |
|---|---|
| AD | Anaerobic Digestion |
| AiIE | Associates in Industrial Ecology |
| APC | Air Pollution Control |
| ATT | Advanced Thermal Treatment |
| BA | Bottom Ash |
| BERR | Department for Business, Enterprise and Regulatory Reform (formerly DTI) |
| BFB | Bubbling Fluidized Bed |
| BPEO | Best Practicable Environmental Option |
| BRE | Building Research Establishment Ltd |
| BVPI | Best Value Performance Indicator |
| CCGT | Combined Cycle Gas Turbine |
| CF | Cash Flow |
| CFB | Circulating Fluidized Bed |
| CH | Community Heating |
| CHP | Combined Heat and Power |
| CHPA | Combined Heat and Power Association |
| CHPQA | Combined Heat and Power Quality Assurance |
| CIWM | Charted Institute of Waste Management |
| CLO | Compost-like output |
| DCF | Discounted Cash Flow |
| Defra | Department for Environment, Food and Rural Affairs |
| DH | District Heating |
| DNOs | Distribution Network Operators |

| | |
|---|---|
| DTI | Department for Trade and Industry (now BERR) |
| EEA | European Environmental Agency |
| EfW | Energy from Waste |
| ENEA | Italian National Agency for New Technologies, Energy and the Environment |
| ESA | Environmental Services Association |
| EU ETS | European Union Emission Trading Scheme |
| FBC | Fluidized Bed Combustion |
| FBG | Fluidized Bed Gasification |
| FICFB | Fast Internal Circulating Fluidized Bed |
| GDP | Gross Domestic Product |
| GE | Gas Engine |
| GHG | Greenhouse Gas |
| GLA | Greater London Authority |
| GWh | Giga Watt hour (1,000,000,000 Wh) |
| HHV | High Heating Value |
| HPA | Health Protection Agency |
| HRSG | Heat Recovery Steam Generator |
| ICHPA | Irish Combined Heat and Power Association |
| IEA | International Energy Agency |
| IFB | Interconnected Bubbling Fluidized Bed |
| IGCC | Integrated Gasification Combined Cycle |
| IPCC | Intergovernmental Panel on Climate Change |
| IRR | Internal Rate of Return |
| ISWA | International Solid Waste Association |
| ktpa | Kilo tonne per annum (1,000,000 kg per annum) |
| kWh | Kilo Watt hour (1,000 watt hours) |
| LATS | Landfill Allowance Trading Scheme |
| LCA | Life Cycle Analysis |
| LECs | Levy exemption Certificates |
| LHV | Lower Heating Value |
| LIER | The Chinese Liaoning Research Institute of Yingkou |
| LTGDC | London Thames Gateway Development Corporation |

| | |
|---|---|
| MBT | Mechanical Biological Treatment |
| MSW | Municipal Solid Waste |
| MWe/MWth | Mega Watt (electrical/thermal) |
| MWh | Mega Watt hour (1,000,000 watt hours) |
| NFFO | Non-Fossil Fuel Obligation |
| NIMBY | Not In My Back Yard |
| NPV | Net Present Value |
| ODPM | Office of the Deputy Prime Minister (now Department for Communities and Local Government) |
| Ofgem | Office for Gas and Electricity Markets |
| ONS | Office for National Statistics |
| ORC | Organic Rankine Cycle |
| PAFC | Phosphoric Acid Fuel Cell |
| PAHs | Polycyclic Aromatic Hydrocarbons |
| PFI | Private Finance Initiative |
| PIU | Performance and Innovation Unit |
| PRASEG | The Associate Parliamentary Renewable and Sustainable Energy Group |
| PRNs | Packaging Recovery Notes |
| RCEP | Royal Commission on Environmental Pollution |
| RDF | Refuse Derived Fuel |
| RO | Renewables Obligation |
| ROCs | Renewables Obligation Certificate |
| RRBF | Refined Renewable Biomass Fuel |
| RTFO | Renewable Transport Fuel Obligation |
| RTI | Resources Transforms International |
| RTP™ | Rapid Thermal Process |
| SCR | Selective Catalytic Reduction |
| SEPA | Scottish Environment Protection Agency |
| SEM | Scanning Electron Microscope Analysis |
| SNCR | Selective Non-Catalytic Reduction |
| SRF | Solid Recovered Fuel |
| ST | Steam Turbine |
| TIF | Twin-internally Circulating Fluidized bed Furnace |

| | |
|---|---|
| tpa | Tonne per annum (1,000 kg per annum) |
| UNEP | United Nations Environment Programme |
| U.S. EPA | United States Environmental Protection Agency |
| VAT | Value Added Tax |
| VOCs | Volatile Organic Compounds |
| WID | Waste Incineration Directive |
| WISARD | Waste – Integrated Systems Assessment for Recovery and Disposal |
| WRAP | Waste & Resources Action Programme |
| WRATE | Waste and Resources Assessment Tool for the Environment |

## Roman Symbols

| | |
|---|---|
| $a$ | Stoichiometric coefficient of gaseous acids |
| $b$ | Stoichiometric coefficient of reagents |
| $C_{Ag}$ | Concentration of gaseous acids in the gaseous bulk ($kmol/m^3$) |
| $C_{As}$ | Concentration of gaseous acids in the solid-gas film ($kmol/m^3$) |
| $D_e$ | Effective diffusivity ($m^2/s$) |
| $k_g$ | Mass transfer coefficient ($m/s$) |
| $k_s$ | First order rate constant ($m/s$) |
| $M_B$ | Molar mass of reagent ($kg/kmol$) |
| $R$ | Particle radius ($m$) |
| $t$ | Time ($s$) |
| $x_B$ | Fractional conversion of reagents |

## Greek Symbols

| | |
|---|---|
| $\theta$ | Time for complete conversion of unreacted particle into a product ($s$) |
| $\rho$ | Density ($kg/m^3$) |

# References

AEA Technology. (2004). *Study of the Economics of Example CHP Schemes*. Defra, London, UK.

AiIE. (2003). *Review of Residual Waste Treatment Technologies*. AiIE, Penrith, UK.

APP. (2006). *Introduction to the Gasplasma Process: An Advanced Gasification Technology*. Company Pack.

Ares, E., Bolton, P. (2002). *Waste Incineration*. Research Paper 02/34. House of Commons Library, London, UK.

Arrieta, F.R.P., Sanchez, C.G. (1999). BIG-GT and CEST Technologies for Sugar Cane Mill. Thermodynamic and Economic Assessments. In Proc. of *The 2nd Olle Lindström Symposium on Renewable Energy, Bioenergy*, June 9-11, Stockholm, Sweden, 184-189.

Babu, S. (2005). *Biomass Gasification for Hydrogen Production – Process Description and Research Needs*. Technology Report. Task 33: Thermal Gasification of Biomass. IEA Bioenergy, Dublin, Ireland.

Babu, S. (2006). *Workshop No. 1: Perspectives on Biomass Gasification*. Task 33: Thermal Gasification of Biomass. IEA Bioenergy. Dublin, Ireland.

BERR. *Regional Energy Consumption Statistics*. See www.berr.gov.uk for further details. Accessed 14/01/2008.

Biomass Task Force. (2005). *Report to Government*. Defra, Crown, London, UK.

BRE. (2003). The *UK Potential for Community Heating with Combined Heat & Power*. Report for The Carbon Trust. BRE, Watford, UK.

BRE. *The Case for District Heating: 1000 Cities Cannot Be Wrong*. See www.bre.co.uk for further details. Accessed 07/01/2008.

Bridgwater, A.V. (2003). Renewable Fuels and Chemicals by Thermal Processing of Biomass. *Chemical Engineering Journal*, **91**, 87-102.

Bridgwater, A.V., Meier, D., Radlein, D. (1999). An Overview of Fast Pyrolysis of Biomass. *Organic Geochemistry*, **30**, 1479-1493.

Bridgwater, A.V., Peacocke, G.V.C. (2000). Fast Pyrolysis Processes for Biomass. *Renewable and Sustainable Energy Reviews*, **4**, 1-73.

Bridgwater, A.V., Toft, A.J., Brammer, J.G. (2002). A Techno-Economic Comparison of Power Production by Biomass Fast Pyrolysis with Gasification and Combustion. *Renewable and Sustainable Energy Reviews*, **6**, 181-248.

Bullard, M., Heaton, R., Osola, M. (2004). *Small-Scale Wood Fuel Heat and CHP Options for South West England*. Bio-Renewables Ltd, Ely, UK.

Burnley, S.J. (2007). The Use of Chemical Composition Data in Waste Management Planning- A Case Study. *Waste Management*, **27**, 327-336.

Channiwala, S.A., Parikh, P.P. A Unified Correlation for Estimating HHV of Solid, Liquid and Gaseous Fuels. *Fuel*, 2002, **81**, 1051-1063.

Chin, T., Yan, R., Chin, T., Liang, Tay, J. H. (2005). Hydrated Lime Reaction with HCl under Simulated Flue Gas. *Ind. Eng. Chem. Res.*, **44**, 3742-3748.

CHPQA. (2007). See www.chpqa.com for further details. Accessed 01/10/2007.

CIWM. (2003). *Energy from Waste: A Good Practice*. IWM Business Services, Northampton, UK.

Clift, R. (2007). *Sustainable Development*. Process Engineering Course Unit. Invited Speaker Seminar, October 16. University College London, London, UK.

Coggins, C. (2006). *Residual Waste as and Energy Resource.* A Report for SUE Waste Management Consortium.

Compact Power. See www.compactpower.co.uk for further details. Accessed 14/11/2006.

CRE Group. (2000). *The Management of Residues from Thermal Processes.* IEA Bioenergy, Dublin, Ireland.

C-Tech Innovation. (2003). *Thermal Methods of Municipal Waste Treatment.* C-Tech Innovation, Chester, UK.

Daoudi, M., Walters, J. K. (1991). A Thermogravimetric Study of the Reaction of Hydrogen Chloride Gas with Calcined Limestone: Determination of Kinetic Parameters. *Chem. Eng. J.*, **47**, 1-9.

De Nitto, F. (2003). *Flue Gas Treatment Processes for MSW Combustion.* Thesis Dissertation (in Italian), Engineering Faculty, Università Degli Studi Di L'Aquila. Italy.

Defra and BERR. (2007). *Renewable Heat Initial Business case.* BERR, London, UK.

Defra. (2004). *The Government's Strategy for Combined Heat and Power to 2010.* Defra, London, UK.

Defra. (2005a). Securing *the Future: Delivering Sustainable Development Strategy.* Defra, London, UK.

Defra. (2005b). *New Technologies Demonstrator Programme: Catalogue of Applications.* Defra, London, UK.

Defra. (2006a). *Climate Change: The UK Programme 2006.* Defra, London, UK.

Defra. (2006b). *Guidance on the Landfill Allowance Schemes: Municipal Waste.* Defra, London, UK.

Defra. (2007a). *UK Biomass Strategy.* Defra, London, UK.

Defra. (2007b). *Waste Strategy for England 2007.* Defra, London, UK.

Defra. (2007c). *Municipal Waste Management: 2005/06 United Kingdom*. e-Digest of Environmental Statistics. Defra, London, UK.

Defra. (2007d). *Incineration of Municipal Solid Waste*. Defra, London, UK.

Defra. (2007e). *Advanced Thermal treatment of Municipal Solid Waste*. Defra, London, UK.

Defra. (2007f). *Climate Change and Waste Management: The Link*. A Briefing note. Defra, London, UK.

Defra. (2007g). *Mechanical Biological Treatment of Municipal Solid Waste*. Defra, London, UK.

Defra. (2007h). *Analysis of The UK Potential for Combined Heat and Power*. Defra, London, UK.

Defra. (2007i). *Evaluation of Progress Towards Meeting The UK Potential for Combined Heat and Power*. Defra, London, UK.

Defra. (2007j). *Guidelines to Defra's GHG Conversion Factors for Company Reporting*. Defra, London, UK.

Drost, D., Eisenlohr, F., Kaiser, B., Kaiser, W., Stahlberg, R. (2004). Report on the Operating Trial with Automotive Shredder Residue (ASR). In Proc. of *The 4th International Automobile Recycling Congress*, March 10-12, Geneva, Switzerland.

DTI. (2006a). *The Energy Challenge: Energy Review Report*. DTI, London, UK.

DTI. (2006b). *Distributed Energy*. DTI, London, UK.

DTI. (2007a). *Meeting the Energy Challenge*. DTI, London, UK.

DTI. (2007b). *Reform of the Renewables Obligation*. DTI, London, UK.

Duo, W., Kirkby, N.F., Seville, J.P.K., Clift, R. (1995). Alteration with Reaction Progress of the Rate Limiting Step for Solid–Gas Reactions of Ca-Compounds with HCl. *Chem. Eng. Sci.*, **50**, 2017–2027.

Duvia, A., Gaia, M. (2002). ORC Plants for Power Production from Biomass from 0.4 MWe to 1.5 MWe: Technology, Efficiency, Practical Experiences and Economy. In Proc. of *The 7th Holzenergie-Synopsium*, October 18, Zurich, Switzerland.

Dynamotive. See www.dynamotive.com for further details. Accessed 01/09/2005.

EDUCOGEN. (2001). *A Guide to Cogeneration*. EDUCOGEN, Brussels, Belgium.

ENER-G. See www.energ.co.uk for further details. Accessed 01/10/2007.

Energylinx. *Sustainable Energy*. See www.energylinx.co.uk for further details. Accessed 11/10/2007.

Enerkem Technologies Inc. See www.enerkem.com for further details. Accessed 09/01/2006.

Ensyn Group Inc. See www.ensyn.com for further details. Accessed 01/09/2004.

Environment Agency. (2002). *IPPC Sector Guidance Note - Combustion Activities*. Environment Agency, Bristol, UK.

Environment Agency. (2006a). *Report on the Landfill Allowances and Trading Scheme (LATS) 2005/6*. Environment Agency, Bristol, UK.

Environment Agency. (2006b). *Sustainability Appraisal and Life Cycle Analysis of Strategic Waste Management Options*. Environment Agency, Cardiff, UK.

Environment Agency. (2007a). *Waste & Resource Assessment Tool for the Environment (WRATE)*. See www.environment-agency.gov.uk for further details. Accessed 01/10/2007.

Environment Agency. (2007b). *Waste Technology Data Centre*. See www.environment-agency. gov.uk for further details. Accessed 01/10/2007.

Environment Agency. (2007c). *Applying for an Accreditation to Reprocess or Export UK Waste Packaging*. Guidance Notes. Environment Agency, Bristol, UK.

Enviros, University of Birmingham, Risk and Policy Analysts, Open University, Thurgood, M. (2004). *Review of Environmental and Health Effects of Waste Management: Municipal Solid Waste and Similar Wastes*. Defra, London, UK.

Enviros. (2005). *Municipal Waste Management Strategy*. Enviros, London, UK.

ERM & Golders Associates. (2006). *Carbon Balances and Energy Impacts of the Management of UK Wastes*. Defra R&D Project WRT 237. Defra London, UK.

Ernst & Young. (2007a). *Renewable Heat Initial Business Case*. BERR and Defra, London, UK

Ernst & Young. (2007b). *Renewable Heat Support Mechanisms*. BERR & Defra, London, UK

ESA. See www.esauk.org for further details. Accessed 09/01/2006.

Eunomia Research & Consulting. (2001). *Costs for Municipal Waste Management in the EU*. European Commission, Brussels, Belgium.

European Commission. (2005). *Biomass- Green Energy for Europe*. European Communities, Luxemburg.

European Environment Agency (EEA). (2003). *Europe's Environment: The Third Assessment*. EEA, Luxemburg.

Eurostat. (2003). *Waste Generated and Treated in Europe*. European Communities, Luxembourg.

Fichtner Consulting Engineers. (2004). *The Viability of Advanced Thermal Treatment of MSW in the UK*. ESTET, London, UK.

Foscolo, P. U. (1997). *Production of Hydrogen-Rich Gas by Biomass Gasification: Application to Small Scale, Fuel Cell Electricity Generation in Rural Areas*. Publishable Final Report for The European Commission in the Framework of the Non Nuclear Energy Programme, JOULE III JOR3-CT95-0037.

Foscolo, P. U., Germanà, A., Jand, N., Rapagnà, S. (2007). Design and Cold Model Testing of a Biomass Gasifier Consisting of Two Interconnected Fluidized Beds. *Powder Technology*, **173**, 179-188.

Fujimura, H., Naruse, K. (2001). Fluidized-Bed Gasification and Slagging Combustion System. In Proc. of *The IT3 Conference*, May 14-18, Philadelphia, USA.

Garrod, N. (2006). The New Energy Recovery Facility for Sheffield. In Proc. of *CIWM-North East Centre Open Meeting*, October 6, Sheffield, UK.

Gasification Technologies Council. See www.gasification.org for further details. Accessed 09/01/2006.

GEM. See www.gem-ltd.co.uk for further details. Accessed 01/09/2004.

Gerrard, A.M. (2000). *Guide to Capital Cost Estimating, 4th Edition*. Institution of Chemical Engineers, Rugby, UK.

GLA. (2003). *City Solutions: New and Emerging Technologies for Sustainable Waste Management*. GLA, London, UK.

Greil, C., Vierrath, H. (2000). Practical Concepts for Parallel Firing, Pre-Gasification and Gas Cleaning. In: NOVEM (ed.). *Addressing the Constraints for Successful Replication of Demonstrated Technologies for Co-combustion of Biomass/Waste.* 1st World Conference and Exhibition on Biomass for Energy and Industry, June 6, Sevilla, Sweden.

Halliday, J., Ruddell, A., Powell, J., Peters, M. (2005). *Fuel Cells: Providing Heat and Power in the Urban Environment*. Tyndall Centre for Climate Change Research. Technical Report 32.

Hernandez-Atonal, F.D., Ryu, C., Sherifi, V.N., Swithenbank, J. (2007). Combustion of Refuse-Derived Fuel in a Fluidised Bed. *Chemical Engineering Science*, **62**, 627-35.

Higman, C., van der Burgt, M. (2003). *Gasification*. Elsevier Science, Burlington, USA.

House of Commons. (2007). *Waste Disposal.* Written Answers to Questions. House of Commons, London, UK.

Howson, J. (2007). Novera Energy, Personal communication.

HPA. (2005). *Position Statement on Municipal Solid Waste Incineration.* HPA, London, UK.

ICHPA. *Prime movers.* See www.ichpa.com for further details. Accessed 07/01/2008.

IEA. (2002). *Distributed Generation in Liberalised Electricity Markets.* OECD/IEA, Paris, France.

IEA. (2003). *Municipal Solid Waste and its Role in Sustainability.* IEA Bioenergy. Dublin, Ireland.

Ilex Energy Consulting. (2005a). *Eligibility of Energy from Waste- Study and Analysis.* DTI, London, UK.

Ilex Energy Consulting. (2005b). *Extending ROC Eligibility to Energy from Waste with CHP.* DTI, London, UK.

IPCC. (2007). *Climate Change 2007: The Physical Science Basis.* Working Group I Contribution to the Fourth assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

Jacobs Babtie. (2005). *Waste Management Treatment Options Appraisal.* Jacobs Babtie, Reading, UK.

Jones, P. (2005). Waste and Resource Management: Challenges Through to 2010. In: Institution of Civil Engineers, (ed.). *Warm and Resource Management.* Proceedings of The Institution of Civil Engineers, **159**, Issue WRI, 39-47.

Jörß, W., Joergensen, B. H., Loeffler, P., Morthorst, P.E., Uyterlinde, M.A., Sambeek, E.J.W. van, Wehnert, T., Groenendaal, B., Marin, M., Schwarzenbohler, H., Wagner, M. (2002). *Decentralised Generation Technologies. Potentials, Success Factors and Impacts in the Liberalised EU Energy Markets.* The DECENT Final Report. COGEN Europe, Brussels, Belgium.

Juniper. (2003). *Review of the Need for Energy from Waste, As Part of the Cheshire Household Waste Management Strategy.* Juniper, Uley, UK.

Juniper. (2007). *Advanced Conversion Technology (Gasification) for Biomass Projects.* Juniper, Uley, UK.

Karlsson, H.T., Klingspor, J., Bjerle, I. (1981). Adsorption of Hydrochloric Acid on Solid Slaked Lime for Flue Gas Clean Up. *J. Air Pollit. Control Assoc.*, **31**, 1177.

KBI Waste and Energy Solutions GmbH. See www.htcw.info for further details. Accessed 01/10/2007.

Kehlenbeck, R., Yates, J.G., Di Felice, R., Hofbauer, H., Rauch, R. (2002). Particle Residence Time and Particle Mixing in a Scaled Internal Circulating Fluidized Bed. *Ind. Eng. Chem. Res.*, **41**, 2637-2645.

Koornneef, J., Junginger, M., Faaij, A. (2007). Development of Fluidized Bed Combustion- An Overview of Trends, Performance and Cost. *Progress in Energy and Combustion Science*, **33**, 19-55.

Kuramato, M., Furusawa, T., Kunii, D. (1985). Development of a New System for Circulating Fluidized Particles within a Single Vessel. *Powder Technology*, **44**, 77-84.

Kuramato, M., Furusawa, T., Kunii, D. (1986). Flow of Dense Fluidized Particles Through an Opening in a Circulation System. *Powder Technology*, **47**, 141-149.

Kwant, K.W., Knoef, H. (2004). *Status of Biomass Gasification in Countries Participating in the IEA and GasNet Activity.* Country Report. EU GasNet & IEA Bioenergy Gasification.

Lee, P., Fitzsimons, D., Parker, D. (2005). *Quantification of the Potential Energy from Residuals (EfR) in the UK.* Technical Report Commissioned by The Institution of Civil Engineers and The Renewable Power Association. Oakdene Hollins Ltd., Aylesbury, UK.

Letsrecycle.com. (2007a). *Novera "Optimistic" of Alternative Funding for Gasification Plant.* See www.letsrecycle.com for further details. Accessed 01/10/2007.

Letsrecycle.com. (2007b). *Judge Throws Out Challenge to Belvedere Incinerator*. See www.letsrecycle.com for further details. Accessed 01/10/2007.

Letsrecycle.com. (2007c). *PRN Prices*. See www.letsrecycle.com/prices/ for further details. Accessed 01/10/2007.

Letsrecycle.com. (2007d). *Showcase for £45m Waste Treatment Plant in East London*. See www. letsrecycle.com/info/waste_management/news for further details. Accessed 01/10/2007.

Letsrecycle.com. (2007e). *Planning Approval for £25m East London Gasification Plant*. See www. letsrecycle.com/info/waste_management/news for further details. Accessed 01/12/2007.

Letsrecycle.com. (2007f). *Shanks Keen to Capitalise on 'Proven' MBT Process*. See www. letsrecycle.com for further details. Accessed 01/12/2007.

Lettieri, P. (2007). *Introduction to Sustainable Development*. Process Engineering Course Unit Lecture Notes. University College London, London, UK.

Levenspiel, O. (1999). *Chemical Reaction Engineering*. Wiley, New York, USA.

Lischke, G., Lehmann, E. (2001). Madrid Integrated Waste Processing Facility- Sorting, Composting, ROWITEC® Fluidized Bed Incineration. In: IMECHE Conference Transactions, (ed.). *Sixth International Conference on Engineering for Profit from Waste*, Wiley, New York, USA, 13-30.

Liuzzo, G., Bemporad, E., Verdone, N., Lacquaniti, L., Palitto, M. (1993). Il Bicarbonato di Sodio nel Trattamento dei Fumi: Considerazioni Teoriche. In: Ingegneria Sanitaria Ambientale, (ed.). *5° Seminario il Trasferimento della Ricerca Ambientale nell'Innovazione dei Servizi*, 49-64.

LTGDC. (2006). *Land Adjacent to Fairview Industrial Estate*. London Borough of Havering. Planning Report PDU/1335a/02. LTGDC, London, UK.

Lurgi-Lentjes. (now Lentjes GmbH). See www.lurgi-lentjes.de for further details. Accessed 01/09/2005.

McLanaghan, S.R.B. (2002). *Delivering the Landfill Directive: The Role of New & Emerging Technologies*. A Report for the Strategy Unit. AiIE, Penrith, UK.

Mitsui Babcock Energy Ltd. (2003). *Submission to GLA City Solutions Stakeholders on Municipal Waste Management*. GLA, London, UK

Mobley, R.K. (2001). *Plant Engineer's handbook*. Butterworth-Heinemann, Woburn, UK.

Mura, G., Lallai, A. (1994). Reaction Kinetics of Gas Hydrogen Chloride and Limestone. *Chem. Eng. Sci.*, **49**, 4491–4500.

Murphy, J.D., McKeogh, E. (2004). Technical, Economic and Environmental Analysis of Energy Production from Municipal Solid Waste. *Renewable Energy*, **29**, 1043-1057.

NEA and IEA. (2005). *Projected Costs of Generating Electricity*. OECD, Paris, France.

Nexus. See www.nexus-tec.com for further details. Accessed 01/09/2004.

Niessen, W.R. ( 2002). *Combustion and Incineration Processes*. Marcel Dekker, New York, USA.

Novera Energy. See www.noveraenergy.com for further details. Accessed 15/09/2006.

Obernberger, I., Thek, G. (2004a). *Basic Information Regarding Decentralised CHP Plants Based on Biomass Combustion in Selected IEA Partner Countries*. Final Report. BIOS BIOENERGIESYSTEME GmbH, Graz, Austria.

Obernberger, I., Thek, G. (2004b). *Techno-Economic Evaluation of Selected Decentralised CHP Applications Based on Biomass Combustion in Selected IEA Partner Countries*. Final Report. BIOS BIOENERGIESYSTEME GmbH, Graz, Austria.

Obernberger, I., Thonhofer, P., Reisenhofer, E. (2002). Description and Evaluation of the New 1,000 kWel Organic Rankine Cycle Process Integrated in the Biomass CHP Plant in Lienz, Austria. *Euroheat & Power*, **10**, 18-25.

ODPM. (2005). *Planning Policy Statement 10: Planning for Sustainable Waste Management*. Crown, London, UK.

Ofgem. (2007a). *Renewables Obligation: Guidance for Licensed Electricity Suppliers (Great Britain)*. Ofgem, London, UK.

Ofgem. (2007b). *Climate Change Levy Exemption for Renewables*. Ofgem, London, UK.

Ofgem. (2007c). *Distributed Energy- Initial Proposals for More Flexible Market and Licensing Arrangements*. Ofgem, London, UK.

ONS. (2007). *Retail Prices Index*. See www.statistic.gov.uk for further details. Accessed 08/01/2007.

Paiola, M. (2007). Ecodeco, The Intelligent Transfer Stations, Personal communication.

Paisley, M.A., Farris, G., Slack, W., Irving, J. (1997). Commercial Development of the Battelle/Ferco Biomass Gasification- Initial Operation of the McNeil Gasifier. In: Overend, R.P. and Chornet, E., (ed.). *Making a Business from Biomass in Energy, Environment, Chemicals, Fibers and Materials*. Proceedings of the Third Biomass Conference of the Americas. Elsevier, New York, USA, 579-588.

Peters, M.S., Timmerhaus, K.D. (1991). *Plant Design and Economics for Chemical Engineers, 4th edition*. McGraw-Hill, New York, USA.

PFI Scotland. (1998). *Baldovie Waste to Energy Plant, Dundee City Council*. The Private Finance Unit, The Scottish Office Finance Group, Edinburgh, UK.

Piddington, P. (2006). *Combined Heat & Power- The Wasted Resource*. A CHPA Presentation to PRASEG. PRASEG, London, UK.

PIU. (2002). *The Energy Review*. Cabinet Office. Crown, London, UK.

Plesch, D., Austin, G., Grant, F. (2005). *Britain's Energy Future: Securing the 'Home Front'*. Foreign Policy Centre, London, UK.

Poll, A.J. (2004). *Variations in the Composition of Household Collected Waste*. AEA Technology Report AEAT/ENV/R/1839. AEA Technology, Harwell, UK.

Porteous, A. (2005). Why Energy from Waste is An Essential Component of Environmentally Responsible Waste Management. *Waste Management*, **25**, 451-459.

RCEP. (1988*). Best Practicable Environmental Option*. 12th Report. HMSO, London, UK.

RCEP. (2000). *Energy- The Changing Climate*. 22nd Report. HMSO, London, UK.

Rensfelt, E., Östman, A. (1996). *Gasification of Waste- Summary and Conclusions of Twenty-Five Years of Development*. IEA Bioenergy, Dublin, Ireland.

RPS-MCOS. (2005). *Feasibility Study of Thermal Treatment Options for Waste in Limerick/Clare/Kerry Region*. Limerick/Clare/Kerry Regional Waste Management Office, Ireland.

Scottish Executive and SEPA. (2003). *The National Waste Plan 2003: Scotland*. Scottish Executive and the Scottish Environment Protection Agency, Scotland, UK.

Selinger, A., Steiner, C. (2004). Waste Gasification in Practice: TwinRec Fluidised Bed Gasification and Ash Melting- Review of Four Years of Commercial Operation. In Proc. of *The IT3 Conference*, May 10-14, Phoenix, USA.

Shanks. (2007). *The Intelligent Transfer Station. A Method for the Treatment of Municipal Solid Waste*. Shanks, Milton Keynes, UK.

Sinnott, R. K., Coulson, J. M., Richardson, J. F. (1999). *Coulson and Richardson's Chemical Engineering: Chemical Engineering Design Volume 6*. Butterworth-Heinemann, Oxford, U.K.

SLR Consulting. (2005). *Delivering Key Waste Management Infrastructure: Lessons Learned from Europe*. Report for CIWM. Bradford-on-Avon, UK.

Solvay. (2004). See www.neutrec.com for further details. Accessed 01/09/2004.

Spliethoff, H. (2001). *Status of Biomass Gasification for Power Production*. IFRF Combustion Journal.

Ståhl, K., Neergaard, M. (1998). IGCC Power Plant for Biomass Utilisation, Värnamo, Sweden. *Biomass & Bioenergy*, **15(3)**, 205-211.

Statistics Bureau. (2003). *Statistical Hand Book of Japan 2003.* Ministry of Public Management, Home Affairs, Posts and Telecommunications, Japan Statistical Association, Japan.

Stern, N. (2007). *The Economics of Climate Change: The Stern Review.* Cambridge University Press, Cambridge, UK.

Sustainable Development. (2000a). *Waste Strategy 2000: England and Wales.* Part 1. Crown, London, UK.

Sustainable Development. (2000b). *Waste Strategy 2000: England and Wales.* Part 2. Crown, London, UK.

Sutherland, K. (2007). Economic Appraisal of Large Projects. In: Simons, S.J.R., (ed.). *Concepts of Chemical Engineering 4 Chemists.* The Royal Society of Chemistry, Cambridge, UK.

Tech Trade GmbH. See www.tech-trade.de for further details. Accessed 01/09/2004.

The Austrian Institute of Chemical Engineering. *The FICFB Gasification Process.* See www.ficfb.at for further details. Accessed 01/09/2005.

Thide Environment. See www.thide.com for further details. Accessed 01/09/2004.

Thomas, C., Tennant, T., Rolls, J. (2000). *The GHG Indicator: UNEP Guidelines for Calculating Greenhouse Gas Emissions for Businesses and Non-Commercial Organisations.* UNEP, Geneva, Switzerland.

Thurgood, M. (1999). *DERL Energy from Waste Facility Dundee Scotland.* Case Study for IEA Bioenergy Task 23 – Energy from Thermal Conversion of MSW and RDF. AEA Technology, Harwell, UK

TPS Termiska Processer AB. See www.tps.se for further details. Accessed 01/09/2005.

U.S. EPA. (2004). *Municipal Solid Waste.* U.S. EPA, Washington, USA.

U.S. EPA. See www.epa.gov for further details. Accessed 09/01/2006.

Uchida, S., Kageyama, S., Nogi, M., Karakida, H., Kakizaki, T., Tsukagoshi, K. (1979). Reaction Kinetics of HCl and Limestone. *J. Chin. Inst. Chem. Eng.*, **10**, 45-49.

UNEP. (2002). *Global status 2002: Sustainable Consumption and Cleaner Production.* UNEP Division of Technology, Industry and Economics, Paris, France.

United Nations. (2002). *Future World Population Growth to be Concentrated in Urban Areas of World.* United Nations Population Division, Department of Economic and Social Affairs, New York, USA.

Waste Watch. *Legislation Affecting Waste.* See www.wasteonline.org for further details. Accessed 17/12/2007.

Weinell, C.E., Jensen, P.I., Dam-Johansen, K., Livbjerg, H. (1992). Hydrogen Chloride Reaction with Lime and Limestone: Kinetics and Sorption Capacity. *Ind. Eng. Chem. Res.*, **31**, 164–171.

Wheeler, P. A., de Rome, L. (2002). *Waste Pre-Treatment: A Review.* R&D Technical Report PI-344/TR, Environment Agency, Bristol, UK

White, P.R., Franke, M. & Hindle, P. (1995). *Integrated Solid Waste Management: A Lifecycle.* Blackie Academic & Professional, London, UK.

Willeboer, W. (1998). Amer Demolition Wood Gasification Project. *Biomass & Bioenergy*, **15**, 245-249.

Williams, P.T. (2005). *Waste Treatment and Disposal.* John Wiley & Sons, Chichester, UK.

Wolff, J., Sato, H., Adlhoch, W. (2000). High-Temperature Winkler Gasification of Municipal Solid Waste. In Proc of *The 2000 Gasification Technologies Conference*, October 8-11, San Francisco, USA.

WRAP. (2006). *The Sustainable Use of Resources for the Production of Aggregates in England.* WRAP, Oxon, UK.

Yan, R., Chin, T., Liang, D. T., Laursen, K., Ong, W. Y., Yao, K., Tay, J. H. (2003). Kinetic Study of Hydrated Lime Reaction with HCl. *Environ. Sci. Technol.*, **37**, 2556-2562.

Yassin, L., Lettieri, P., Simons, S., Germanà, A. (2005). Energy Recovery from Thermal processing of Waste: A Review. In: Institution of Civil Engineers, (ed.). *Engineering Sustainability*. Proceedings of The Institution of Civil Engineers, **158**, Issue ES2, 97-103.

Yassin, L., Lettieri, P., Simons, S., Germanà, A. (2007). Study of the Process Design and Flue Gas Treatment of an Industrial-Scale EfW Combustion Plant. *Ind. Eng. Chem. Res.*, **46**, 2648-2656.

# Sample calculations

## A.1 Mass & energy balances for a moving-grate combustion plant

In this case study, the waste is treated in 2 moving-grate combustors at 17.24 t/h and the plant operates for 312 days a year. The composition of the waste treated by the plant is shown below in Table A.1.

**Table A.1 Composition of the waste treated by the moving-grate combustion plant**

| | **Components** | **% wt** |
|---|---|---|
| Combustibles | C | 32.80 |
| | *H* | 4.48 |
| | *N* | 0.78 |
| | *O* | 18.35 |
| | *S* | 0.20 |
| | *Cl* | 0.70 |
| | *Ash* | 11.47 |
| | *Moisture* | 31.94 |

Overall plant availability = $\eta_{plant\ availability} = \frac{hr_p}{hr_y} = \frac{312*24}{365*24}*100 = 85.5\%$

where $hr_p$ and $hr_y$ are the plant annual operating hours and number of hours in a year, respectively.

$$\text{Overall plant capacity} = M_{waste} = m_{waste} * hr_p * n_{pl} = 17.24 * (312 * 24) * 2$$

$$= 258{,}186 \ \textit{tonne per annum} \ (tpa)$$

where $M_{waste}$ is the annual amount of waste treated in (*tpa*), $m_{waste}$ is the waste feed rate in (*t/h*) and $n_{pl}$ is the number of process lines.

Using Table A.1, the proximate and ultimate analysis of the waste are obtained, as shown in Table A.2. The proximate analysis shows the moisture content, combustibles, ash content and lower heating value (*LHV*) of the waste. On the other hand, the ultimate analysis, gives the elemental compositions of the waste on a dry ash free basis (*daf*), in terms of carbon, hydrogen, oxygen, as well as nitrogen, sulphur and chlorine.

**Table A.2 Waste composition of the moving-grate combustion plant**

| **Proximate analysis** | | | | **Ultimate analysis (wt % daf)** | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Moisture (%) | Combustibles (%) | Inerts (%) | LHV (kcal/kg) | C (%) | H (%) | O (%) | N (%) | S (%) | Cl (%) |
| 31.9 | 56.6 | 11.5 | 3000 | 56.7 | 7.9 | 32.4 | 1.4 | 0.4 | 1.2 |

The combustion process requires primary and secondary air of 70,705 $Nm^3/h$ and 20,939 $Nm^3/h$ for each process line, respectively (given). Hence, total air required is 183,288 $Nm^3/h$. Each process line generates 107,881 $Nm^3/h$ of exhaust gases (given).

$$\text{Amount of bottom ash generated} = 12\% \ of \ m_{waste} = \frac{12}{100} * 17.24 = 2.1 \ t/h$$

$$= 4.2 \ t/h \text{ for both process lines}$$

$$\text{Amount of APC residues generated} = 6\% \ of \ m_{waste} = \frac{6}{100} * 17.24 = 1.05 \ t/h$$

$$= 2.1 \ t/h \text{ for both process lines}$$

Overall system efficiency calculations

Knowing that:

$$1 \ cal = 4.186 \ J \qquad (A.1)$$

and

$$1 \ W = 1 J/s \qquad (A.2)$$

Thermal capacity of waste = $E_{th} = m_{waste} * CV_{waste} = \frac{(17.24*1000)(3000*4.186)}{3600*1000}$

$= 60.1\ MWth$

$= 120.2\ MWth$ (for both process lines)

where $CV_{waste}$ is the calorific value of waste in ($MJ/kg$).

Gross electrical generation efficiency of the steam turbine = $\eta_{steam\ turbine} = 30\%$ (given)

Gross electricity generated = $E_{electricity,gross} = \eta_{steam\ turbine} * E_{th} = \frac{30}{100} * 120.2 = 36.1\ MWe$

Auxiliary consumption = $E_{auxiliary} = 2.0\ MWe$ (given)

Net electricity generated = $E_{electricity,net} = E_{electricity,gross} - E_{auxiliary} = 36.1 - 2.0 = 34.1\ MWe$

Net electrical generation efficiency = $\frac{E_{electricity,net}}{E_{th}} * 100 = \frac{34.1}{120.2} * 100 = 28.3\%$

= Overall system efficiency

# A.2 Technical & economic performances of a 50 ktpa FBG+CCGT plant for electricity-only generation

## A.2.1 Technical performance

The technical performance of the 50 ktpa FBG+CCGT for electricity-only generation is examined by obtaining its overall system efficiency. This is defined as the net generated electricity to the energy input to the system, as shown in Equation A.3.

$$System\ efficiency = \frac{Net\ electricity\ generated}{Energy\ input\ to\ system} * 100 \tag{A.3}$$

However, to obtain this value, the gasification efficiency and the performance of the CCGT unit need to be determined. This section shows the calculations used for the technical analysis.

$CV_{RDF}$ = 4000 kcal/kg (given)

$= 4000 * \frac{4.186}{1000} = 16.7\ MJ/kg$ (see Equation A.1)

Plant availability = $\eta_{plant\ availability}$ = 90% (assumed)

Plant annual operating hours $= hr_p = \eta_{plant\ availability} * hr_y = \frac{90}{100} * (365 * 24)$

$= 7{,}884\ h/a$

RDF feed rate $= m_{RDF} = \frac{M_{RDF}}{hr_p} = \frac{50{,}000}{7{,}884} = 6.34\ t/h$

Thermal capacity of RDF $= E_{th} = m_{RDF} * CV_{RDF} = \frac{16.7 * 6.34 * 1000}{3600}$

$= 29.42\ MWth$ (see Equation A.2)

Thermal capacity of syngas $= E_{th,syngas} = \eta_{th,gasifier} * E_{th} = \frac{70}{100} * 29.42 = 20.59 MWth$

where $\eta_{th,gasifier}$ is thermal efficiency of the gasifier at 70% (assumed)

The gross electrical generation efficiency of the CCGT, $\eta_{CCGT}$, is obtained using literature date published by Bridgwater et al. (2002), which is presented in Figure A.1 for a range of thermal energy input of 1-40 *MWth*.

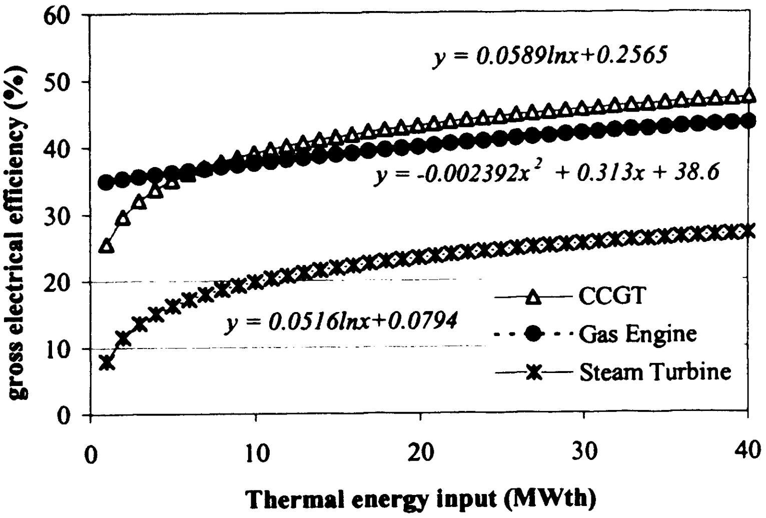


**Figure A.1 Gross electricity generation efficiencies of the prime movers**

The thermal energy input to the CCGT unit is $E_{th,syngas}$, which is the thermal capacity of the syngas. Therefore, using Figure A.1, the $\eta_{CCGT}$ is calculated as follows:

$$\eta_{CCGT} = 0.0589 * \ln(E_{th,syngas}) + 0.2565 = 0.0589 * \ln(20.59) + 0.2565 = 0.4347 \text{ or } 43.47\%$$

$$\text{Gross electricity generated} = E_{electricity,gross} = \eta_{CCGT} * E_{th,syngas} = 0.4347 * 20.59 = 8.95 \ MWe$$

$$\Rightarrow E_{electricity,gross} * hr_p = 8.95 * 7{,}884 = 70{,}578 \ MWhe$$

$$\text{Auxiliary consumption} = E_{auxiliary} = 15\% \ of \ E_{electricity,gross} = \frac{15}{100} * 8.95 \ \text{(assumed)}$$

$$= 1.34 \ MWe \text{ or } 10{,}565 \ MWhe$$

$$\text{Net electricity generated} = E_{electricity,net} = E_{electricity,gross} - E_{auxiliary} = 8.95 - 1.34 = 7.61 \ MWe$$

$$\Rightarrow E_{electricity,net} * hr_p = 7.61 * 7{,}884 = 59{,}992 \ MWhe$$

$$\text{Net electrical generation efficiency} = \frac{E_{electricity,net}}{E_{th}} * 100 = \frac{7.61}{29.42} * 100 = 25.87\%$$

$$= \text{Overall system efficiency}$$

## A.2.2 Economic performance

In order to evaluate the cost effectiveness of the gasification system, an economic model is developed comprising of capital costs, operating costs and projected annual revues. The model uses a basic discounted cash flow analysis (DCF) (Gerrard, 2000, Peters & Timmerhaus, 1991, Sutherland, 2007), which relates the values of costs and revenues that occur over the economic life of the project in terms of present worth, i.e. the amount that a future sum of money is worth today, given a specified rate of return. This section reports the calculations used for the gate fees, NPV, IRR and levelised costs of waste treatment.

Capital costs

The capital cost of the 50,000 *tpa* FBG+CCGT plant consists of the costs of the gasification system and CCGT unit. For the capital cost of the gasification system, a Novera Energy-type fluidized bed gasification system is used, which costs £15m for a 70,000 *tpa* plant (Defra, 2005b). The general relationship between cost and scale is given below in Equation A.4.

$$\frac{Cost_1}{Cost_2} = \left(\frac{Scale_1}{Scale_2}\right)^n \qquad \text{(A.4)}$$

where $Cost_1$ is cost of the proposed plant in (*£*), which is at $Scale_1$ in (*tpa*); $Cost_2$ is cost of reference plant in (*£*), which is at $Scale_2$ in (*tpa*); and $n$ is the scale exponent. The scale exponent is derived from historical data for similar plants and is usually in the range of 0.6 to 0.8 (Gerrard, 2000, Peters & Timmerhaus, 1991).

Using Equation A.4 for $n = 0.6$ & $0.8$, the capital cost for a 50,000 *tpa* plant is calculated as follows:

$$\text{Capital cost} = \left(\left(\frac{50{,}000}{70{,}000}\right)^{0.6} * 15{,}000{,}000\right) = £12{,}257{,}854, \text{ when } n = 0.6, \text{ and}$$

$$= \left(\left(\frac{50{,}000}{70{,}000}\right)^{0.8} * 15{,}000{,}000\right) = £11{,}460{,}111, \text{ when } n = 0.8$$

Therefore, this gives an average capital cost of £11,858,982

In this analysis, all cost data are updated and reported in ($£_{2006}$), using appropriate indices from the Office for National Statistics (ONS). The cost data were published by Defra in 2005, so to update the average capital cost to a 2006 value, it is multiplied by 1.03. This is based on the Retail Prices Index (RPI), which is the most familiar general purpose domestic measure of inflation in the UK (ONS, 2007). Hence, the average capital cost of the gasification system is £11,858,982*1.03 = £12,214,752

The capital cost for CCGT unit, with a 9.0 *MWe* gross electricity generating capacity is *€744/kWe* (EDUCOGEN, 2001). Using a conversion rate of £1= €1.45, the capital cost of the CCGT unit is:

$$\text{Capital cost} = \text{unit cost}^{*}\ E_{electricity,gross} = \frac{744}{1.45} * (8.95 * 1000) = \text{£}4{,}593{,}355$$

Therefore, the total capital cost of a 50,000 *tpa* FBG+CCGT plant is:

$$\text{£}12{,}214{,}752 + \text{£}4{,}593{,}355 = \text{£}16{,}808{,}107 \text{ or } \text{£}336.16/\text{t} \left(\frac{16{,}808{,}107}{50{,}000}\right).$$

Operations costs

The operating costs of the 50,000 *tpa* FBG+CCGT plant consist of maintenance & consumable costs, labour, ash disposal, maintenance of CCGT unit and plant overheads. Table A.3 shows the model parameters used for the operating cost calculations.

**Table A.3 Model parameters used for the annual operating cost calculations** †

| Parameter | Value |
|---|---|
| Maintenance | £20.0/t of input waste (AiIE, 2003).<br>$\Rightarrow$ cost of maintenance * amount of waste treated<br>$= C_{maintenance} * M_{RDF} = 20 * 50{,}000 =$ £1,000,000 |
| Labour | 15 employees with average salaries of €45,000 (Thurgood, 1999).<br>$\Rightarrow$ cost of labour * number of employee<br>$= C_{labour} * n_{employees} = \frac{45{,}000}{1.45} * 15 = £465{,}517$ |
| Ash disposal | 20% of input waste, of which 1/3 is bottom ash and 2/3 is air pollution control residues (Howson, 2007). The bottom ash is assumed to be recycled, while the APC residues is sent to a hazardous landfill.<br>$\Rightarrow$ cost of hazardous landfill * amount landfilled<br>$= C_{hazardous\ landfill} * M_{amount\ landfilled} = 401.21 * \left(\frac{20}{100} * \frac{2}{3} * 50{,}000\right)$<br>$= £694{,}733$ |
| Maintenance of CCGT unit | £3.6/MWhe (EDUCOGEN, 2001).<br>$\Rightarrow$ cost of maintenance * annual gross electricity generated<br>$= C_{maintenance,CCGT} * (E_{electricity,gross} * hr_p) = 3.6 * (8.95 * 7{,}884) = £267{,}711$ |
| Plant overheads | 2% of capital costs (Bridgwater, 2002).<br>$\Rightarrow \frac{2}{100} * 16{,}808{,}107 = £336{,}162$ |

† Small variations will appear in final values due to rounding figures up/down

Total operating costs $= \sum operating\ costs = £2{,}764{,}124/a$ or $£55.28/t \left(\frac{2{,}764{,}124}{50{,}000}\right)$

Revenues

The projected annual revenues from the 50,000 *tpa* FBG+CCGT plant include sales from electricity, eligibility for ROCs, LECs, PRNs, sales of bottom ash and income from gate fee. Table A.4 shows the model parameters used for the revenues calculations.

**Table A.4 Model parameters used for revenue calculations**

| **Parameter** | **Value** |
|---|---|
| Sales from electricity | 2.50 p/kWh (Jacobs, 2005, Enviros, 2005).<br>⇒ electricity price * annual net electricity generated<br>$= P_{electricity} * (E_{electricity,net} * hr_p) = \frac{2.5}{100} * (7.61 * 1000 * 7{,}884) = £1{,}499{,}790$ |
| Eligibility for ROCs | 3.43 p/kWh (Ofgem, 2007a).<br>⇒ ROC price * annual net electricity generated * biomass fraction<br>$= P_{ROC} * (E_{electricity,net} * hr_p) = \frac{3.43}{100} * (7.61 * 1000 * 7{,}884) * \frac{68}{100}$<br>$= £1{,}399{,}245$ |
| LECs | 0.44 p/kWh (Ofgem, 2007b).<br>⇒ LEC price * annual net electricity generated * biomass fraction<br>$= P_{LEC} * (E_{electricity,net} * hr_p) = \frac{0.44}{100} * (7.61 * 1000 * 7{,}884) * \frac{68}{100}$<br>$= £179{,}903$ |
| PRNs | £2/t for 19% of waste treated (letsrecycle.com, 2007c, Environment Agency, 2007c).<br>⇒ PRN price * annual amount of waste treated<br>$= P_{PRN} * M_{RDF} = 2 * 50{,}000 * \frac{19}{100} = £19{,}000$ |
| Sales of bottom ash | £7/t (WRAP, 2006).<br>⇒ Bottom ash price * annual amount of bottom ash recycled<br>$= P_{Bottom\ ash} * M_{Bottom\ ash} = 7 * \left( \frac{20}{100} * \frac{1}{3} * 50{,}000 \right) = £23{,}333$ |
| Gate fee | £36.55/t, which accounts for ROCs (see discounted cash flow analysis).<br>⇒ Gate fee * annual amount of waste treated<br>$= P_{Gate\ fee} * M_{RDF} = 36.55 * 50{,}000 = £1{,}827{,}647$ |

Total annual revenues = $\sum annual\ \ revenues = £4{,}948{,}918/a$

Discounted cash flow analysis

The gate fee is calculated using a DCF analysis to balance the net present values of costs and revenues, over the plant life-time of 30 years, and includes an operator profit of 20%. The gate fee is calculated using Equation A.5, where *PV* is the present value and *n* is number of years.

$$Gate\ fee = \sum_{n=1}^{30} \left[ PV(costs) - PV(income) \right] \tag{A.5}$$

The present value of a future amount is calculated using equation A.6, where *i* is the discount rate of 6% (assumed).

$$PV = \frac{future\ amount}{(1+i)^n} \tag{A.6}$$

Table A.5 reports the total costs (column *E*) and annual revenues (column *F*) excluding gate fees for the duration of the project. The present values of the total costs and annual revenues are also determined in columns *G* and *H*, respectively. Hence,

$$Gate\ fee = \left( 56{,}767{,}521 * \left( 1 + \frac{20}{100} \right) - 42{,}963{,}771 \right) = £25{,}157{,}254$$

This value is then annualised using a capital recovery factor and divided by the amount of waste treated so that the value is reported in (*£/t*).

$$Gate\ fee = \frac{25{,}157{,}254 * CRF}{M_{RDF}} = \frac{25{,}157{,}254 * \left( \frac{i(1+i)^n}{(1+i)^n - 1} \right)}{50{,}000} = £36.55/t$$

NPV = $\sum_{n=1}^{30} \frac{CF_n}{(1+i)^n} - TPC =$ £11,353,504, as shown in Table A.5. $CF_n$ is the annual cash flow at the *n*th year and *TPC* is the total plant cost.

IRR = 11.81%, which is calculated as the discount rate that makes the NPV equal to zero

Levelised cost

The levelised cost is calculated as the ratio of the total plant life-time expenses against total expected outputs, expressed in terms of present worth (NEA & IEA, 2005).

$$\text{Level cost} = \frac{\sum_{n=1}^{30}\left[PV(total\ \cos ts)\right]}{\sum_{n=1}^{30}\left[PV(annual\ electricity\ generated)\right]} = £68.7/MWhe \text{ or}$$

$$= \frac{\sum_{n=1}^{30}\left[PV(total\ \cos ts)\right]}{\sum_{n=1}^{30}\left[PV(annual\ waste\ treated)\right]} = £82.5/t$$

## Table A.5 Discounted cash flow analysis for a 50 ktpa FBG+CCGT plant

| | Year | Capital costs | Operating costs (1) | Total costs | Revenues excl. gate fee | PV (Total costs) | PV (Revenues excl. gate fees) | Total revenues incl. gate fees | Annual cash flow | Cumulative cash flow | NPV | Cumulative NPV |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | £16,808,107 | £0 | £16,808,107 | £0 | £16,808,107 | £0 | £0 | -£16,808,107 | -£16,808,107 | -£16,808,107 | -£16,808,107 |
| 2007 | 1 | £16,808,107 | £2,764,124 | £2,764,124 | £3,121,271 | £2,607,664 | £2,944,595 | £4,948,918 | £2,184,795 | -£14,623,312 | £2,061,127 | -£14,746,980 |
| 2008 | 2 | £0 | £2,817,457 | £2,817,457 | £3,121,271 | £2,507,527 | £2,777,920 | £4,948,918 | £2,131,461 | -£12,491,851 | £1,896,993 | -£12,849,987 |
| 2009 | 3 | £0 | £2,870,790 | £2,870,790 | £3,121,271 | £2,410,371 | £2,620,679 | £4,948,918 | £2,078,128 | -£10,413,723 | £1,744,836 | -£11,105,151 |
| 2010 | 4 | £0 | £2,924,124 | £2,924,124 | £3,121,271 | £2,316,180 | £2,472,339 | £4,948,918 | £2,024,795 | -£8,388,928 | £1,603,827 | -£9,501,324 |
| 2011 | 5 | £0 | £2,924,124 | £2,924,124 | £3,121,271 | £2,185,075 | £2,332,395 | £4,948,918 | £2,024,795 | -£6,364,134 | £1,513,044 | -£7,988,279 |
| 2012 | 6 | £0 | £2,924,124 | £2,924,124 | £3,121,271 | £2,061,392 | £2,200,373 | £4,948,918 | £2,024,795 | -£4,339,339 | £1,427,400 | -£6,560,879 |
| 2013 | 7 | £0 | £2,924,124 | £2,924,124 | £3,121,271 | £1,944,709 | £2,075,824 | £4,948,918 | £2,024,795 | -£2,314,545 | £1,346,604 | -£5,214,275 |
| 2014 | 8 | £0 | £2,924,124 | £2,924,124 | £3,121,271 | £1,834,631 | £1,958,324 | £4,948,918 | £2,024,795 | -£289,750 | £1,270,381 | -£3,943,894 |
| 2015 | 9 | £0 | £2,924,124 | £2,924,124 | £3,121,271 | £1,730,784 | £1,847,476 | £4,948,918 | £2,024,795 | £1,735,044 | £1,198,473 | -£2,745,421 |
| 2016 | 10 | £0 | £2,924,124 | £2,924,124 | £3,121,271 | £1,632,815 | £1,742,902 | £4,948,918 | £2,024,795 | £3,759,839 | £1,130,635 | -£1,614,787 |
| 2017 | 11 | £0 | £2,924,124 | £2,924,124 | £3,121,271 | £1,540,392 | £1,644,247 | £4,948,918 | £2,024,795 | £5,784,633 | £1,066,636 | -£548,150 |
| 2018 | 12 | £0 | £2,924,124 | £2,924,124 | £3,121,271 | £1,453,200 | £1,551,176 | £4,948,918 | £2,024,795 | £7,809,428 | £1,006,261 | £458,111 |
| 2019 | 13 | £0 | £2,924,124 | £2,924,124 | £3,121,271 | £1,370,943 | £1,463,374 | £4,948,918 | £2,024,795 | £9,834,222 | £949,303 | £1,407,413 |
| 2020 | 14 | £0 | £2,924,124 | £2,924,124 | £3,121,271 | £1,293,343 | £1,380,541 | £4,948,918 | £2,024,795 | £11,859,017 | £895,569 | £2,302,982 |
| 2021 | 15 | £0 | £2,924,124 | £2,924,124 | £3,121,271 | £1,220,135 | £1,302,397 | £4,948,918 | £2,024,795 | £13,883,811 | £844,876 | £3,147,858 |
| 2022 | 16 | £0 | £2,924,124 | £2,924,124 | £3,121,271 | £1,151,070 | £1,228,677 | £4,948,918 | £2,024,795 | £15,908,606 | £797,053 | £3,944,911 |
| 2023 | 17 | £0 | £2,924,124 | £2,924,124 | £3,121,271 | £1,085,916 | £1,159,129 | £4,948,918 | £2,024,795 | £17,933,400 | £751,937 | £4,696,847 |
| 2024 | 18 | £0 | £2,924,124 | £2,924,124 | £3,121,271 | £1,024,449 | £1,093,518 | £4,948,918 | £2,024,795 | £19,958,195 | £709,374 | £5,406,222 |
| 2025 | 19 | £0 | £2,924,124 | £2,924,124 | £3,121,271 | £966,461 | £1,031,621 | £4,948,918 | £2,024,795 | £21,982,989 | £669,221 | £6,075,443 |
| 2026 | 20 | £0 | £2,924,124 | £2,924,124 | £3,121,271 | £911,756 | £973,227 | £4,948,918 | £2,024,795 | £24,007,784 | £631,341 | £6,706,783 |
| 2027 | 21 | £0 | £2,924,124 | £2,924,124 | £3,121,271 | £860,147 | £918,139 | £4,948,918 | £2,024,795 | £26,032,578 | £595,604 | £7,302,387 |
| 2028 | 22 | £0 | £2,924,124 | £2,924,124 | £3,121,271 | £811,459 | £866,169 | £4,948,918 | £2,024,795 | £28,057,373 | £561,891 | £7,864,278 |
| 2029 | 23 | £0 | £2,924,124 | £2,924,124 | £3,121,271 | £765,528 | £817,140 | £4,948,918 | £2,024,795 | £30,082,167 | £530,086 | £8,394,364 |
| 2030 | 24 | £0 | £2,924,124 | £2,924,124 | £3,121,271 | £722,196 | £770,887 | £4,948,918 | £2,024,795 | £32,106,962 | £500,081 | £8,894,445 |
| 2031 | 25 | £0 | £2,924,124 | £2,924,124 | £3,121,271 | £681,317 | £727,252 | £4,948,918 | £2,024,795 | £34,131,756 | £471,774 | £9,366,219 |
| 2032 | 26 | £0 | £2,924,124 | £2,924,124 | £3,121,271 | £642,752 | £686,087 | £4,948,918 | £2,024,795 | £36,156,551 | £445,070 | £9,811,289 |
| 2033 | 27 | £0 | £2,924,124 | £2,924,124 | £3,121,271 | £606,370 | £647,252 | £4,948,918 | £2,024,795 | £38,181,345 | £419,877 | £10,231,167 |
| 2034 | 28 | £0 | £2,924,124 | £2,924,124 | £3,121,271 | £572,047 | £610,615 | £4,948,918 | £2,024,795 | £40,206,140 | £396,111 | £10,627,277 |
| 2035 | 29 | £0 | £2,924,124 | £2,924,124 | £3,121,271 | £539,667 | £576,052 | £4,948,918 | £2,024,795 | £42,230,934 | £373,689 | £11,000,967 |
| 2036 | 30 | £0 | £2,924,124 | £2,924,124 | £3,121,271 | £509,120 | £543,445 | £4,948,918 | £2,024,795 | £44,255,729 | £352,537 | £11,353,504 |
| TOTAL | | | | £104,211,820 | | £56,767,521 | £42,963,771 | £148,467,550 | £44,255,729 | | £11,353,504 | |

(1) The operating costs include a landfill tax escalator of £8/t of waste landfilled, which is capped after 2010/11

# A.3 Environmental performance a 50 ktpa FBG+CCGT plant for electricity-only generation and combined heat & power

## A.3.1 Calculations for $CO_2$ production

Based on the following stoichiometric relationship in Equation A.7 and using Table A.6, the environmental performance of the 50 ktpa FBG+CCGT plant is calculated as follows:

$$C + O_2 \rightarrow CO_2 \qquad \text{(A.7)}$$

1 *mole* of *C* gives 1 *mole* of $CO_2$

12 *g* of *C* give 44 *g* of $CO_2$

or

273 *kg* of *C* give 1 *tonne* of $CO_2$

The plant treats RDF with a carbon content of 44.7%, which is based on proximate analysis. Hence,

610 *kg* of RDF give 1 *tonne* of $CO_2$

or

1 *tonne* of RDF gives 1,639 *kg* of $CO_2$

**Table A.6 Technical performance of the 50 ktpa FBG+CCGT plant in electricity-only and CHP modes**

| Operation model | Electricity-only | Combined heat & power |
|---|---|---|
| Gross generated electricity | 8.95 MWe or 70,578 MWhe | 8.95 MWe or 70,578 MWhe |
| Net generated electricity | 7.61 MWe or 59,992 MWhe | 7.61 MWe or 59,992 MWhe |
| Gross heat output | - | 11.4 MWe or 89,987 MWhe |
| Net heat output | - | 9.7 MWe or 76,489 MWhe |
| Electrical efficiency | 25.9 % | 25.9 % |
| Thermal efficiency | - | 33.0 % |
| Overall system efficiency | 25.9 % | 58.9 % |

For electricity-only FBG+CCGT plant

As determined earlier,

1 *tonne* of RDF gives 1,639 *kg* of $CO_2$

Using Table A.6, 50,000 *tonne* of RDF give 81,950 *tonne* of $CO_2$ and produce 70,578,375 *kWh* of electricity. Hence,

1 *kWh* gives 1161 *g* of $CO_2$

However, since 68% of the RDF is assumed biodegradable, only 32% of the $CO_2$ is non-biogenic. Therefore,

1 *kWh* gives 372 *g* of $CO_2$

For FBG+CCGT plant with CHP

1 *tonne* of RDF gives 1,639 *kg* of $CO_2$

Using Table A.6, 50,000 *tonne* of RDF give 81,950 *tonne* of $CO_2$ and produce 70,578,375 *kWh* of electricity and 89,987,428 *kWh* of heat. Hence,

1 *kWh* gives 510 *g* of $CO_2$

However, since 68% of the RDF is assumed biodegradable, only 32% of the $CO_2$ is non-biogenic. Therefore,

1 *kWh* gives 163 *g* of $CO_2$

## A.3.2 $CO_2$ savings by a 50 ktpa FBG+CCGT plant with CHP compared to separate heat and power generation

For separate heat generation (heat-only boilers)

Average carbon emission factor is 242 $gCO_2/kWh$ (Defra, 2004). Hence, if heat-only boilers are used to generate 89,987,428 *kWh* of heat, then their total $CO_2$ emissions are:

Carbon emission factor * Gross heat output = $CEF_{heat-only\ boilers} * (E_{th,gross} * hr_p)$

$$= \frac{242}{1{,}000{,}000} * 89{,}987{,}428 = 21{,}777\ \textit{tonne}\ \text{of}\ CO_2\ \textit{per annum}$$

For separate fossil fuel power generation

Average carbon emission factor is 523 $gCO_2/kWh$ (Defra, 2007j). Hence, if 70,578,375 *kWh* of electricity are imported from the grid, then their total emissions are:

Carbon emission factor * Gross electricity generated

$$= CEF_{electricity\ from\ grid} * (E_{electricity,gross} * hr_p)$$

$$= \frac{523}{1{,}000{,}000} * 70{,}578{,}375 = 36{,}912\ \textit{tonne}\ \text{of}\ CO_2\ \textit{per annum}$$

Therefore, FBG+CCGT with CHP $CO_2$ savings are:

$$\left(\left(CEF_{heat-only\ boilers} * E_{th,gross}\right) + \left(CEF_{electricity\ from\ grid} * E_{electricity,gross}\right) - \left(CEF_{heat-only\ boilers} * (E_{th,gross} + E_{electricity,gross})\right)\right) hr_p$$

$$= \frac{(242 * 89{,}987{,}428) + (523 * 70{,}578{,}375) - (163 * (89{,}987{,}428 + 70{,}578{,}375)}{1{,}000{,}000}$$

= 32,465 *tonne* of $CO_2$ *per annum*

# A.4 Number of residential, commercial and industrial users of CHP

Using Table A.6, the number of potential residential, commercial & industrial users for the heat and power from the 50 *ktpa* FBG+CCGT with CHP plant is calculated as follows:

Heat available for export

Facility thermal energy output = $E_{th,net}$ = $9.70\,MWth$

Amount of heat available for export = $E_{th,net} * hr_p * \eta_{distribution}$

$$= 9.7 * 7{,}884 * \frac{90}{100} = 68{,}840\,MWhth$$

where $\eta_{distribution}$ is the efficiency of the heat distribution process at 90%

Electricity available for export

Net generated electricity = $E_{electricity,net}$ = $7.61\ MWe$

Electricity available for export = $E_{electricity,net} * hr_p * \eta_{transmission}$

$$= 7.61 * 7{,}884 * \frac{90}{100} = 53{,}992\,MWhe$$

where $\eta_{transmission}$ is the efficiency of the electricity transmission & distribution process at 90%

Number of residential, commercial and industrial users of CHP

The 2006 average London electricity & gas consumptions for the residential and commercial & industrial sectors are shown in Table A.7.

**Table A.7 2006 average London electricity & gas consumption for the residential and commercial/industrial sectors**

| | Sector | |
|---|---|---|
| | Residential | Commercial/industrial |
| Electricity consumption | 4,193 kWh | 70,149 kWh |
| Gas consumption | 17,426 kWh | 446,851 kWh |

Source: BERR (2008)

$$\text{No. of residential electricity users} = \frac{\mathit{Electricity\ available\ for}\ \exp\mathit{ort}}{\mathrm{Re}\,\mathit{sidential\ electricity\ consumption}}$$

$$= \frac{(53{,}992 * 1000)}{4{,}193} = 12{,}877 \text{ users}$$

$$\text{No. of comm/industrial electricity users} = \frac{\mathit{Electricity\ available\ for}\ \exp\mathit{ort}}{\mathit{Comm\,/\,industrial\ electricity\ consumption}}$$

$$= \frac{(53{,}992 * 1000)}{70{,}149} = 770 \text{ users}$$

$$\text{No. of residential gas users} = \frac{\mathit{Heat\ available\ for}\ \exp\mathit{ort}}{\mathrm{Re}\,\mathit{sidential\ gas\ consumption}}$$

$$= \frac{(68{,}840 * 1000)}{17{,}426} = 3{,}950 \text{ users}$$

$$\text{No. of comm/industrial gas users} = \frac{\mathit{Electricity\ available\ for}\ \exp\mathit{ort}}{\mathit{Comm\,/\,industrial\ electricity\ consumption}}$$

$$= \frac{(68{,}840 * 1000)}{446{,}851} = 154 \text{ users}$$

# Publications

Yassin, L., Lettieri, P., Simons, S.J.R., Germanà, A. (2008). Techno-Economic Performance of Energy-from-Waste Fluidized Bed Combustion & Gasification Processes. Submitted to *Chemical Engineering Journal.*

Yassin, L., Lettieri, P., Simons, S.J.R., Castillo-Castillo, A., Leach, M., Ryu, C., Swithenbank, J., Sharifi, V.N. (2008). From Traditional Incineration to More Advanced Fluidized Bed Gasification Technology for the Thermal Processing of Waste. Submitted to *Waste and Resource Management.*

Castillo-Castillo, A., Leach, M., Yassin, L., Lettieri, P., Simons, S.J.R., Ryu, C., Swithenbank, J., Sherifi, V.N. (2008). The Potential Role of Different Scales of Incineration and Fluidised Bed Gasification Technologies in Future Waste Management Strategies. Prepared for submission to *Waste and Resource Management.*

Yassin, L., Lettieri, P., Simons, S., Germanà, A. (2007). Appropriate Scales and Technologies for Energy Recovery by Thermal Processing of Waste in the Urban Environment. In Proc. of *The 8th UK Particle Technology Forum*, September 26-27, Robinson College, Cambridge, UK.

Yassin, L., Lettieri, P., Simons, S., Germanà, A. (2007). Thermal Conversion of Biomass and Waste. In Proc. of *The 12th International Conference on Fluidization*, May 13-18, Vancouver, Canada.

Yassin, L., Lettieri, P., Simons, S., Germanà, A. (2007). Study of the Process Design and Flue Gas Treatment of an Industrial-Scale EfW Combustion Plant. *Ind. Eng. Chem. Res.*, **46**, 2648-2656.

Yassin, L., Lettieri, P., Simons, S., Germanà, A. (2006). Energy Recovery from Waste: A Case Study. In Proc. of *CIWM 2006 incorporating The 5th International Symposium on Waste Treatment Technologies*, June 12-16, Paignton, UK.

Yassin, L., Lettieri, P., Simons, S., Germanà, A. (2006). Thermal Processing of Municipal Solid Waste. In Proc. of *The International Conference on Fluidized Bed Combustion*, May 21-24, Vienna, Austria.

Yassin, L., Lettieri, P., Simons, S., Germanà, A. (2005). Sustainability in The Urban Environment by Thermal Processing of Waste. In Proc. of *AIChE Annual Meeting*, October 30th –November 4th, Cincinnati, USA.

Yassin, L., Lettieri, P., Simons, S., Germanà, A. (2005). Process Design of An Energy-from-Waste Combustion Plant. In Proc. of *The Particle Systems Analysis Conference*, September 21-23, Stratford-upon-Avon, UK.

Yassin, L., Lettieri, P., Simons, S., Germanà, A. (2005). Energy Recovery from Thermal processing of Waste: A Review. In: Institution of Civil Engineers, (ed.). *Engineering Sustainability*. Proceedings of The Institution of Civil Engineers, **158**, Issue ES2, 97-103.

Yassin, L., Lettieri, P., Simons, S., Germanà, A. (2005). Appropriate Scales and Technologies for Energy Recovery by Thermal Processing of Waste in The Urban Environment. In Proc. of *The 7th World Congress in Chemical Engineering*, July 10-14, Glasgow, UK.

Yassin, L., Lettieri, P., Simons, S., (2005). Appropriate Scales and Technologies for Energy Recovery by Thermal Processing of Waste in The Urban Environment. In Proc. of *SUE: Vision into Action Conference*, February 28th – March 2nd, Birmingham, UK.

Yassin, L., Lettieri, P., Simons, S. (2004). Appropriate Scales and Technologies for Energy Recovery by Thermal Processing of Waste in The Urban Environment. In Proc. of *The 6th UK Particle Technology Forum*, June 15-16, University College London, London, UK.