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Techno-economic performance of energy-from-waste fluidized bed combustion and gasification processes in the UK context

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ABSTRACT

This paper presents the technical and economic performance of energy-from-waste (EfW) fluidized bed combustion and gasification processes and reports on the implications of different scales and technologies on costs and efficiencies. Mass and energy balances of the processes were performed and the cost effectiveness of the different waste treatment options, for the generation of electric power, was assessed using a discounted cash flow analysis. For the different waste treatment options, the study concludes that gasification processes have higher overall system efficiencies than combustion processes. In particular, fluidized bed gasification with combined cycle gas turbine (CCGT) is the most attractive treatment option in terms of cost and efficiency. Although fluidized bed gasification has limited commercial operation in the UK, they are compatible with high levels of source segregation and, therefore, have the potential to contribute towards integrated waste management practices. 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 Renewable Obligation Certificates (ROCs), supportive policies and active R&D by major industry players and research institutions are important factors for the full commercialisation of the gasification processes, especially, for plant scales larger that 50 ktpa.
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1. Introduction

In 2005/2006, the UK produced 35.1 million tonnes of municipal solid waste. 64% was landfilled, while 27% was recycled/composted and only 8% was incinerated with energy-from-waste [1]. Although recycling and composting of waste has nearly quadrupled since 1996/1997, the UK still lags behind Europe in how we manage our waste. Fig. 1 illustrates municipal waste management in the EU in 2003 and shows that only Greece and Portugal landfill more waste than the UK in Europe [1]. The Netherlands and Denmark dispose of almost no municipal waste to landfill, and Belgium, Sweden, Germany and Luxembourg all landfill less than a quarter of their municipal waste. Therefore, landfilling is a missed and 'wasted' opportunity and if we are to deliver a more sustainable economy, we must do more with less. Useful resources can be recovered from waste, whether as materials through recycling and composting or as energy or fuel through efficient biological and thermal processes [2]. However, this may require the diversification of waste management approaches that are optimal in environmental, societal, technological and economic terms. It also calls for the establishment of integrated facilities that can accommodate more than one waste management option.

The UK waste management policy is largely derived from EU legislations, which fall into three categories [3]:

- Horizontal legislations that set the overall framework for the management of waste, 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;
- Specific waste stream legislations, such as Packaging and Packaging Waste Directive (94/62/EC).

These legislations and directives have resulted in shifting the emphasis towards sustainable waste management practices and led the UK Government to produce national waste strategies that aim to decouple waste growth from economic growth thus, breaking the link between the latter and the environmental impact of waste. This is set in the Government's sustainable development strategy, which through the waste hierarchy emphasises the reduction, reuse, recycle/compost and use of waste as a source of energy [4].

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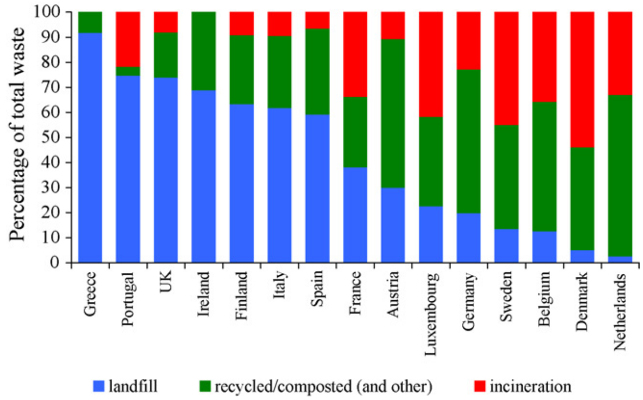


Fig. 1. Municipal waste management in the European Union in 2003.

Regarding this, energy-from-waste (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 Government'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 [5]. 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 [6].

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 in its recent waste strategy for England [7]. The focus of this study is on the recovery of energy by the thermal treatment of waste using combustion and gasification technologies.

In the UK, EfW technologies are predominately direct combustion or incineration processes. Moving grate, rotary kiln and fluidized bed combustors are all proven and 'bankable' processes. They are widely used commercially because of their applicability to large-scale use and their versatility. Fluidized bed combustors, in particular, are becoming more popular because of their ability to handle waste of widely varied properties and the many advantages in controlling emissions [8].

However, public perception of the combustion processes is less than favourable and has to some extent hindered the development of EfW technologies in the UK. 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 [9]. 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 [10], also supported by several studies [11], 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. Finally, EfW diverts waste from landfill and not from recycling/composting. Experience in other countries more 'advanced' in recycling policy implementation than the UK, such as Austria, Denmark, Germany and the Netherlands, indicates that high recycling rates can co-exist with high EfW rates [12].

The main success of these advanced countries in developing infrastructure for the diversion of waste from landfill is because they had relevant policy, planning and financial mechanism in place for a relatively long time, compared to the UK. In Denmark, for example, EfW facilities are built near communities who welcome the cheap energy and heat they provide. While, a landfill ban in Austria has increased landfill cost to over €280/t, thus forcing local authorities and industry to look for alternative routes to deal with waste, such as EfW and mechanical biological treatment (MBT) [13].

Advanced thermal treatment processes, and in particular gasification processes, are seen as alternatives to the traditional direct combustion 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 direct 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 [14].

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 and Japan [15]. 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. Nonetheless, 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 [16], 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 incineration. Alongside the wide range of measures set out in the 2007 Energy White Paper for meeting our long-term energy challenges [6], the UK Government has proposed greater levels of support for gasification under a banded Renewable Obligation [17]. 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 combined heat and power (CHP) were recently made eligible for ROCs subject to compliance with the Combined Heat and Power Quality Assurance.

In addition to ROCs, Defra signed contracts with Novera and ENER-G in late 2006 to build waste gasification plants in Dagenham 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, 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.

The main objective of this study is to evaluate the technical and economic performance of EfW combustion and gasification systems and report the implications of different scales and technologies on costs and efficiencies. The study is part of the research programme of EPSRC's Sustainable Urban Environment (SUE) Waste Management Consortium [18]. The research project investigates the appropriate scales and technologies for energy

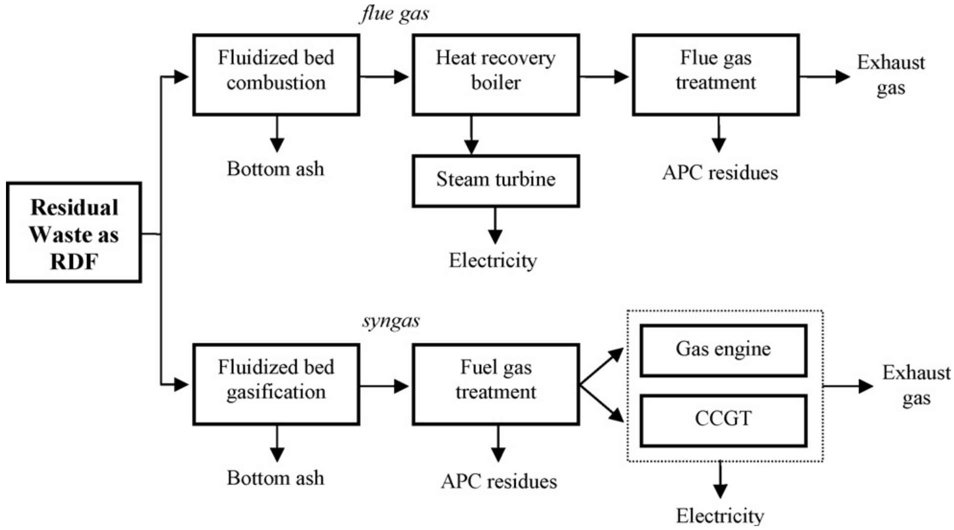


Fig. 2. Energy recovery from waste – two process options.

recovery from waste by combustion and gasification, in order to identify the most energy-efficient process designs based on energy conversion efficiencies, environmental impact and economics. This study focuses on the application of fluidized bed processes for the small-to-medium scale generation of electrical power from urban waste.

2. Methodology

2.1. Waste treatment options

Two different scale scenarios of 50 and 100 ktpa were considered for this comparative analysis 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:

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

Generally, the residual wastes remaining after re-use and recycling can be sent directly or as RDF to dedicated facilities, such as combustors, or other EfW plants incorporating ATT processes, such as gasification. It can also be co-combusted with other fuels, such as coal, in power generation, cement production or other large thermal processes. Energy is then recovered as heat, which can be used for district and industrial heating and/or power, which can be sold to the national grid [19]. In combustion processes, the steam produced is fed into an energy recovery system, which generates electricity by employing a steam turbine. Any contaminants in the flue gas, such as particulates and acidic pollutants, are removed by a flue gas treatment system before the gas is released to the atmosphere. The main residues from the combustion process are bottom ash (BA) and air pollution control residues (APC). The bottom ash is discharged from the bottom end of the combustion chamber and is an inert material that 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.

For gasification processes, the syngas or the gasification product gas is largely composed of H_2, CO and small amounts of CO_2, H_2O, CH_4, N_2 and ash residue or fly ash. This syngas has a calorific value and can replace fossil fuels in high efficiency power generation, heat, combined heat and power applications and in the production of liquid fuels and chemicals via synthesis gas. Any contaminants in the syngas are removed by a wet scrubbing system before the gas is utilised by the energy recovery systems or further processed into chemicals and fuels. For power generating applications, the syngas is combusted and used with conventional steam turbines or utilised directly in dedicated gas engines and turbines. The inorganic materials in the waste, such as ash and metals, are vitrified in the gasifier and the resultant products (bottom ash) are inert and recycled as a secondary aggregate.

The cost and technical performance of using a steam turbine for the combustion process and a gas engine and CCGT for the gasification process are evaluated in this study. Fig. 2 illustrates the two thermal treatment processes studied for the generation of electric power from urban waste. In the following sections, 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 Section 3, while the results are discussed in Section 4 and a sensitivity analysis, which takes account of uncertainties in the model input parameters, is performed in Section 5.

2.2. Mass and energy balances

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 and are summarised in Table 1 [20]. The proximate analysis shows the fixed carbon, moisture, volatiles and ash contents of the waste used, as well as its lower heating value (LHV). The ultimate analysis gives the elemental compositions of the waste on a dry ash free basis, in terms of carbon, hydrogen, oxygen, nitrogen, sulphur and chlorine. The RDF has ash and moisture contents of 20% and 15.8%, respectively, which corresponds to a LHV of 4000 kcal/kg or16.7 MJ/kg.

Performing the mass and energy balances enable the comparison of the technical performance of the different waste treatment options by determining their overall system efficiencies. System

Table 1
Proximate and ultimate analysis of the waste used

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	69.63	5.75	22.25	0.88	0.62	0.87

efficiencies are defined as the ratio of the net generated electricity to the energy input to the system (see Eq. (1)). However, to obtain these values, the combustion and gasification efficiencies, as well as the performance of the different prime moves, i.e. steam turbines, gas engines and CCGT units, need to be obtained.

$$\text{System efficiency}\,[\%] = \frac{\text{Power output}\,[\text{MW}]}{\text{Energy input to system}\,[\text{MW}]} \times 100 \tag{1}$$

2.3. Process and energy conversion system efficiencies

Gasifiers have thermal or cold gas efficiencies between 70% and 93%, with most operating at between 75% and 88% [21–23]. The cold gas efficiency [24] can be defined as the ratio of the energy content of the syngas to the energy content of the waste feedstock (see Eq. (2)). 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 as part of the sensitivity analysis, where the effects of changes in the cold gas efficiency on the economic parameters 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.

$$\text{Cold gas efficiency}\,[\%] = \frac{\text{Heating value of product gas}\,[\text{MW}]}{\text{Heating value of feedstock}\,[\text{MW}]} \times 100 \tag{2}$$

The performances of the prime movers were obtained using literature date published by Bridgwater et al. [25], which are presented in Fig. 3 for a range of thermal energy input of 1–40 MW_{th}. Fig. 3 illustrates the relationship between the thermal energy input to the prime movers and their corresponding gross electrical generation efficiencies. In this analysis, the electrical generation efficiency is defined as the ratio of power output to the energy supplied to the prime mover (see Eq. (3)).

$$\text{Electrical generation efficiency}\,[\%] = \frac{\text{Power output}\,[\text{MW}]}{\text{Energy input to prime mover}\,[\text{MW}]} \times 100 \tag{3}$$

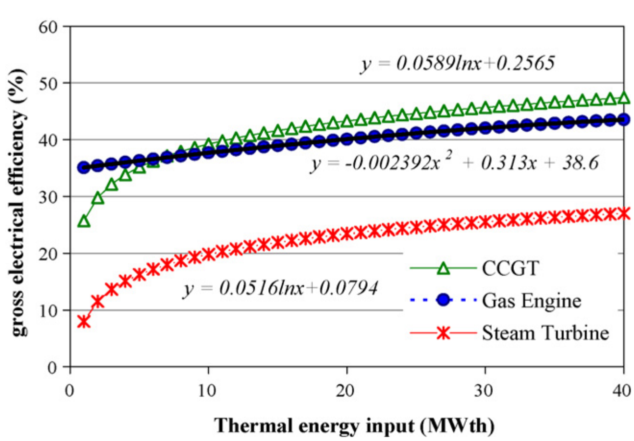


Fig. 3. Gross electricity generation efficiencies of the prime movers.

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 Fig. 3 for a given thermal energy input.

For the fluidized bed combustion process, an average internal energy consumption or site power use of 1.2 and 1.9 MWe were used for the scale scenarios of 50,000 and 100,000 tpa, respectively, which are comparable to that of other fluidized bed combustion systems in Europe and UK [20,26]. 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. These values are based on similar fluidized bed gasification processes employing gas engines and CCGT units [27].

3. Model assumptions

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 [8]. 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) [28–30], 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 cur-

Table 2
Capital costs of EfW incineration plants[a]

Plant scale (ktpa)	Capital cost (€million)[b]
50	18–27
100	35–50
150	53–63
200	56–81
400	102–140

[a] Not including fluidized bed plants.
[b] Based on an exchange rate of £1 = €1.40 (14/12/2007).

rent 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 [25].

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.

3.1. Capital costs

The available data in the literature for the capital costs of ATT processes, such as gasification and pyrolysis, vary significantly from one plant to another [31,32]. McLanaghan [8] reported capital costs of €11–130 million for 32–360 ktpa gasification and pyrolysis plants in the UK. In Europe, capital costs range from €13–82 million for 20–200 ktpa plants. On the other hand, Table 2 summaries the capital costs of combustion for scales ranging from 50 to 400 ktpa. These costs are for mass-burn incineration and are largely moving grate incinerators, which are proven and well established in the UK. Therefore, there is less uncertainty associated with the costs of these processes compared with gasification and pyrolysis.

In this work, the capital costs for a Novera Energy-type facility have been adopted for the gasification units since the facility uses a similar technology and plant configuration to those considered in this study [33]. The capital costs of the different prime movers and pre-treatment of the waste into RDF were taken from EDUCOGEN [34] and the Ilex report to the Department of Trade & Industry [35], respectively. The rest of the cost data were obtained from Germanà & Partners. All cost data are updated and reported in (€$_{2006}$), using appropriate indices from the Office for National Statistics (ONS). The capital costs reported in this study represent the total plant costs (TPC), which cover main equipment costs (EC), direct plant costs (DPC) and indirect plant costs (IPC). The main equipment costs cover:

- Waste and residue storage and transport systems;
- Combustion/gasification system with heat exchanger network;
- Gas cleaning system;
- Energy generation system.

Direct costs include costing for piping, auxiliary systems and services, electrical, instrumentation and control and civil work, while indirect costs constitute engineering and supervision, contingency and contractor fee. The model excludes land costs, grid connection costs, waste collection costs and revenues from material recycling prior to thermal treatment.

Table 3
Capital costs estimates

Component cost	Factor used	
Direct plant costs (DPC)		
Equipment cost (EC)	100%	EC
Piping	8%	EC
Auxiliary systems and services	12%	EC
Electrical	10%	EC
Instrumentation and control	10%	EC
Civil work	20%	EC
Total direct plant cost	160%	EC
Indirect plant cost (IPC)		
Engineering and supervision	12%	EC
Total direct and indirect costs	172%	EC
Contingency	10%	DPC + IPC
Contractor fee	10%	DPC + IPC
Total plant cost (TPC)	172% EC + 20% DPC + IPC	

The main equipment and direct costs are obtained from previous working experiences and contracts by Germanà & Partners, whereas the indirect costs are obtained by factorial estimation using cost factors published by Gerrard and Peters & Timmerhaus and are summarised in Table 3 [28,29]. Where the cost data are unavailable, Eq. (4) is used, which gives the general relationship between costs and scale.

$$\frac{C}{C_r} = \left(\frac{S}{S_r}\right)^n \quad (4)$$

where C is the cost of proposed plant at scale S, which is in terms of the amount of waste treated; C_r is the cost of the reference plant at scale S_r and n is the scale exponent. The scale exponent, n, is derived from historical data for similar plants and is usually in the range of 0.6–0.8 [28].

3.2. Operating costs

The operating costs of combustion processes range from €49–77/t for plant capacities of 50–400 ktpa, while operating costs of €28–77/t were given for gasification and pyrolysis processes with plant capacities of 32–360 ktpa [8]. In this study, the different operating costs involved are described as follows:

- Maintenance – The systems would operate for 329 days a year, with maintenance costs at 3% of TPC for the combustion process and 5% for gasification [20,33];
- Consumables and utility – These are system capacity dependent, while the electrical consumption by the auxiliary units are subtracted from the gross electrical output of the systems;
- Labour – An average salary of €45,000 is assumed, with the number of employees being system capacity dependent [20]. 16 and 24 staff are assumed to run and maintain the 50 and 100 ktpa systems in two daily shifts;
- Ash disposal – 20% of the input waste is ash (1/3 bottom ash and 2/3 APC residues). The bottom ash is assumed to be recycled, while the APC residues are sent to a special landfill. The costs of landfill including transport and landfill tax are shown in Table 4. The landfill tax was increased by £8/year until it reached £48/t and then kept at that rate for the duration of the project life-time [36];
- Energy conversion system – The operating costs of the gas engine, CCGT and steam turbine are shown in Table 5 [34];
- RDF pre-treatment – The operating costs for mechanical treatment are taken at €8.4/t and €4.2/t of feed waste at 50 and 100 ktpa, respectively [35];
- Plant overheads – This is assumed at 50% of labour costs.

Table 4
Landfill operating costs

Cost (€/t)	Landfill type	
	Non-hazardous landfill	Hazardous landfill
Landfill cost incl. transport	33.6	112
Landfill tax (rate for 2007/2008)	33.6	33.6
Total cost	67.2	145.6

3.3. 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 revenues generated from EfW facilities include:

- Revenue from 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 3.4 for further detail).
- Revenue from electricity sales – This was assumed at €35/MWh, which is an industry standard base value [37];
- Revenue from Renewable Obligation Certificates (ROCs) – A conservative value of €48.0/MWh was used, which is the ROCs buyout price for the 2007/2008 period [38]. Sixty eight percent of the waste is regarded as biodegradable and therefore, eligible for ROCs [39];
- Revenue from 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 €6.17/MWh [40];
- Revenue from 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). A market rate of €4.2/t was used [41];
- Revenue from sales of secondary aggregates – The price value for bottom ash as secondary aggregates range from €9.8–14/t according to The Waste & Resources Action Programme [42]. A value of €9.8/t was used.

3.4. 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 systems. This includes operation and maintenance, labour costs and final disposal of ash. It also takes into account the capital costs of the facility and revenues generated. The gate fees for MSW plants in the UK using ATT processes vary between €35–140/t, while gate fees of €50–77/t have been reported for new large-scale EfW incineration [8,14,43]. 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 Eq. (5)). The impact of ROCs on the gate fee for the gasification systems was also evaluated.

$$\text{Gate fee} = \sum_{n=1}^{30}[\text{PV(costs)} - \text{PV(income)}] \quad (5)$$

Table 5
Operating costs of energy conversion systems

Energy conversion system	Cost range (€/MWhe)	Average used (€/MWhe)
Gas engine	5.8–9.2	7.5
Combined cycle gas turbine	4.6–5.4	5.0
Steam turbine	1.5–2.3	1.9

3.5. Levelised cost of waste treatment

Another way to perform comparisons between different technologies with different capital investment, operation and power output, is to calculate their levelised cost of waste treatment. This is the accepted method for the economic comparison of different power generation plants. It quantifies the unitary cost of electricity produced during the plant life-time and is reported in €/MWh. 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 [44].

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 the effect of inflation was excluded as it was assumed that it influences all cash flows to the same degree. In addition, 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 Eq. (6), where i is the discount rate, CF_n is the annual cash flow (revenues-operating costs) at the nth year and TPC is the total plant cost. The IRR was calculated as the discount rate that makes the NPV equal to zero [30].

$$\text{NPV} = \sum_{n=1}^{30} \frac{\text{CF}_n}{(1+i)^n} - \text{TPC} \quad (6)$$

4. Results and discussion

The results of the technical and economic performance of EfW fluidized bed combustion and gasification systems, generating electricity from MSW, are presented in this section. The developed model allows the net electrical efficiencies associated with each system to be calculated and, therefore, the overall system efficiencies are also obtained. The capital and operating expenditures and the projected revenues generated from the sale of recovered energy and materials are also evaluated.

4.1. Technical performance

The net electricity generated by the different treatment options and their overall system efficiencies for the two plant scales of 50 and 100 ktpa are reported in Table 6 and shown in Fig. 4. The results demonstrate that the ability of gasification processes to employ more efficient energy conversion systems, such as gas engines and CCGT units, enables them to have greater electrical generation efficiencies and, as a result, they can have better overall system performance 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 24% and 27% for both scale scenarios of 50 ktpa and 100 ktpa, respectively. Fluidized bed gasification systems using gas engine (FBG + GE) have overall efficiencies of 23% and 25%, while efficiencies of 18% and 22% are reported for the combustion systems (FBC + ST).

The results also show the greater sensitivity of the technical performance 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 6–10% for the gasification systems. This highlights the nature of the combustion processes, which are centralised operations and technically more efficient at larger scales.

Table 6
Technical performance of treatment options

Plant scale	50 ktpa			100 ktpa		
Treatment options	FBG + GE	FBG + CCGT	FBC + ST	FBG + GE	FBG + CCGT	FBC + ST
Thermal energy of waste	29.4 MW_{th}			58.8 MW_{th}		
Waste flow rate	6.3 t/h			12.7 t/h		
Gross electrical generation efficiency of prime movers (%)	38.4	40.9	24.9	40.8	45.0	28.4
Gross generated electricity (MWe)	7.9	8.4	6.6	16.8	18.6	15.1
Site power use (MWe)	1.1	1.3	1.2	2.2	2.8	1.9
Net generated electricity (MWe)	6.8	7.2	5.4	14.6	15.8	13.2
Overall system efficiency (%)	23.3	24.4	18.3	24.7	26.8	22.4

Table 7
Economic performance of treatment options

Plant scale	50 ktpa			100 ktpa		
Treatment options	FBG + GE	FBG + CCGT	FBC + ST	FBG + GE	FBG + CCGT	FBC + ST
Capital cost	28.0 € million 560 €/t	28.8 € million 576 €/t	30.1 € million 603 €/t	44.9 € million 449 €/t	45.0 € million 450 €/t	48.1 € million 481 €/t
Operating cost	4.3 € million 87 €/t	4.2 € million 84 €/t	4.1 € million 82 €/t	7.8 € million 78 €/t	7.5 € million 75 €/t	6.5 € million 65 €/t
NPV	17.6 € million 351 €/t	17.3 € million 347 €/t	17.3 € million 346 €/t	30.4 € million 304 €/t	29.7 € million 297 €/t	27.6 € million 276 €/t
IRR (%)	11.3	11.1	10.9	11.7	11.6	10.9

4.2. Economic performance

The economic performance of the fluidized bed combustion and gasification systems are summarised in Table 7 for the two plant scales of 50 and 100 ktpa. The capital and operating costs are reported for each system and the cost effectiveness of these waste treatment options were compared using NPV and IRR, as well as estimated gate fees and levelised costs of waste treatment. The results show that gasification systems represent the cheapest option, with capital costs ranging from €29–45 million. FBG + CCGT systems have higher costs than FBG + GE, 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 and gas cleaning systems to recover heat and clean the large volumes of flue gas generated.

Although the capital costs of FBC + ST presented in this economic evaluation may appear to be higher than the reported costs in the literature, it is important to remember that; firstly, the capital costs presented in Table 7 illustrate the total plant costs of the different treatment options. Secondly, most data in the literature are quoted for moving-grate incineration, which represents the most proven combustion technology for MSW treatment and are consequently cheaper. Thirdly, only plant scales up to 100 ktpa are considered in this evaluation, which do not fully capture the benefits of economies of scales associated with large EfW incineration plants, such as lower capital and operating costs per tonne of waste treated.

For the purpose of comparison, the capital costs of two commercial combustion processes in the UK are shown in Table 8. The Dundee plant employs Kvaerner bubbling fluidized bed combustion boiler units [26], while the Kirklees plant uses Lurgi moving-grate technology [45]. The reported capital costs for the Dundee and Kirklee plants are €409/t and €360/t, respectively. Using the costs for the Dundee plant, 50 and 100 ktpa fluidized bed combustion systems would cost €640/t and €518/t, which are within 6–8% of the costs reported in this evaluation for FBC + ST.

Table 8 also shows the higher capital costs of fluidized beds compared to moving-grate systems. This reflects the greater operational reliability of moving-grate systems, which have larger capacities and have been operating in the UK on a commercial basis longer than fluidized beds. As a result, the costs of the moving-grate systems are well-established, as 17 out of the UK's 19 waste combustion facilities employ these technologies. In addition, they are also available from credible suppliers who have proven track records and therefore, they have the lowest risk of implementation relative to any other technologies. Fluidized bed systems on other hand have been operated at commercial scales for capacities ranging from 70 to 150 ktpa of MSW in Europe and Japan [14]. The Dundee plant is the only fluidized bed facility in commercial operation in the UK, while Allington's 500 ktpa facility is currently undergoing testing and will fully operational in 2008. However, despite their higher costs, fluidized bed systems are compatible with high levels of source segregation. The recycling, composting and recovery targets within UK waste management strategies, coupled with the requirement to divert waste from landfill, require a diversification of waste management approaches. It also requires 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. They also offer greater pollution control than moving grate systems, with better heat and mass transfers. This in turn, results in greater energy efficiencies and makes the technology better equipped to handle waste of varying calorific value.

The calculated operating costs of the different treatment options show that combustion systems have the lowest costs, with reported

Table 8
Fluidized bed vs. moving grate combustion processes

EfW plants	Technology	Scale (ktpa)	Power (MWe)	Capital cost
Dundee	Fluidized bed	120	8.3	€409/t (1999)
Kirklees	Moving-grate	136	9.0	€360/t (2003)

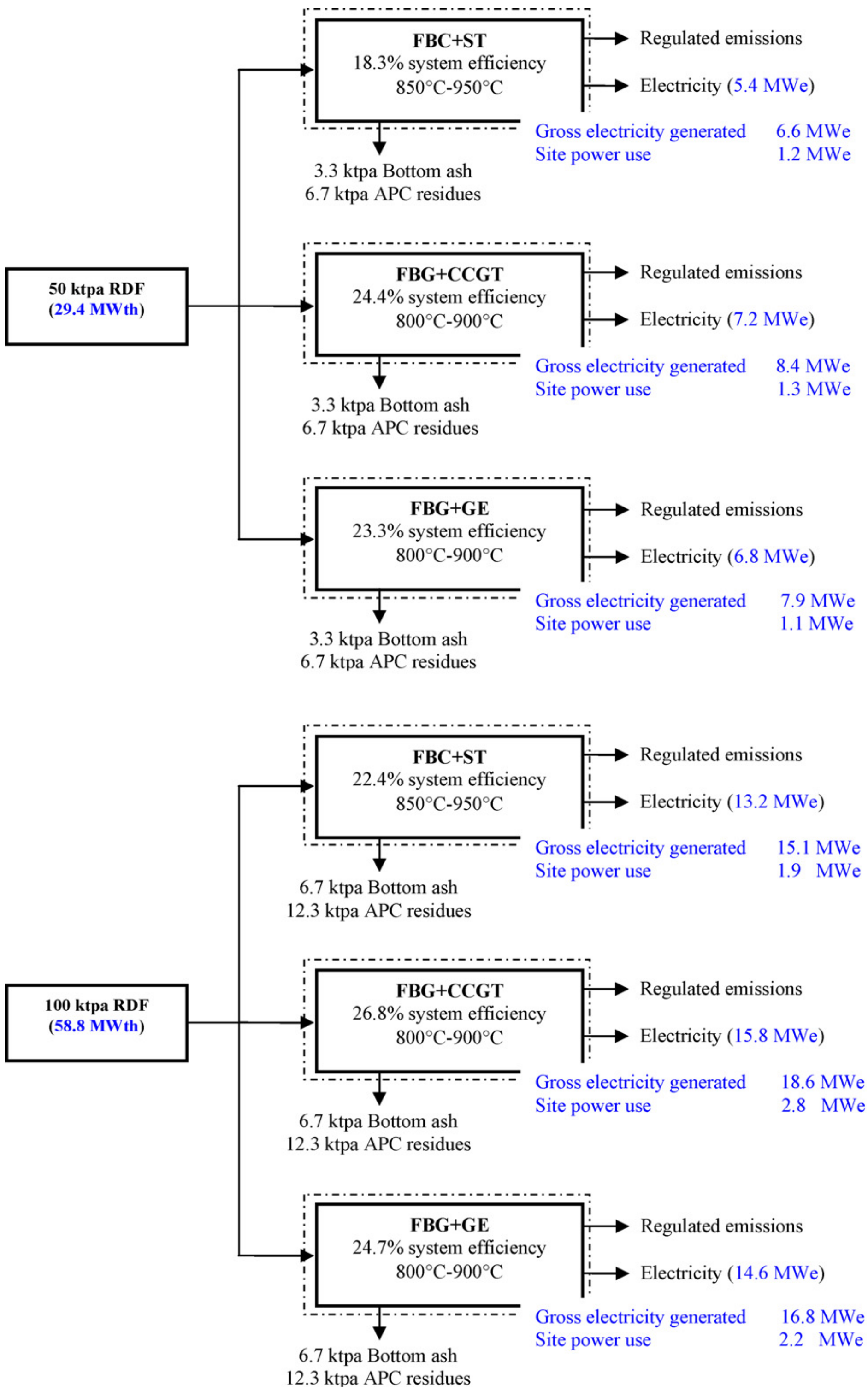


Fig. 4. Schematic diagrams of mass and energy balances for the treatment of 50 ktpa (top) and 100 ktpa (bottom) of RDF.

annual costs of €82/t and €65/t for the plant capacities of 50 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 20%. This is compared to an average reduction of 11% for the FBG + GE and FBG + CCGT systems, as their operating costs fall to €78/t and €75/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 5. Nevertheless, this cost is offset by their cheaper capital costs, which in turn is reflected in their high NPV and IRR values, as shown in Table 7.

The NPV for the FBG + GE systems is €351/t and €304/t for the plant scale scenarios of 50 ktpa and 100 ktpa, with an average IRR of 11.5%. The FBC + ST systems are the least attractive treatment option, with NPV of €346/t and €276/t and an average IRR of 10.9%. Fig. 5 illustrates the cumulative NPV for the different treatment options

Table 9
Gate fees and levelised cost of waste treatment

Treatment options	FBG + GE	FBG + CCGT	FBC + ST	FBG + GE	FBG + CCGT	FBC + ST
Gate fees (€/t)						
Without ROCs	104	100	111	80	73	73t
With ROCs	69	63	111	43	32	73
Levelised costs (€/MWh)	118	111	148	96	87	97

over the project life-time. It shows that the economic performance of the different treatment options is comparable at the plant scale scenario of 50 ktpa. As the plant scale increases to 100 ktpa, the gasification systems become more attractive, with FBG + GE being the most attractive option.

Table 9 shows the gate fees and levelised costs of waste treatment. These indicators are 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 + GE and FBG + CCGT have gate fees of €104/t and €99/t, respectively, while FBC + ST is the least attractive treatment option with a gate fee of €111/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 35% reduction in the gate fee to €73/t. The gate fee reduces by 23% to €80/t for FBG + GE and by 26% to €73/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. Therefore, the effects of incorporating revenues from ROCs into the analysis are also reported in Table 9. The results show that the gate fees reduce by €42–48/t and €30–41/t for the gasification systems at 50 ktpa and 100 ktpa, thus enabling them to be more attractive and cheaper treatment options than combustion by 38–55%.

The levelised costs of waste treatment 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 9 reports the levelised costs for the different treatment options in terms of the annual amounts of electricity generated. The results show that the gasification systems are the least cost options for investment,

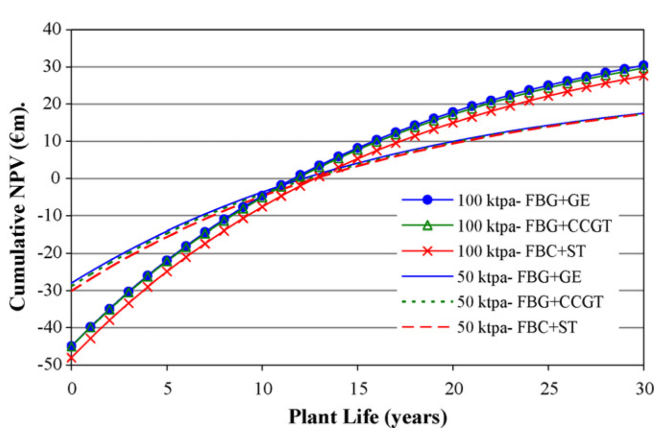


Fig. 5. Cumulative NPV for the different treatment options.

Table 10
Techno-economic performance of combustion & gasification systems

	Fluidized bed process type	
	Gasification	Combustion
Technical performance		
Thermal energy of waste (MW_{th})	29–59	29–59
Mass flow rate (t/h)	6–13	6–13
Gross electrical generation efficiency (%) of prime movers	38–4	25–28
Net generated electricity (MWe)	7–17	5–13
Overall system efficiency (%)	23–27	18–22
Economic performance		
Capital costs (€/t)	449–576	481–603
Operating costs (€/t)	75–87t	65–82
NPV @ 6% discount rate (€/t)	297–351t	276–346
IRR (%)	11.1–11.7	10.9)
Gate fees		
Without ROCs (€/t)	73–104	73–111
With ROCs (€/t)	33–69	73–111
Levelised costs		
In terms of electricity generated (€/MWe)	87–118	97–148

with levelised costs of €118/MWh for FBG + GE and €111/MWh for FBG + CCGT at the 50 ktpa plant scale capacity. FBC + ST is the highest cost option with level cost of €148/MWh. 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 35% reduction in the levelised cost to €97/MWh. The levelised cost reduces by 19% for FBG + GE to €96/MWh and by 22% to €87/MWh for FBG + CCGT, which is still the cheapest treatment option at both scales.

In summary, the technical and economic comparisons of the different waste treatment options are presented in Table 10.

5. Sensitivity analysis

In this section, the effects of changing the model input parameters or system variables on the economic performance of the different waste treatment options are evaluated. The sensitivity analysis was carried out on all waste treatment options, as each system variable can affect the overall performance to a different degree. Fifteen different system variables have been chosen for the sensitivity analysis and the effects of a ±10% change of these variables on the levelised costs of waste treatment and gate fees has been assessed. 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 for the sensitivity analysis are presented for the most influential parameters in Tables 11 and 12. In Table 11, the sensitivity analysis shows that the calorific value of the waste, energy conversion efficiencies of the prime movers and gasifier efficiency have the greatest impact on the levelised costs, whereas the gate fees are shown to be affected

Table 11
Impact on levelised costs of waste treatment

Plant scale scenarios		50 ktpa			100 ktpa		
Waste treatment options		FBG + GE	FBG + CCGT	FBC + ST	FBG + GE	FBG + CCGT	FBC + ST
Base scenario (€/MWh)		118	111	148	96	87	97
Model input parameters		Effects of changes on levelised costs					
Calorific value of waste (%)	+10	−9.21	−9.21	−10.73	−8.73	−8.81	−10.33
	−10	11.66	11.63	13.67	10.96	11.03	13.02
Conversion efficiency of prime movers (%)	+10	−9.21	−9.21	−10.73	−8.73	−8.81	−10.33
	−10	11.66	11.63	13.67	10.96	11.03	13.02
Gasifier efficiency (%)	+10	−9.21	−9.21	0.00	−8.73	−8.81	0.00
	−10	11.66	11.63	0.00	10.96	11.03	0.00
Capital cost (%)	+10	3.15	3.26	5.09	2.91	2.97	5.09
	−10	−3.15	−3.26	−5.09	−2.91	−2.97	−5.09
Operating hours (%)	+10	−0.84	−0.65	−2.96	−0.44	−0.33	−2.44
	−10	−1.24	−0.93	−4.68	−0.61	−0.43	−3.86
Discount rate (%)	+10	2.05	2.12	2.25	1.89	1.93	2.25
	−10	−1.99	−2.07	−2.19	−1.84	−1.88	−2.20
Ash disposal cost (%)	+10	1.56	1.58	1.54	1.80	1.84	1.93
	−10	−1.56	−1.58	−1.54	−1.80	−1.84	−1.93
Plant life (%)	+10	−1.03	−1.07	−1.13	−0.95	−0.97	−1.13
	−10	1.32	1.37	1.45	1.22	1.25	1.45
Labour cost (%)	+10	1.73	1.75	1.71	1.50	1.53	1.61
	−10	−1.73	−1.75	−1.71	−1.50	−1.53	−1.61
RDF operating cost (%)	+10	0.67	0.68	0.66	0.39	0.40	0.42
	−10	−0.67	−0.68	−0.66	−0.39	−0.40	−0.42
No market for BA (%)		3.59	3.63	3.54	4.15	4.23	4.45

by the capital costs, as well as electricity prices and ROCs, as illustrated in Table 12. A graphical representation of the most sensitive system variables affecting the levelised costs and gate fees for the 100 ktpa FBG + CCGT scenario are shown as an example in Fig. 6. The most influential model input parameters are further discussed in the following sections.

5.1. *Effects of 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 12. Therefore, it is crucial that changes 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 plant performance is related to its input, waste with higher calorific value will result in more energy recovery and, thus achieving better plant performance in terms of efficiency and economics. 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 fluidized beds, it equips the technology to cope 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.

5.2. *Effects of gasifier cold gas 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 performance 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% [46].

5.3. *Effects of prime mover electrical generation efficiency*

The electrical generation efficiencies of the gas engines, CCGT and steam turbines have great impact on the economic performance of the different waste treatment options and are directly related to their overall system efficiencies. The sensitivity of the levelised costs to these system variables is greater when compared to their impact on the gate fees, as reported in Tables 11 and 12. The conversion efficiencies used in this evaluation are reasonable and within the range of most published data. However, one has to recognise that the applications of gas engines and turbines in EfW processes are not common in the UK at present for MSW treatment as opposed to steam turbines. This is in spite the fact that they are widely used for power generating applications using fossil fuels.

Table 12
Impact on gate fees

Plant scale scenarios		50 ktpa			100 ktpa		
Waste treatment options		FBG+GE	FBG+CCGT	FBC + ST	FBG + GE	FBG + CCGT	FBC + ST
Base Scenario (€/t)		104	100	111	80	73	73
Model input parameters		Effects of changes on gate fees					
Calorific value of waste (%)	+10	−10.66	−13.39	−4.10	−19.75	−34.78	−6.74
	−10	10.66	13.39	4.10	19.75	34.78	6.74
Gasifier efficiency (%)	+10	−10.66	−13.39	0.00	−19.75	−34.78	0.00
	−10	10.66	13.39	0.00	19.75	34.78	0.00
Conversion efficiency of prime movers (%)	+10	−10.66	−13.39	−4.10	−19.75	−34.78	−6.74
	−10	10.66	13.39	4.10	19.75	34.78	6.74
Capital cost (%)	+10	7.11	8.24	7.05	9.75	14.59	8.41
	−10	−7.11	−8.24	−7.05	−9.75	−14.59	−8.41
Electricity price (%)	+10	−5.62	−6.84	−2.90	−10.54	−17.64	−4.97
	−10	5.62	6.84	2.90	10.54	17.64	4.97
ROCs (%)	+10	−5.25	−6.38	0.00	−9.83	−16.46	0.00
	−10	5.25	6.38	0.00	9.83	16.46	0.00
Discount rate (%)	+10	4.62	5.36	3.12	6.34	9.49	3.72
	−10	−4.50	−5.22	−3.04	−6.18	−9.24	−3.63
Ash disposal cost (%)	+10	3.53	3.98	2.13	6.03	9.02	3.19
	−10	−3.53	−3.98	−2.13	−6.03	−9.02	−3.19
Operator profit (%)	+10	3.77	4.21	2.31	5.58	8.18	2.75
	−10	−3.77	−4.21	−2.31	−5.58	−8.18	−2.75
Labour cost (%)	+10	3.92	4.42	2.37	5.02	7.52	2.66
	−10	−3.92	−4.42	−2.37	−5.02	−7.52	−2.66
Plant life (%)	+10	−2.33	−2.69	−1.57	−3.19	−4.77	−1.87
	−10	2.98	3.46	2.01	4.09	6.12	2.40
RDF operating cost (%)	+10	1.52	1.72	0.92	1.30	1.95	0.69
	−10	−1.52	−1.72	−0.92	−1.30	−1.95	−0.69
PRNs (%)	+10	−0.63	−0.72	−0.38	−1.08	−1.62	−0.57
	−10	0.63	0.72	0.38	1.08	1.62	0.57
	no PRN	6.34	7.16	3.84	10.85	16.24	5.74
Operating hours (%)	+10	−0.08	0.08	5.51	0.04	−0.19	8.24
	−10	0.07	0.37	−4.10	0.37	0.15	−6.74
No market for BA (%)		9.11	10.27	4.10	15.57	23.31	6.74

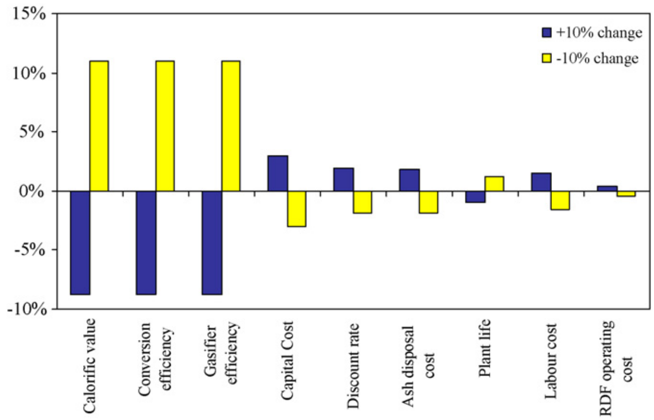
CCGT units, in particular, achieve the highest thermal-to-electricity efficiency of any commercial power generation technology. They also have the lowest specific investment costs in terms of the amounts of electricity generated [34]. However, because of the lack of proven track record for gasification 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 [14]. Others, like Novera Energy, are reconfiguring their processes to incorporate more conventional and, hence, 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 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 processes with syngas combustion is between 10% and 20% [7]. This is comparable, if not lower, with burning the waste directly in traditional moving-grate combustion systems without any pre-treatment, which have efficiencies of 14–27%.

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. 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 and turbines, are rendering applications in EfW projects increasingly 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 polices and incentives, such as ROCs, and through active R&D by major industry players and research institutions.

5.4. Effects of 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 €69/MWh in a recent auction in October 2007, a value of €48/MWh 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. As a result, the actual price for ROCs will remain above the buy-out price



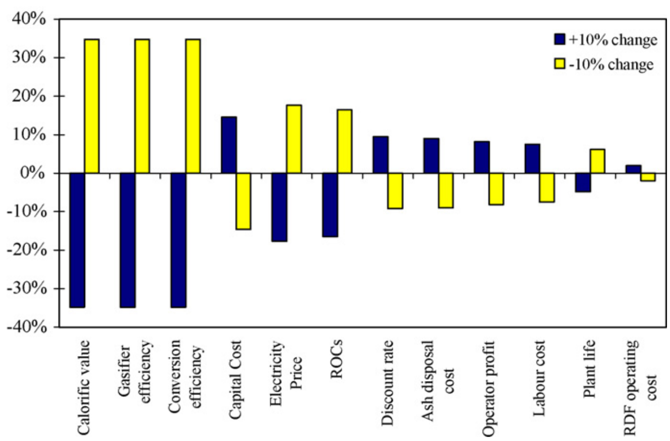


Fig. 6. Effects of changes in model input parameters on levelised costs (top) and gate fees (bottom) for a 100 ktpa FBG + CCGT only.

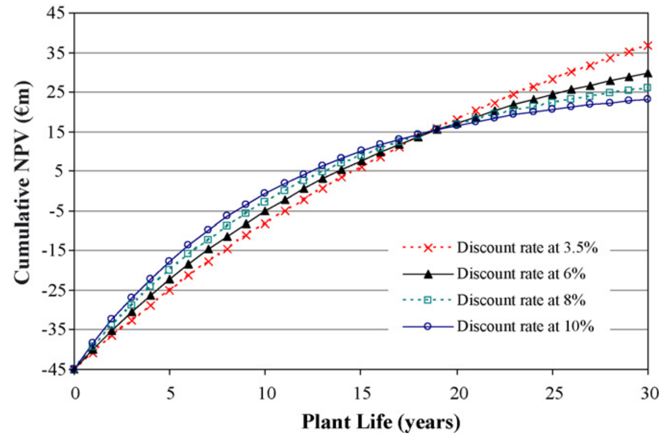


Fig. 7. Effect of discount rates on the NPV for FBG + CCGT at 100 ktpa only.

Table 13
Effect of discount rates on levelised costs and gate fee

Discount rate (%)	3.5	6.0	8.0	10.0
Gate fees excluding ROCs (€/t)	64	100	82	91
Levelised costs (€/MWh)	80	87	93	99

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 is €35/MWh, 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.

5.5. Effects of capital costs

The economic performance of the different waste treatment options is sensitive to their capital costs, as expected. The sensitivity of the gate fees to changes in the capital costs is greater when compared to their impacts on the levelised costs. The capital 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%. Nonetheless, uncertainties or errors of ±30% are typical in study estimates of this type [25].

5.6. Variations in discount rate

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 UK Treasury rate for public sector projects.

Fig. 7 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 performance 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 13.

6. Conclusions

EfW is an important component of an integrated waste management strategy. It is also an alternative source of energy, which by displacing fossil fuels can help reduce greenhouse gas emissions and increase the share of renewables in power generation. The technical and economic performance of EfW fluidized bed combustion and gasification systems have been reported in this study with the implications of different scales and technologies on costs and efficiencies. Two different scale scenarios of 50 ktpa and 100 ktpa plant capacities were considered for the generation of electric power using steam turbines for the combustion processes and gas engines and CCGT for the gasification processes. 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.

For the different waste treatment options, the study 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 performance of 23–27%, 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 performance, capital costs of €449–576/t were reported for the gasification options, compared to €481–603/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 lower system efficiency, compared to fluidized bed gasification coupled with CCGT, which is the most attractive treatment option in terms of gate fees and levelised costs of waste treatment.

Although fluidized bed gasification systems have limited commercial operation 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, supportive policies and active R&D by major industry players and research institutions, are important factors for the full commercialisation of the gasification processes, especially for plant scales larger that 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 costs, while the gate fees was affected by the capital costs, as well as electricity and ROC prices.

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