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Economic evaluation of improvements in a waste-to-energy combined heat and power plant

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ABSTRACT

Improving the efficiency of waste-to-energy combined heat and power plants increases their production of both electricity and heat. Economic evaluation of such improvements enables adequate decisions to be made between the various alternatives with respect to economic viability of the plant. In this study, the cost and profitability of different modifications to improve efficiency in a waste-to-energy plant are considered: these include the re-arrangement of air heaters, the introduction of a reheater, flue gas condensation (FGC) and an integrated gasification-combustion process. The base case and the modifications are evaluated and compared when operating either as a combined heat and power plant or as a power plant. Modelling, simulation and cost estimations were performed with the Aspen Plus software. Although the integrated gasification-combustion technology with FGC has the highest exergy efficiency, its higher capital cost is greater than all of the other alternatives. Modification 6, which involves both re-arrangement and changing the air heating medium has the lowest capital cost with respect to enhancing exergy efficiency. Modifications 1 and 7, involving FGC, are the best alternatives for the capital cost per total unit of revenue generated. These modifications not only provides the highest heat production but also the highest net present value (NPV). The base case and the modifications investigated all have positive NPV, indicating that a waste-to-energy combined heat and power plant is an attractive investment. However, an increase of about 122% in the gate fees would be required for a system with only electricity production to be profitable.

1. Introduction

The current increase being experienced in the generation of waste endangers human health and the environment. The ability to manage large quantities of waste is one of the greatest challenges facing the present and future generations (World Energy Council, 2016). One possible solution is to minimise waste by reusing or recycling large fractions of waste materials (European Union, 2008). A suitable approach for treating undesired end products remaining after recycling is the energy recovery method (Solheimslid et al., 2015; World Energy Council, 2016).

Utilization of energy from waste helps in treating non-reusable and non-recyclable waste as well as converting the valuable energy resource into electricity and heat (World Energy Council, 2016). The technology used for recovering energy from waste employs not only combustion but also gasification, pyrolysis and anaerobic digestion. Of these, the combustion process is used the most widely for treating waste materials of different types and sizes (Astrup et al., 2015; Burnley et al., 2011).

Waste combustion technology is well established in many European countries (Grosso et al., 2010). Sweden, for instance, has about 34 waste-to-energy combustion plants and recovers more energy from waste per capita than any other country in Europe (Avfall Sverige, 2018). The capacity of the waste combustion plants in Sweden is, in fact, greater than the amount of combustible waste produced in the country: in 2017, a total of 6,150,150 tonnes of industrial and household waste were treated and converted into more than 18.3 TWh of energy, of which 2.2 TWh was for electricity and 16.1 TWh for heating (Avfall Sverige, 2018).

Recovering energy via waste combustion technology has reduced the volume and mass of solid waste by 90% and 70%, respectively (Cheng and Hu, 2010; Menikpura et al., 2016). However, its electrical efficiency is generally low when compared with other combustion plants as a result of low steam properties: this, on the other hand, prevents surface corrosion on the heat exchanger tubes in the boiler (Ionescu et al., 2013; Malkow, 2004) caused mainly by the concentration of alkaline chlorides in the flue gases (Lee et al., 2007). The steam temperature and pressure of a

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waste-to-energy plant are therefore often limited to 400 °C and 40 bar, respectively (Lombardi et al., 2015). Furthermore, waste-to-energy technology is capital intensive (Leme et al., 2014) due to high financial investments and high maintenance and operating costs (Menikpura et al., 2016). The investment cost is about three times higher than for a woodchip CHP and four times higher than for a pulverized coal power plant (Taherzadeh and Richards, 2016).

Enhancing energy efficiency may help in reducing costs, increasing energy conversion and minimising the environmental impact of combustion. The exergy method has been shown to be an efficient tool for evaluating the efficiency of recovering energy from the combustion of waste. Grosso et al. (2010) analysed the use of the energy efficiency factor, R1, within the waste frame directive along with the exergy efficiency as performance criteria of waste-to-energy plants in Europe. Their results showed that the exergy method is a reliable way of assessing efficiency, as the R1 formula does not account for changes in the size of the plant or climate conditions. Solheimslid et al. (2015) evaluated the efficiency of a combined heat and power plant fired by municipal solid waste in Bergen, Norway, using different methods to calculate the chemical exergy of the solid waste; the results obtained from the different methods used in their investigations are in good agreement.

Possible measures for improving the design of waste combustion plants have been examined by several researchers. Lee et al. (2007), for example, examined the use of different corrosion-resistant alloys as cladding for the boiler tubes that could withstand high steam temperatures, thus enabling an increment in the properties of the steam in the superheater. However, the corrosion-resistance materials need to be evaluated and balanced with respect to cost-effectiveness. A net electricity efficiency of above 30% was achieved with energy from a waste plant in Amsterdam (the Netherlands) when the boiler operated at a steam temperature of 440 °C and pressure of 130 bar (Gohlke, 2009; Murer et al., 2011). Here, the plant was incorporated with a steam reheater, had an excess air ratio of 1.4 and a condensate pressure of 0.03 bar. The boiler tubes were protected with Inconel; more heat was recovered from the boiler's heat exchangers by cooling the flue gas exit temperature from 180 °C to 130 °C. Main and Maghon (2010) examined different improvement measures that were applicable for enhancing the efficiency of modern energy from waste (EFW) facilities located at Hameln/Germany, Arhus/Denmark, Heringen/Germany, Naples/Italy and Ruedersdorf (Berlin) Germany. The improvement methods evaluated were compared to the waste combustion technology of the base plant, operating at steam conditions of 40 bar and 400 °C, a flue gas temperature of 190 °C and an excess air level of 60%. They observed that reducing the excess air to 39% in the EFW at Hameln/Germany; reducing in the flue gas temperature at the boiler outlet from 180 °C to 100 °C using heat exchangers in the EFW at Arhus/Denmark; introducing an external superheater using auxiliary fuels at 520 °C and 90 bar in the EFW at Heringen/Germany; increasing the steam parameters to 500 °C and 90 bar in the EFW at Naples/Italy and operating a boiler with an intermediate reheater in the EFW at Ruedersdorf (Berlin)/Germany increased the energy efficiency of the base process plant by 1.1%, 6.8%, 12.6%, 14.6% and 13.5%, respectively. However, when compared with the base plant, no increase was observed in the boiler efficiency for the changes made in the EFW plants at Naples/Italy and Ruedersdorf (Berlin)/Germany, showing that there is no room for significant improvement to be made when the energy method is used for efficiency evaluation. It agrees with the statement that energy efficiency is bound to lead to misconception, misevaluations and poor decision-making (Gaggioli and Wepfer, 1980). It does not account for entropy generated within the system, providing only information of inputs and outputs of energy in the process and excluding its quality (Luis, 2013). Further improvement in the energy recovery from waste can also be realized through preheating the combustion air and water, using the low temperature streams in the plant or flue gas at the boiler (Lombardi et al., 2015).

The recirculation of flue gas has been shown to enhance energy recovery from waste by improving homogeneity and mixing the gases to provide a more efficient combustion (Liuzzo et al., 2007; Murer et al., 2011). While examining the effect of flue gas recirculation (FGR) of a municipal solid waste fired plant, Liuzzo et al. (2007) noticed that when FGR was used as the secondary air in the boiler, it not only reduced the formation of NO_x in the flue gas but also increased the energy recovery of the overall system by 3%.

A further measure of efficiency improvement is the application of a combined heat and power process (co-generation) in the waste-to energy plant. Here, energy from a waste plant is supplied to a district heating system via a condensing heat exchanger with a feed temperature in the range of 75 °C to 110 °C, while the return temperature varies between 40 °C and 55 °C (Gohlke, 2009). The energy efficiency of waste combustion typically ranges between 20 and 30% for electricity production only, whereas about 85% can be reached in the combined heat and power plant (Ryu and Shin, 2013). Sweden has a well-developed district heating system (Gohlke and Martin, 2007) that enables the recovery of more energy per ton of waste combusted, with more than 82% of waste-to-energy plants producing both electricity and heat (Avfall Sverige, 2018).

The effect that pre-treating waste before combustion has on energy recovery was studied by Consonni et al. (2005a). They investigated strategies of using municipal solid waste to recover energy in a waste-to-energy plant involving the direct combustion of waste without pretreatment, subjecting it to light mechanical treatment and converting it into refuse-derived fuel. They found that whilst pre-treating the waste increases its heating value marginally it does, however, reduce the net production of electricity due to the loss of combustible materials. Consonni et al. (2005b) examined further the environmental impact and cost implications of the four strategies. Their observations showed that treating waste before it is used in a waste-to-energy plant is neither environmentally nor economically beneficial. Cimpan and Wenzel (2013) compared the energy savings of pre-treating waste material using mechanical treatment and mechanical biological treatment with direct combustion in a waste-to-energy plant, and found that direct combustion without pre-treatment achieved the highest energy savings.

Although the different improvement methods in the recovery of energy from waste as reported by past researchers will enhance the efficiency of the process, their cost implications and profitability were not addressed. Moreover, most of the waste-to-energy plants investigated produce only electricity and were evaluated based on the energy efficiency method. Therefore, the aim of this study is to investigate different improvement options in a waste combustions process, as well as their cost and economic viability. The specific objectives are: (i) to evaluate the exergy efficiency of a waste-to-energy combined heat and power plant, (ii) to investigate possible improvements in this sector, (iii) to evaluate an economic analysis of such improvements and (iv) to compare improvements that could be made in the combined heat and power plant with electricity production only.

2. Methodology

The cost of improving efficiency was evaluated by comparing the ratio of cost increment and the exergy efficiency enhancement of each modification with the base case plant. Seven modifications of the base case process plant were considered, and involved the re-arrangement of air heaters along with changing the heating medium; reheating; flue gas condensation and an integrated gasification and combustion. A sensitivity analysis was performed in order to examine the effects of uncertainties in the price of the income generated and the operating costs estimated. In addition, a profitability assessment of each improvement method was made to ascertain their economic viability. Furthermore, the modifications were evaluated and compared with the case study process plant operating either as a combined heat and power (CHP) plant or as a power plant. The conditions of the base plant and the various modifications are shown in Table 1. In all cases, municipal solid waste together with industrial waste corresponding to an energy input of 100 MW was used. The seven modifications and the base case process were modelled and simulated using Aspen Plus V9.

The base case plant (BC) is a municipal heat and power grate boiler fired by solid waste currently under construction. The process flow diagram of the plant and descriptions of its equipment as modelled in Aspen Plus are shown in Fig. 1 and Table 2, respectively. The stack temperature is 160 °C and 20% flue gas recirculation is employed in the boiler. The full system comprises a condensate pump, a feed-water pump, a boiler with a combustion part that includes the boiler tubes and a heat exchanger part (evaporator, superheater and economizer), a feed-water heater, a deaerator and two air heaters (using steam). The solid waste fuel used in the process, obtained from the city of Borås in Sweden, is comprised of 70% industrial waste and 30% municipal solid waste. The former is composed of wood, paper and plastics; the latter has an average composition of food waste (24.61%), paper packaging (19.26%), plastic packaging (11.10%), cardboard (1.87%), metal packaging (2.76%), glass packaging (3.58%), diapers and tissues (20.62%), combustible (12.73%), electronic waste (0.43%), hazardous waste (0.46%) and other materials (2.58%) (Moghadam and Karimkhani, 2010). The solid waste has a lower heating value of 11.6 MJ/kg as received, with a moisture content of 33.1 wt-% (Pettersson et al., 2013); a chemical analysis of the waste fuel in weight percentage, calculated on a dry basis (db) is reported as (C: 46.2); (H: 6.1); (O: 28.03); (N: 1.1); (S: 0.2); (Cl: 0.47) and (Ash: 17.9) (Jones et al., 2013).

Modification 1 (M 1), as shown in Fig. 1, has the same design and operating parameters as in the base case plant, except for the addition of flue gas condensation (FGC). The flue gas, at a stack temperature of 160 °C, is cooled down to 50 °C, which is below the dew point temperature. It is reheated thereafter to 110 °C, in order to avoid condensation and low temperature corrosion.

In Modification 2 (M2), the temperature and pressure of the steam in the case study process are increased from 420 °C to 440 °C and 50 bar to 130 bar, respectively. In addition, an intermediate reheater is integrated into the system, which reheats the wet steam after the first turbine extraction (14 bar) from 180 °C to 320 °C. The high steam parameters are those used in the waste-to-energy plant of Afval Energie Bedrijf, Amsterdam (Murer et al., 2011). Here, the furnace membrane walls are protected by Inconel, a corrosion-resistant material suitable for use in high temperature applications.

Modification 3 (M3), which is similar to Modification 2 (M2), has flue gas condensation integrated to utilise the exergy otherwise lost to the surroundings.

Modification 4 (M4), represented in Fig. 1, involves the integration of waste gasification with the waste boiler, as has been applied in the waste gasification plant in Lahti, Finland (Taherzadeh and Richards, 2016). Solid waste was first gasified at a temperature of 900 °C to produce combustible gases, which were then cooled down to 400 °C prior to the gas-cleaning process. The cleaned gas was then combusted in a gas boiler for the production of electricity and heat. The gasifier used air as the gasifying medium, while the combustion section of the plant operated at a steam temperature and pressure of 540 °C and 121 bar, respectively.

Modification 5 (M5) has the same process configuration as Modification 4, with the addition of flue gas condensation (FGC).

Modification 6 (M6) is similar to the base case plant. The two air heaters have been removed and a high-pressure feed-water heater and a new air heater added instead. The air heater was integrated into the system after the economizer and heated by the flue gas. The stack temperature, which was 160 °C in the base case plant, was reduced to 130 °C.

Modification 7 (M7) is similar to Modification 6 but incorporates flue gas condensation in order to utilise the exergy lost to the surroundings (Fig. 1).

2.1. Evaluation of efficiency

Exergy analysis was used to evaluate the improvement in efficiency in the process plant based on the exergy input and output of the system. The input exergy of the waste stream was calculated from the elemental composition of the waste fuel using the model developed by (Eboh et al., 2016). The exergy efficiency of the process was calculated using Eq. (1):

$$\eta_{ex} = \frac{\dot{E}x_{Q_h} + \dot{W}_{net}}{\sum_i \dot{E}x_i} = \frac{\sum_a(\text{Exergy available})}{\sum_i(\text{Exergy input})} \quad (1)$$

Table 1
The parameters of the base case plant and the different improvement modifications made.

Variables	Unit	BC Base case plant	M1 Flue gas Condensation (FGC)	M2 High steam parameter +reheater	M3 M2 + FGC	M4 Waste gasification + gas boiler	M5 M4 + FGC	M6 Changing the medium for pre- heating air	M7 M6 + FGC
Energy input	MW	100	100	100	100	100	100	100	100
Extraction press. HPT	bar	10	10	14	14	10	10	10	10
Extraction press. IPT	bar	5	5	5	5	5	5	5	5
Extraction press. LPT	bar	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Flue gas recirculation	%	20	20	20	20	20	20	20	20
Excess air	%	39	39	39	39	5	5	39	39
Stack temperature	°C	160	110	160	110	160	110	130	110
Steam temperature	°C	420	420	440	440	540	540	420	420
Steam pressure	Bar	50	50	130	130	121	121	50	50
Reheat steam temp.	°C	–	–	320	320	–	–	–	–
Reheat steam press.	bar	–	–	14	14	–	–	–	–

Source: BC is from design data of a waste plant under construction in Sweden; M2 and M3 are modified from the operation conditions of Afval Energie Bedrijf, Amsterdam (Murer et al., 2011); M4 and M5 are modified from the operation conditions of a waste gasification plant in Lahti, Finland (Taherzadeh and Richards, 2016).

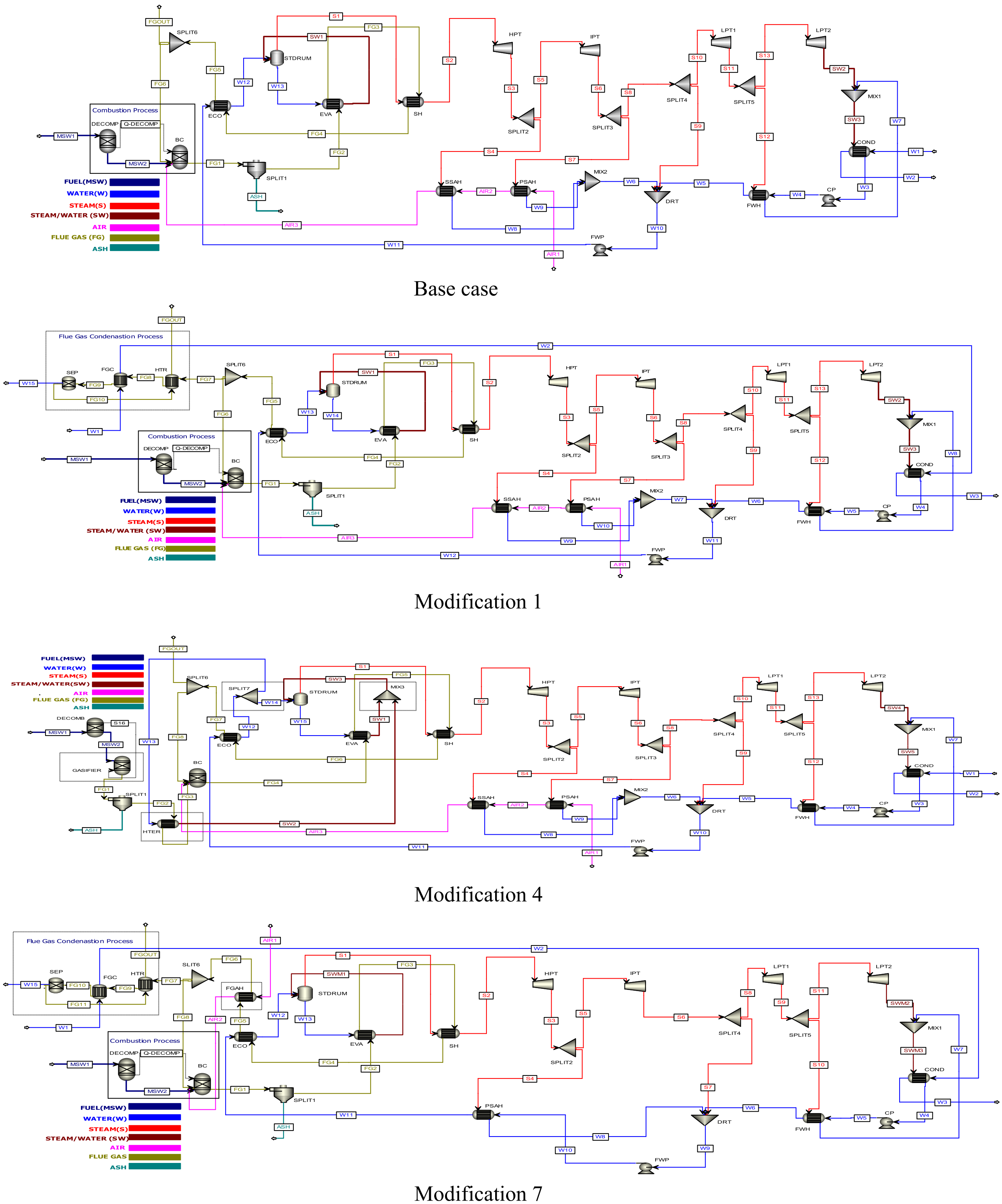

Fig. 1. Process flow diagram of the base case and modified waste-to-energy CHP plant, modelled in Aspen Plus. The dotted areas show the new equipment in the modification compared to the base plant. The equipment symbols are described in Table 3.

where $\dot{E}x_{Q_h}$ is the exergy flow rate associated with the production of district heat, $\dot{W}_{net}$ is the net work output rate and $\dot{E}x_i$ is the exergy rate input to the system.

2.2. Evaluation of costs and finances

The various methods pertaining to the improvement of the efficiency of the base case study investigated were compared with the capital cost involved in the improvement so that accurate decisions could be made. The costs and financial analyses were calculated using the Aspen process economic analyser. This is one of the most sophisticated software used in the industry for estimating costs (Towler et al., 2013a): using a detailed method of cost estimation, it evaluates the cost of process design by examining the costs of the components that constitute the system. It involves estimating the cost of the equipment purchased based on the sum of the cost of the material, i.e. labour and overhead costs as well as the profit made by the manufacturer. The cost of the equipment installed was estimated from the bulk materials and labour requirements. The information in the software was based on the cost data provided by the vendor in 2015.

The profitability analysis was carried out using the investment parameters listed in Table 3.

The information provided in the table was used to calculate the operation and maintenance costs, the net present value (NPV) and the internal rate of return (IRR), based on the assumption that the economic life of the process plant is 20 years. Also, the analysis assumes a salvage value of zero. As industrial plants continue to function for many years after the end of their economic life (Towler et al., 2013b), the salvage value determines the estimated worth of the capital cost of a project at the end of its useful life and is used to calculate the annual depreciation. The straight-line depreciation method is employed here, as it is the simplest and most commonly used (Towler et al., 2013b). It is determined by subtracting the salvage value from the capital cost, and then dividing the result by the economic life of the project. The main income considered here is the revenue generated from electricity, district heat and gate fees. A utilization factor of 91% was presumed, which corresponds to the plant having 8000 operating hours/year. The revenue prices and most of the assumptions made were based on waste combustion plants in Sweden (Taherzadeh and Richards, 2016).

2.3. The cost of improving efficiency

The cost of improving efficiency compares the increase in capital costs with the enhancement of efficiency resulting from the different modifications. It is calculated here as the ratio of the increment in the capital cost to the increment in the exergy efficiency. The best option for improvement is selected when the fraction is at the lowest value: this is the option with the lowest capital cost for enhancing the efficiency of the system.

Table 3
The investment parameters used in the economic analysis of waste-to-energy CHP plants.

Name	units	value
Cost index[a]		2015 in USD
Tax Rate*	%/y	22
Interest rate*	%/y	6
Economic life of the plant[b]	y	20
Depreciation method[c]		Straight-line
Working capital[c]	%/y	15
Operating hours[a]	h/y	8000
Ash treatment[d]	USD/ton	55
District heating network & support cost[d]	USD/kWh	0.045
Flue gas treatment[e]	USD/ton	14
Waste pretreatment[d]	USD/ton	30
District heating cost[d]	USD/kWh	0.09
Electricity cost[d]	USD/kWh	0.05
Gate fees[d]	USD/ton	55

Source: [a]AspenTech (2012); [b]European Commission (2017); [c]Towler et al. (2013b); [d]Taherzadeh and Richards (2016); [e]Bosmans et al. (2013); *Communication with plant operator.

2.4. Sensitivity analysis

The price of electricity, district heating, gate fees and operating costs are based on estimations and can change with time. A sensitivity analysis was carried out to ascertain the uncertainty of these prices on the economic viability of process plants. The production prices, operating costs, and the income from the process plants were therefore varied from the range of −40% to +40% of the base price. For electricity production only, price variations of 0–140% were used in order to determine the economic feasibility of the system. The range of price variations were chosen so as to cover the break-even point. The sensitivity analysis was made by adjusting one parameter only (an income or a production cost) while keeping the others constant.

3. Results and discussion

3.1. The cost of improving efficiency

The enhancements made to improve the efficiency of the process were compared with the capital cost and profit of the system in order to ascertain its economic viability.

The base case waste combustion plant, which has an exergy efficiency of 25% and a capital investment cost of $ 176 million, was improved by considering the seven different modifications described in this work. The capital investment cost for 27 ton/h waste input used in this study is comparable with investment cost estimated to be between $ 145 and $ 207 million for a capacity of 25 to 35 ton/h fuel input as reported by Taherzadeh and Richards (2016) for the cost of waste-to-energy plant in part of the Europe.

Modification 6, which involves not only re-arrangement but also changing the air heating medium (from steam to flue gas), does not have a significant effect on the efficiency increment of the base plant. It is, however, the best option for improvement with regards to the lowest capital cost per unit increase in efficiency (Fig. 2). The result is a 0.6% decrease in the capital cost of the base case process plant. It is also the second-best alternative for the lowest capital cost per total revenue earned.

Modifications 1 and 7, which incorporate flue gas condensation, are the second-best options for efficiency improvement when compared with the costs involved and the two best alternatives for the capital cost per total unit of revenue generated (Fig. 2). This can be attributed to the flue gas condensation component integrated into the systems, which enhances the production of heat and increases the overall efficiency of the base case by 4%, as seen in both methods.

Modifications 4 and 5, which include waste gasification, have the highest exergy efficiency, namely 30.1% and 30.5%, respectively. The improvements in efficiency experienced in these modifications are the result of increasing the steam conditions to 540 °C and 121 bar from the 420 °C and 50 bar of the base case. However, the capital investment cost per increase in efficiency is higher than for the other alternatives, as shown in Fig. 2. Here, the improvement methods are not favourable when the capital cost of the enhancement is considered. This is attributed to a huge difference in the capital cost compared to the base case, although it should be noted that this refers only to the cost associated with an increase in efficiency and says nothing about the total revenue. In the case of the flue gas condensation process experienced in Modification 5, the cost of efficiency increment can be decreased by 6%.

Modifications 2 and 3, both of which have a reheater, are the next improvement methods with a high capital investment cost per efficiency increase. Nevertheless, these two methods help eliminate the moisture in the steam that causes erosion of the turbine blades, and would thus also reduce the maintenance cost of

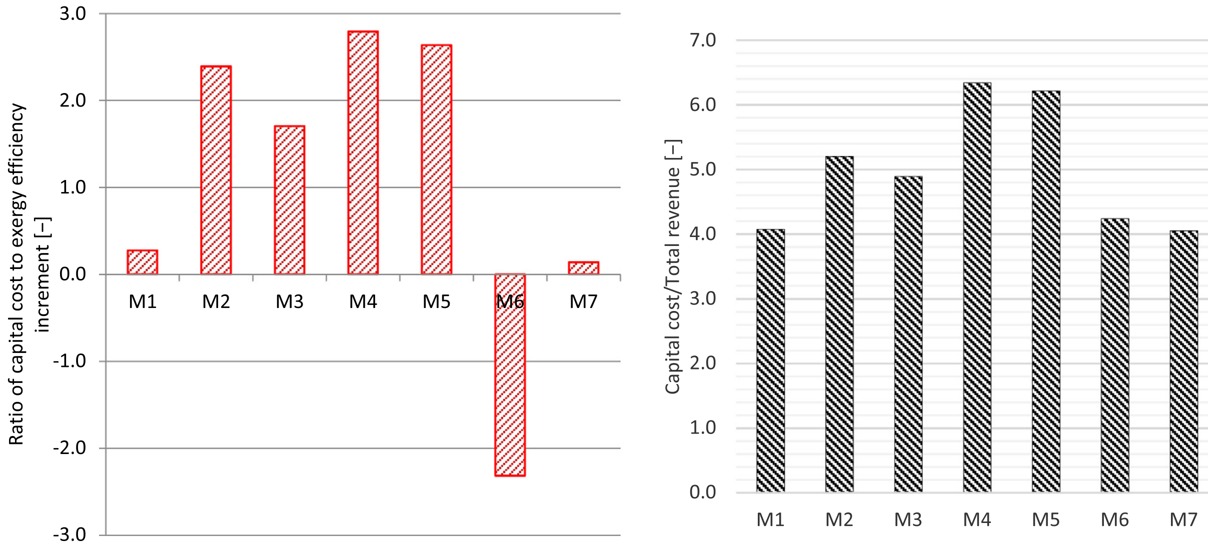

Fig. 2. The ratio of the increment in the capital cost to the increment in the exergy efficiency and capital cost per total revenue.

the turbine. A reduction in the cost of enhancing efficiency of about 29% can be achieved using Modification 3, which employs flue gas condensation.

3.2. Economic evaluations

The net present value (NPV) and internal rate of return (IRR) of the process plants investigated are presented in Fig. 3. It shows that Modifications 1 and 7 have the highest NPV and IRR, with an increase of 30% and 12%, respectively, when compared with the base case process plant, indicating that these are more economically viable than the other improvement options. Flue gas condensation incorporated into the systems increases the heat that can be produced, which has a significant impact on the overall income (Fig. 4). These two modification processes have the highest amount of heat production.

Modification 6 is the next efficiency improvement alternative with 7% and 3% increments, respectively, in the NPV and IRR of the base case. These are also attributed to the high production of heat in this system, which contributes significantly to the total revenue generated. It is the best method for heat production when the flue gas condensation is not integrated in the process plant (Fig. 4). The IRR of 12.21% calculated in Modification 6 is in agreement with 12.21% and 12.22% obtained by Udomsri et al. (2010) and Zhao et al. (2016) respectively for a waste combustion plant of similar arrangement.

In Modifications 2, 4 and 5, reductions in the NPV and IRR (Fig. 3) were observed, i.e. the base case process plant is seen to be more economically viable, and hence they are not the best options for efficiency enhancement of the base case. However, a positive value of the NPV in the different improvement methods shows that they are in fact profitable.

The flue gas condensation process was not considered in the evaluation of a waste combustion plant producing only electricity. Therefore, only the efficiency improvements of Modifications 2, 4 and 5 were investigated and compared with the base plant. In Fig. 5, the negative values of the net present value show that both the base case plant and the different modification processes were not economically feasible, indicating that the district heating network contributes significantly to the profitability of a waste-to-energy plant. The revenue generated by the combined heat and power plant, shown in Fig. 4 by the base case (BC) (the least income earned), is M$ 16.7 more than the highest revenue generated in Fig. 5 by Modification 4 (the highest income earned) in the waste combustion plant producing only electricity. It can also be observed in Fig. 5 that Modification 4 generates the highest revenue, although it does have the lowest net present value when compared with other improvement options.

The variations in the price range due to uncertainties in the price of district heat and electricity, gate fees and production costs are presented in Fig. 6. The indication is that the price of district heat and its maintenance costs have a significant impact on the

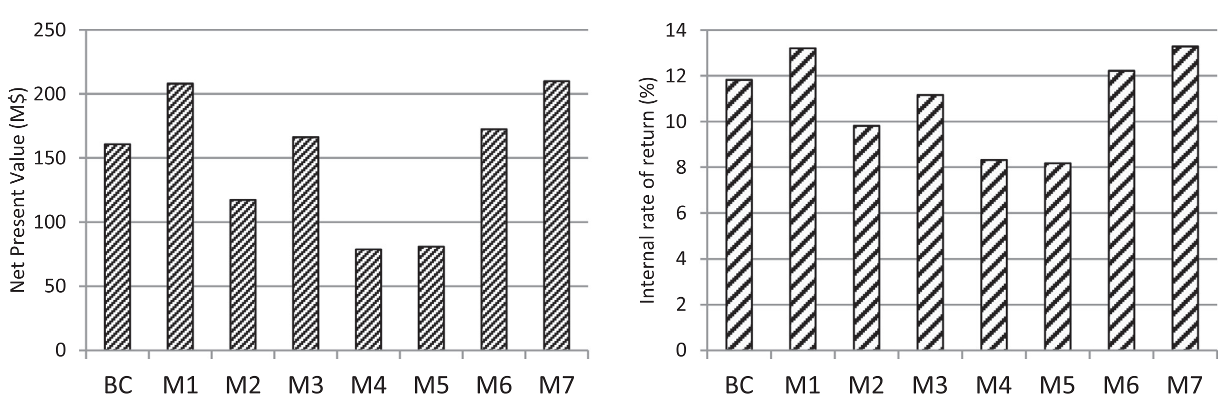

Fig. 3. Net Present Value (NPV) and Internal Rate of Return (IRR) for the base case and various modifications.

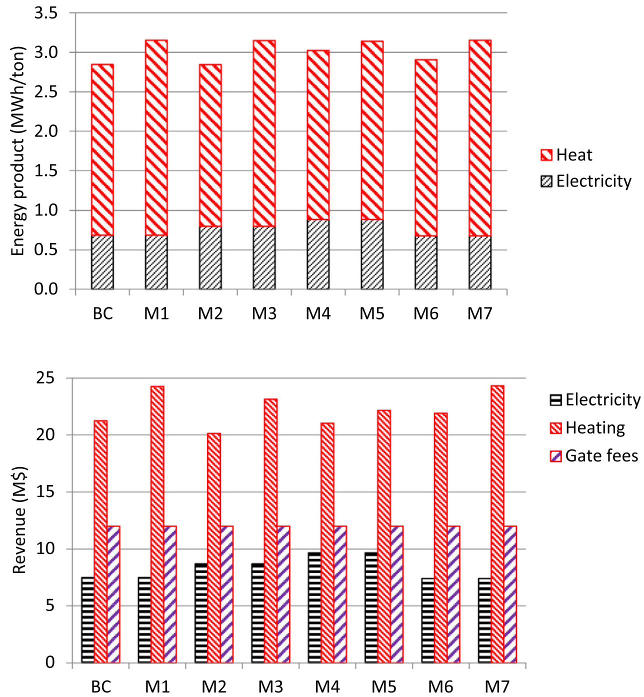

Fig. 4. Energy production and annual revenues for the base case and all seven modifications.

economic viability of the plant: more than 70% of the energy products and 49% of the annual income of the waste combustion plants investigated are derived from the production of district heat (Fig. 4).

Fig. 6c shows the effect that NPV has on the variations in the price of electricity produced and the gate fees paid. It can be seen that gate fees affect the economic viability of waste combustion with electricity production only: this is in agreement with previous economic assessments of energy recovery from solid waste (Leme et al., 2014). The base case plant, as shown in Fig. 6c, becomes more attractive at about a 122% increase in the price of gate fees.

3.3. The impact of improvements in waste-to-energy plants in a circular economy

A circular economy involves a reduction in the use of waste and resources by maintaining the value of products, materials and resources for a long time (European Commission, 2015). The energy recovered from waste combustion can be one of the key factors for the successful conversion of waste into a valuable resource when managed efficiently. According to The European Commission (2017), waste-to-energy can contribute effectively in the transition to a circular economy provided that it is firmly guided by the waste hierarchy: the top priorities should be based on the minimization of environmental effects and the optimization of resource efficiency. One of the ways of achieving this target is to use state-of-the-art energy-efficient waste combustion technologies, as investigated in this study. Modifications 4 and 5, involving integrated waste gasification-combustion methods, are the most efficient options for improving the waste combustion process and thereby supporting the transition to a circular economy. These two modification processes have the highest exergy efficiencies, with lesser emissions to the environment. In general, waste-to-energy CHP plants are better alternatives for improving efficiency; they help provide an action plan for achieving a circular economy that is more in agreement with the waste hierarchy than waste combustion plants that produce electricity only.

In order for the transition towards a circular economy to be smooth, the increase in the capacity of energy recovery from waste combustion needs to be balanced to ensure that recycling and reuse are not jeopardized (European Commission, 2017). The overcapacity of waste-to-energy facilities, especially in the northern part of Europe, has been seen as the result of a high demand for heat via district heating networks. Sweden and Denmark have the highest incineration capacity of 591 kg/capita and 587 kg/capita, respectively, (European European Commission, 2017). However, there is no overcapacity of incineration as far as the entire EU member states are concerned: the eastern and southern parts of the EU are highly dependent on landfill and, moreover, they lack adequate waste combustion facilities (European Commission, 2017). The high processing capacity in Sweden contributes, for instance, to the low profitability of Waste-to-Energy plants in Norway, as much of their municipal solid waste is exported to Sweden due to of lower gate fees (Lausselet et al., 2016). According to Lausselet et al. (2017), Sweden could accept lower fees thanks to the higher income generated from its well-developed district heating system.

The circular economy action plan, which involves changing from mixed waste to separate collection, will affect the composition of waste used in waste combustion plants. Although the plan will increase the recycling rates of valuable materials and decrease environmental emissions from the waste combustion processes, the energy production from waste-to-energy plants will, however, be reduced. Moreover, with the full implementation of a circular

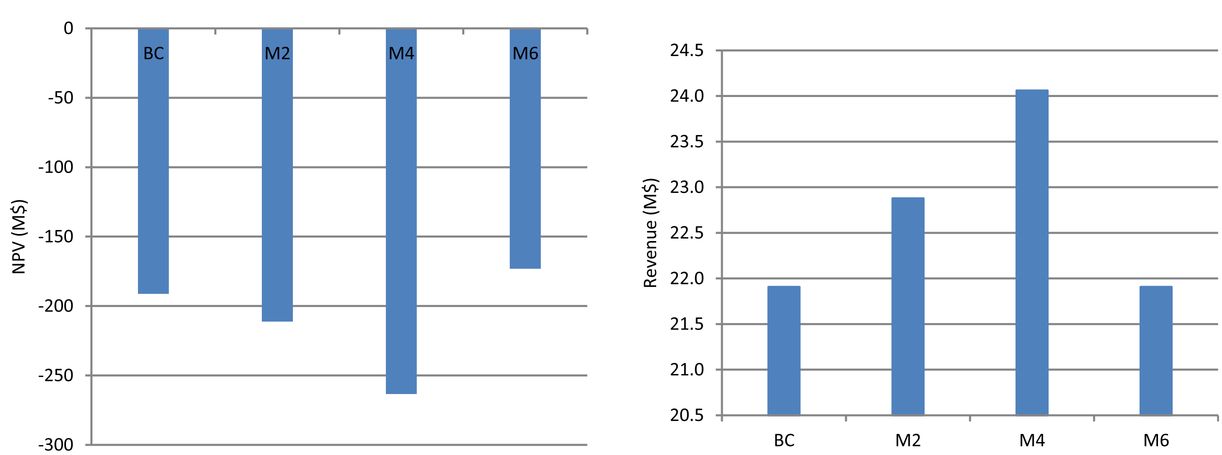

Fig. 5. Net Present Value and total revenue generated for plants producing electricity only.

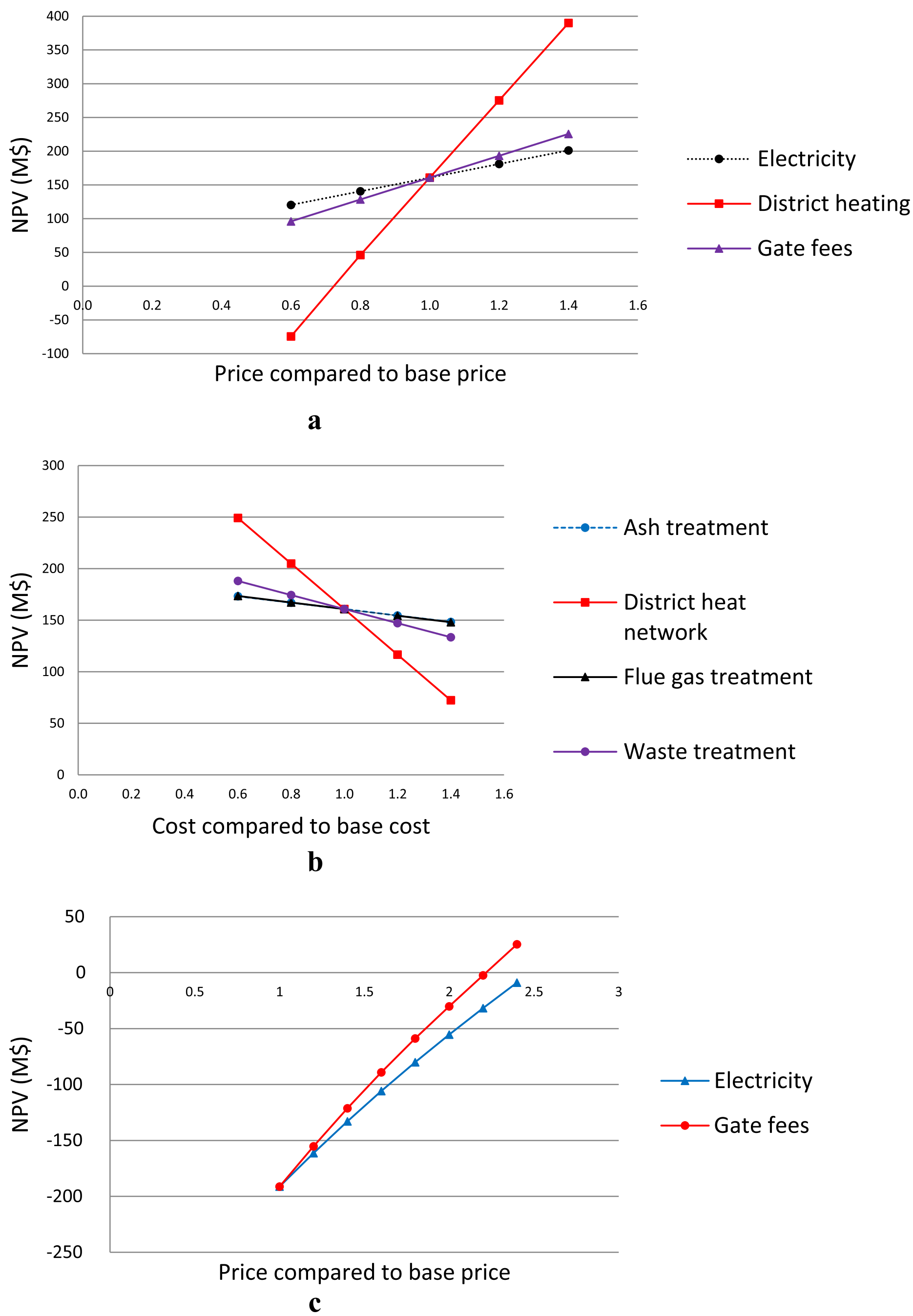

Fig. 6. NPV of the base case with variations in (a) the price of the income generated, (b) production costs for CHP and (c) variations in the price of the income for electricity production only.

economy plan, waste combustion plants will be useful detoxifying facilities for eliminating toxic constituents in the environment.

4. Conclusions

Evaluations of improvements that can be made in a waste combustion plant may be more effective when the costs of such improvements are considered. It enables adequate decisions to be reached between various enhancement alternatives for the profitability of the process plant. Seven different modifications for improving the efficiency of WTE plants CHP and their economic performance have been assessed. Modification 5, which is a combination of waste gasification, a gas boiler and flue gas condensation achieved the highest percentage of improvement in efficiency. It does, nevertheless, involve a higher capital cost than the other alternatives. The capital cost for improving efficiency is seen to be most economical in this optimization by re-arrangement of the air heater and changing the air heating medium (from steam to flue gas), but it shows only a very marginal increase in efficiency. Modifications 1 and 7 with flue gas condensation are the best alternatives for the capital cost per total unit of revenue generated. Moreover, these two modifications are seen to be the most lucrative ventures, with the highest net present values and internal rates of return. District heating network is the most profitable income generated by waste process plants: it has a significant impact on the viability of the project over the expected range of variations in both the income and the production cost. The improvement methods that have been identified as having a high degree of efficiency enhancement do not necessary make them more economically feasible than other alternatives. Economic viability is required for the efficient evaluation of possible improvements that may be made to a system. In general, a waste-to-energy combined heat and power plant is an attractive investment with a positive net present value, as seen in the base case plant and from the different modification methods studied.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wasman.2019.09.008.

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