Original Article

WM&R

Waste Management & Research
2015, Vol. 33(6) 561–569

DOI: 10.1177/0734242X15587368
wmr.sagepub.com
SAGE

Feasibility analysis of municipal solid waste mass burning in the Region of East Macedonia – Thrace in Greece

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Abstract

The present work conducts a preliminary techno-economic feasibility study for a single municipal solid waste mass burning to an electricity plant for the total municipal solid waste potential of the Region of Eastern Macedonia – Thrace, in Greece. For a certain applied and highly efficient technology and an installed capacity of 400,000 t of municipal solid waste per year, the available electrical power to grid would be approximately 260 GWh per year (overall plant efficiency 20.5% of the lower heating value). The investment for such a plant was estimated at €200m. Taking into account that 37.9% of the municipal solid waste lower heating value can be attributed to their renewable fractions, and Greek Law 3851/2010, which transposes Directive 2009/28/EC for Renewable Energy Sources, the price of the generated electricity was calculated at €53.19/MWh_e. Under these conditions, the economic feasibility of such an investment depends crucially on the imposed gate fees. Thus, in the gate fee range of 50–110 € t^{-1}, the internal rate of return increases from 5% to above 15%, whereas the corresponding pay-out time periods decrease from 11 to about 4 years.

Keywords

Municipal solid waste, mass burning to electricity, waste to energy, economic feasibility, incineration gate fee

Introduction

Waste-to-energy (WTE) is an established option for municipal solid waste (MSW) treatment, motivated by both the necessity to minimise the environmental stresses of landfilling and the aim to increase the share of renewable energy (Gohlke, 2009; Hackl and Mauschitz, 2008). European Directive 2008/98/EC classifies WTE within the 'recovery' category of the conceptual hierarchy of the waste management options, only if the R1 criterion for energy efficiency is fulfilled. This criterion had led to optimised WTE plants with increased efficiency and a sound impact on greenhouse gas emissions (Gohlke, 2009). In EU-27, MSW incineration had increased its share from 15% of total MSW production, in 2000, to 22% in 2012, whereas options of higher priority had exhibited almost similar increases in the same period. For example, MSW recycling had increased its share from 15% to 23%, and composting from 11% to 18% (Cucchiella et al., 2012, 2014).

Although Directives 2008/98/EC and 2009/28/EC (European Commission, 2008, 2009) form a common ground from WTE motivation, WTE spreading is influenced by factors, such as the welfare and development of individual states or sub-national regions, the waste management infrastructures and the structure of the local energy markets (Sommer and Ragossnig, 2011). Thus, the 22% average share of WTE in the European Union (EU) rises to 54% in Denmark and 49% in Sweden, and exceeds 30% in Germany, France, Netherlands, Belgium and other north and central European countries (Cucchiella et al., 2014). Actually, MSW mass burning is estimated to have already reached installed overcapacities in some central European regions, as indicated by the decline of the imposed gate fees (Friege and Fendel, 2011), although it is not yet introduced in the Balkans and in the Baltic states (Cucchiella et al., 2014).

Overall, waste management in the EU, has resulted in the reduction of the least favourable option of landfilling, from a 60% share in 2000, to less than 40% in 2012. Thus, although landfilling is almost negligible in central Europe, it exceeds 50% in southern Europe and even 90% in former Eastern Europe and the Balkans (Cucchiella et al., 2012, 2014). In Greece, landfilling corresponded to about 82% of total MSW in 2012 (Cucchiella et al., 2014), and by the time this study was elaborated, no WTE plant was commissioned or under construction.

Despite their high initial investment costs, which require a minimum capacity to obtain economic feasibility (Cucchiella et al., 2012), MSW mass burning is suggested as the option of

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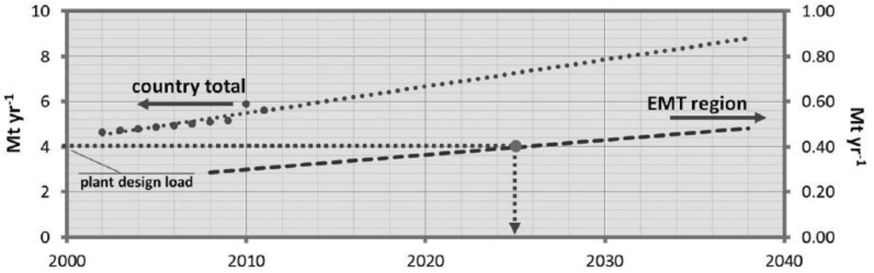

Figure 1. MSW generation in Greece, from 2002–2011 (Eurostat, 2014), and linear projection to the end of the lifetime of the MSW mass burning plant. The evolution of MSW generation in the EMT region was regarded to be proportional to that of the whole country.
EMT: Eastern Macedonia – Thrace.

choice for regions where landfilling is still the main route for waste disposal (Friege and Fendel, 2011), since it does not require sophisticated MSW management systems. In Europe, mass-burning is usually designed to handle raw waste without any pre-treatment (Friege and Fendel, 2011), and with up to 90% volume reduction (Achillas et al., 2013; Tabasová et al., 2012), it substantially contributes to the renewable energy share (Sommer and Ragossnig, 2011).

In this context, the purpose of this article is to evaluate the techno-economic feasibility of a single MSW mass burning to electricity plant in the Region of Eastern Macedonia – Thrace (EMT) in Northern Greece, an option that might lead to a solution regarding MSW treatment in this region, and to conduct a preliminary sensitivity analysis regarding the price of electricity to grid, the initial investment and the annual operating costs, which are expected to impose a considerable impact.

Methodology

In the present study, the techno-economic feasibility study was based on the following.

1. The estimation of MSW production in the 25-year period of plant's expected lifetime, in the examined region, which determines the nominal capacity of the plant.
2. The composition of local MSW, in order to calculate their renewable fraction and the price at which the generated electricity will be sold.
3. The preliminary design and the thermodynamic analysis of this plant, in order to calculate its electrical power output and whether the plant fulfils the R1 criterion of the Waste Framework Directive 2008/98/EC (European Commission, 2008). In turn, the nominal electrical power output determines the revenues from electricity.
4. The estimation of the required initial investment (capital expenditure, CAPEX) and of the annual operating costs (operating expenditure, OPEX), which affect the feasibility of such an investment.
5. And finally, the sensitivity analysis of the economic feasibility of such an investment, with respect to the parameters that mostly affect this feasibility.

In this context, the study was based on a commercially available mass-burning technology, which has already been applied in Brescia, Italy, for the mass burning of 400,000 t y^{-1} MSW (30 MWe/45.7 MWth) and is referred as a benchmark of high efficiency (Gohlke, 2009). Recent data regarding the elemental analysis and the composition of regional MSW (Komilis et al., 2012) were used for the thermodynamic analysis and the calculation of the electrical power output. The nominal capacity of the plant was estimated according to the official data of MSW generation in Greece and in the EMT region. The basic economic functions for the installation/operation were taken from the literature (Tsilemou and Panagiotakopoulos, 2006). The corresponding methodologies are described in detail in the following paragraphs.

MSW production in the EMT region

In 2008, 0.277 mt of MSW was generated in the EMT region (DIAAMATH, 2013) and corresponded to 5.45% of the total MSW of the country. It was assumed that MSW generation in the EMT region will follow the same trend as the total MSW generation rate in Greece (Eurostat, 2014), under the same proportion as the one measured in 2008.

In Figure 1 the MSW evolution from 2002 to 2011 was linearly extrapolated to the end of the 25-year lifetime of the plant. Based on the maximum production of MSW in 2010 (0.322 mt y^{-1}; Figure 1), the design load of the plant was set at 0.4 mt y^{-1}, increased by a safety factor of about 20%. Taking into account the maintenance periods, the annual operating time was 8000 h y^{-1} (nominal capacity 50 t h^{-1}).

The heating value of the MSW is crucial for both technical and economic feasibility of the plant (Montejo et al., 2011). With a European average value of about 10 MJ wet kg^{-1} (Sommer and Ragossnig, 2011), the net (lower) calorific value (lower heating value) is reported to vary between 9.0 and 20.0 MJ kg^{-1}, exhibiting seasonal and geographical variations. Unprocessed waste tends to the lower limit of the aforementioned range and separated biogenic fractions to the upper limit (Ozbay and Durmusoglu, 2013).

The MSW composition and the elemental analyses of the various fractions of the local MSW, are shown in Table 1, along with

Table 1. Composition and heating value of MSW in EMT (DIAAMATH, 2013; Komilis et al., 2012) (typical values in parentheses (Tchobanoglous et al., 1993, WASTE2GO, 2014)).

	%wt.^{4}			Moisture		%wt. (dry)						MJ kg^{-1}					
	EMT^{b}	Greek average	EU average	Moisture %	%wt.^{a}	C	H	O	N	S	Ash	HHV^{a}		HHV^{b}		LHV^{b}	
Food waste	45.8	(40)	(31)	71.2	20.3	48.0	7.7	32.7	5.8	0.5	5.4	20.8	(12.5)	6.0	(5.0)	3.8	(5.5–38.3)
Paper–cardboard	15.3	(29)	(29)	5.9	22.1	39.4	6.0	42.2	0.1	0.0	12.3	14.4	(15.6)	13.6	(17.7)	12.2	(4.0–26.4)
Plastics	16.5	(14)	(8)	0.4	25.3	74.9	11.1	5.8	0.1	0.1	8.0	37.9	(32.5)	37.8	(33.5)	35.3	(17.4–49.4)
Metals	3.4	(3)	(5)	2.5	5.1	4.5	0.6	4.3	0.1	0.0	90.5	1.6	(0.7)	1.6	(0.7)	1.4	(0.1–1.4)
Glass	4.3	(3)	(11)	2.0	6.5	0.5	0.1	0.4	0.1	0.0	98.9	0.2	(0.15)	0.2	(0.15)	0.2	(0.0–0.2)
Inert materials	2.0	(15)	(11)	8.0	2.8	26.3	3.0	2.0	0.5	0.2	68.0	12.2		11.2		10.4	
LWFT	5.20			10.5	7.25	60.6	7.75	21.4	4.2	0.2	6.0	26.6	(19.3)	23.8		22.1	(14.7–31.1)
DSNTP	6.2			5.9	9.0	39.4	6.0	42.2	0.1	0.0	12.3	14.4		13.6		12.2	(4.0–21.0)
Other	1.3			8.0	1.8	26.3	3.0	2.0	0.5	0.2	68.0	12.2		11.2		10.4	
Total	**100.0**			**34.9**	**100.0**	**46.7**	**6.9**	**23.1**	**1.6**	**0.1**	**21.6**	**20.8**		**13.6**		**11.7**	

DSNTP: Diapers–sanitary napkins–toilet paper; EMT: Eastern Macedonia – Thrace; HHV: higher heating value; LHV: lower heating value; LWFT: Leather–Wood–Fabric–Tyres.
[a]Dry basis.
[b]Wet basis.

typical higher heating values (HHVs) and lower heating values (LHVs) of the various fractions found in literature (Tchobanoglous et al., 1993, WASTE2GO, 2014). The HHV of those fractions were calculated by their elemental compositions, through the correlation (Komilis et al., 2012):

$$\mathrm{HHV} = 350{,}26\mathrm{C} + 1241.74\mathrm{H} - 146.13\mathrm{O}\ \mathrm{kJ\ dry\ kg}^{-1} \tag{1}$$

in which C, H, and O denote the dry weight percentage of the corresponding elements. The HHV and LHV of the supplementary diesel fuel were taken equal to 46.6 and 43.4 MJ kg^{-1}, respectively. Deviations of the weight percentages of the main MSW fractions, among values for the EMT region and for the Greek and the European averages, can be attributed to the predominantly rural character of the region and the low average income, compared with the rest of the country. In general, food waste decreases with the standard of living and packaging waste (paper–cardboard and plastics) increases.

Preliminary design and thermodynamic analysis of the WTE incineration plant

As stated above, the present analysis was based on the technology used in Brescia. The capacity of the Brescia facility is 400 kt of MSW per year, i.e. the same with the capacity of the potential plant, examined herein. The basic units of such a plant include the MSW reception and supply (to the feeder) system, the moving griddle incinerator, the boiler, the steam turbine generator system, the condensation unit, the air pollution control (APC) system and the system for ash collection. The moving griddle incinerator includes a system of four grates (one for drying, two sequential grates for combustion and the final incineration grate) with 30° inclination. The incinerator is capable of handling raw MSW with 5–15 MJ kg^{-1}, LHV. The combustor is equipped with auxiliary oil burners in order to preheat the combustion chambers and to sustain temperature above 850 °C in case the MSW's LHV drops. On average, 1 kg of diesel is required per tonne of MSW. Utilising 60% air excess, the operation temperature of the combustor is 900 °C (effluent at 130 °C). The boiler and the superheater generate steam at 400 °C and 40 bar, which is supplied to a system of four turbines with successive bleed outs (Figure 2). The unit can generate electricity and low enthalpy heat for domestic heating, but the cogeneration option was not considered herein (i.e. the cogeneration heat exchangers (CHE1–3) were excluded from the analysis). Of the generated electricity, 19% was considered to be consumed internally within the plant. A performed thermodynamic analysis resulted in the basic operation features of the turbine system (Figure 2), which were essential for the calculation of electricity generation and the corresponding revenues.

The APC unit of the plant utilises dry scrubbing (with quick and hydrated lime and activated carbon) to control HCl and SOx emissions and micro-pollutants (dioxins, mercury, etc.). Flying ash from the incinerator and particulates from the dry scrubbing are collected in bag filters. NOx is reduced by selective non-catalytic reduction. Overall, the selected technology obtains low concentrations of all pollutants at the effluent gases, well within European limits (WTERT, 2013).

Feasibility analysis

The performed feasibility analysis was based on: (1) literature estimations regarding CAPEX and OPEX; (2) the thermodynamic analysis of the power generation process; (3) the calculation of the electricity selling price, according to the calculation of the renewable fraction of the local MSW and the corresponding

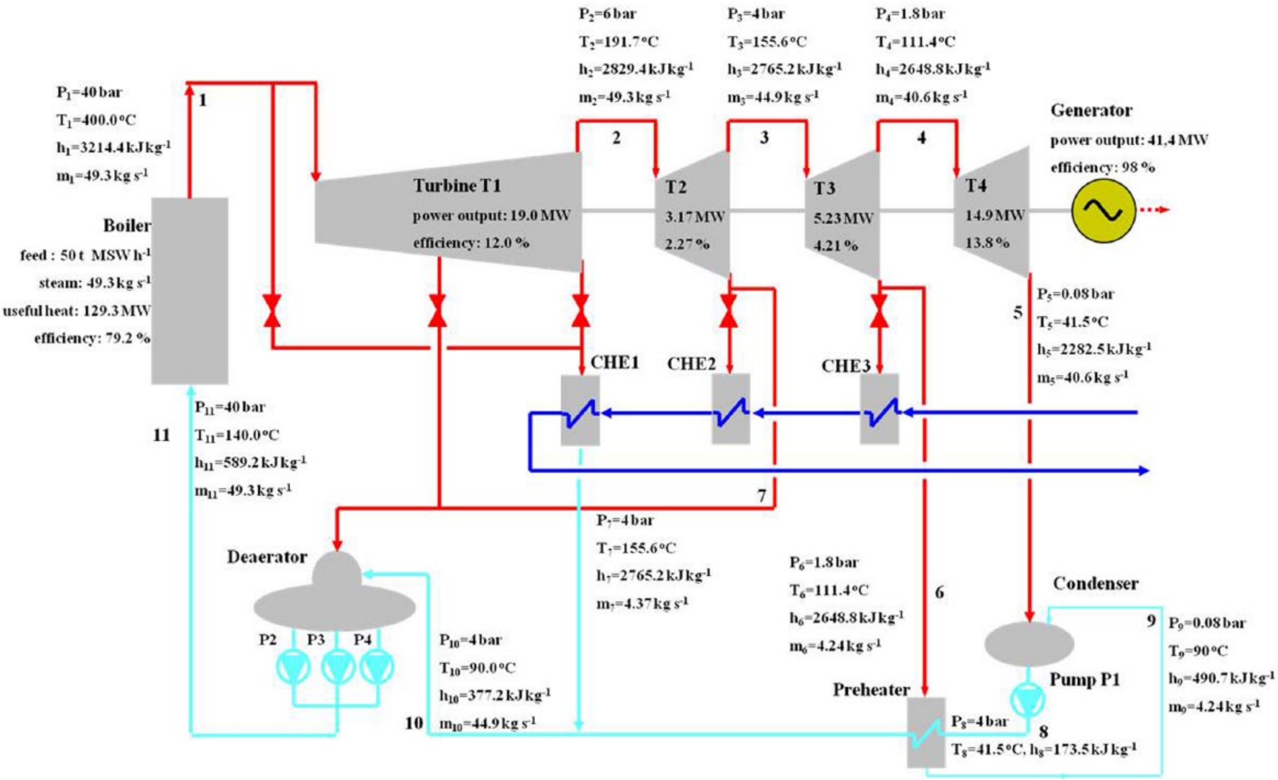

Figure 2. The steam turbine flow diagram of the examined MSW mass burning to electricity plant (WTERT 2013).
CHE: cogeneration heat exchanger; MSW: municipal solid waste.

legal framework; and (4) on a range of possible gate fees, according to the European experience.

CAPEX (I) and OPEX (OC) were estimated according to the correlations:

$$I = 5000 \times C^{0.8} \quad [€] \tag{2}$$

$$OC = 700 \times C^{-0.3} \quad \left[€ \text{ wet } t^{-1}\right] \tag{3}$$

in which C denotes the plant's capacity in wet tonnes per year, and they were proposed for European WTE plants, with grate incineration and energy recovery as electricity and/or heat, in the capacity range of 20–600 wet kt y^{-1} (Tsilemou and Panagiotakopoulos, 2006). Since these correlations refer to 2003, they were adjusted to 2013, with 2.7% average annual inflation, and they led to I and OC values in reasonable agreement with recent literature. For example, Friege and Fendel, in 2011, proposed a specific total investment equal to 597 € wet t^{-1}, for a CHP incineration plant consisting of two lines of 150,000 wet t y^{-1}, i.e. a total CAPEX of €179.1m in Germany (Friege and Fendel, 2011). Adjusting equation (2) to 2011, for the same WTE plant, capital investment is calculated at €171.2m. To the same end, the 410 kt y^{-1} Lakeside WTE incineration plant, commissioned in 2010 in the UK, is reported with an overall CAPEX of about €215m (Whiting et al., 2013), still in agreement with the projected estimation of equation (2), which is €201.7m for 410 kt y^{-1}. In Greece, the lack of WTE plants does not allow us to provide country-specific cost indicators. In the same context, the annual OPEX was reported to be of the order of 14.5–17.4 € t^{-1}, in 2005 (17.5–21.0 € t^{-1} if adjusted to 2013 with 2.7% average annual inflation) (Whiting et al., 2013), whereas equation (3) (Tsilemou and Panagiotakopoulos, 2006) leads to a value of 14.6 € t^{-1} (19.1 € t^{-1}, if adjusted to 2013).

Sensitivity analysis

The feasibility analysis was based on reported cost estimations, which inherently induce a degree of uncertainty. Thus, we conclude our work by examining the sensitivity of our results against the uncertainty of the initial investment and the annual operating costs. Beyond these, the sensitivity analysis also included the effect of a potential variation of electricity marginal price, which may also affect our results. Since the economic viability of WTE incineration solutions is directly reflected to the height of the gate fees required for sound economics, our sensitivity analysis was performed against the gate-fee value that leads to pay out periods (POT) equal to 5 y (the latest being the criterion of choice, for an investment profitability).

Results and discussion

As stated previously, the design load of the plant was set at 0.4 m t y^{-1}, and considering an annual operation time of 8000 h y^{-1}, the nominal plant's capacity was 50 t of MSW per h.

Boiler efficiency

According to the elemental analysis of Table 1, the stoichiometric O_2 for combustion was 32.6 kmoles kg^{-1} of wet MSW (air composition: 72.0% N_2, 20.7% O_2, 1.26 % H_2O and 0.03% CO_2).

Table 2. Exhaust gas composition for 60% excess air, along with the coefficients of the analytical expressions for the heat capacities (cp) of exhaust gasses, and the calculated losses owing to exhaust gas sensible heat (L_{ESH}).

Exhaust gas composition		Coefficients of cp expressions (Cengel and Boles, 2011)				L_{ESH}
	Mol wet kg^{-1} of MSW	a	b	c	d	kJ wet kg^{-1} of MSW
CO_2	25.383	22.26	5.98E-02	−3.50E-05	7.47E-09	10.47
H_2O	44.920	32.24	1.92E-03	1.06E-05	−3.60E-09	160.88
O_2	24.823	25.48	1.52E-02	−7.16E-06	1.31E-09	78.25
N_2	197.105	28.9	−1.57E-03	8.08E-06	−2.87E-09	605.67
NO_2	0.054	22.9	5.72E-02	−3.52E-05	7.87E-09	0.22
SO_2	0.028	25.78	5.80E-02	−3.81E-05	8.61E-09	0.12
Total	**292.312**					**949.83**

MSW: municipal solid waste.

The excess air was 60% (WTERT, 2013), in relative agreement with typical values for such plants (Friege and Fendel, 2011; Gohlke, 2009). Therefore, the air supply to the combustor was 251.7 moles of air per wet kg of MSW. The calculated exhaust gas composition is shown in Table 2 (for NO_2, data were taken from existing units of the same technology, CO is of the order of 40 ppb and neglected (WTERT, 2013)).

The energy losses of the combustor were attributed to the exhaust gas sensible heat at vent temperature (130 °C), the latent heat of the steam content of the exhaust gas and the sensible heat of the ash removed from the bottom of the burner at approximately 425 °C (WTERT, 2013). The exhaust gas sensible heat losses (L_{ESH}) were calculated by the integration of the analytical expressions of the heat capacities of the exhaust gases:

$$c_p = a + b \times T + c \times T^2 + d \times T^3, \text{kJ mol}^{-1}\text{K}^{-1} \quad (4)$$

at the exhaust gas temperature. The corresponding coefficients and the calculated energy losses owing to exhaust gas sensible heat are also presented in Table 2, and they were equal to 950 kJ kg^{-1} of wet MSW, i.e. the 8.1% of the LHV of the wet MSW at the inlet (Table 1).

The specific latent heat of water condensation was taken equal to 40.7 kJ mol^{-1}, and the corresponding latent heat losses were found equal to 1828 kJ kg^{-1} of wet MSW, i.e. the 15.6% of the MSW's LHV. Considering the specific heat capacity of ash equal to 1.047 kJ kg^{-1} °C^{-1} and an ash outgoing temperature of 425 °C, the heat losses owing to ash removal was 58.7 kJ kg^{-1} of wet MSW, i.e. the 0.5% of the MSW's LHV. Heat losses owing to unburned carbon and radiation were considered negligible. Thus, the total heat losses were 2831 kJ kg^{-1} of wet MSW, and the useful heat, taking into account the 1 kg of diesel per wet tonne of MSW, was 10,773 kJ kg^{-1} (129.3 MJ s^{-1}). The boiler efficiency was equal to 10,773/13,610 = 79.2%, whereas 13,610 is the total HHV at the inlet, i.e. the sum of the HHV of the MSW (13,563 MJ t^{-1} wet, Table 1) and the HHV of the auxiliary diesel fuel (46,536 MJ t^{-1} of diesel × 10^{-3} t of diesel per tonne of wet MSW = 46.5 MJ wet t^{-1} MSW).

Electricity generation

According to the mass and energy balances and the thermodynamic analysis of the steam turbine unit of Figure 2, the net electrical power output (i.e. the turbines power generation minus the power consumption of the pumps, within the steam turbine flow diagram of Figure 2) was found equal to 41.4 MW for full load operation of the plant at its nominal capacity. According to data regarding similar units already in operation, 19% of the net electrical power output is consumed within the power plant and for its own electricity needs (WTERT, 2013). Thus, the electrical energy available to grid was 33.5 MW and the overall efficiency 20.5%, with respect to the LHV of the MSW and the auxiliary diesel fuel, which is quite close to typical values suggested in literature (Friege and Fendel, 2011; Gohlke, 2009). In cases of sole electricity generation, the overall plant efficiency is reported to range between 18% and 26%, although it is not always quite clear if these values refer to electrical energy generated or electrical energy available to grid (Brinck et al., 2011). Higher steam temperatures and certain improvements regarding the operation of the turbine system are reported to be able to increase efficiency even above 30% (Murer et al., 2011; Panepinto and Genon, 2014).

The R1 criterion

The greenhouse gas performance of WTE facilities is directly related to their energy efficiency (Gohlke, 2009; Ragoßnig et al., 2008), and for this reason, energy efficiency determines their classification as recovery or disposal installations (Gohlke, 2009; Ragoßnig et al., 2008). Annex II of the Waste Framework Directive 2008/98/EC (European Commission, 2008), defines the so-called R1 criterion:

$$R1 = \frac{E_P - E_F - E_I}{0.97 \times (E_F + E_W)} \quad (5)$$

in which E_P is equal to 2.6 times the produced electricity, including the electricity consumed by the plant itself, i.e. the total 41.39 MW for 8000 h y^{-1} (3,099,440 GJ, in annual base), plus 1.1 times the produced heat (which in this case is zero, since the cogeneration option was not taken into account); E_F is the fossil fuel LHV input to the system (in this case 43.4 MJ kg^{-1} of the auxiliary diesel, i.e. 17,360 GJ y^{-1}); E_W is the LHV of the wet MSW, i.e. 400 kt y^{-1} multiplied by 11,718 MJ t^{-1}, which equals 4,687,017 GJ y^{-1}; and E_I all other (except E_F and E_W) energy supplied to the system, mainly for the electrical energy consumption during the maintenance shut-down period, and for this specific

Table 3. Preliminary feasibility analysis of the proposed WTE plant for gate fees at 90 € t^{-1} of wet MSW.

Initial investment(10^6€)	197,843.79		
Subsidy (10^3 € y^{-1})	79,137.52		
Equity capitals(10^3 € y^{-1})	118,706.28		
Operating cost (10^3 € y^{-1})	7,625.08		
Depreciation (10^3 € y^{-1})	11,870.63		
Electricity revenues (10^3 € y^{-1})	14,263.43	IRR on EBTD	24.09%
Gate fees (10^3 € y^{-1})	36,000.00	IRR on net profit	13.32%
EBTD (10^3 € y^{-1})	42,638.35	POT on EBTD	2.8 y
Net profit (10^3 € y^{-1})	22,768.11	POT on net profit	5.2 y

EBTD: earnings before taxes and depreciation; IRR: internal rates of return; POT: pay out time.

technology is considered equal to the 2% of the generated electricity, all E_P, E_F, E_I and E_W expressed in GJ y^{-1}. The coefficient 0.97 refers to losses through radiation and ash removal. Thus, the R1 criterion, for full load plant operation at its nominal capacity, was 0.67, above the 0.65 limit, set by the Directive 2008/98/EC, showing that this mass burning plant can be characterised as an energy recovery unit, even without the cogeneration option.

Economics and feasibility

The initial investment cost (I) and the operational cost (OC), which were calculated according to Tsilemou and Panagiotakopoulos (2006), for 2003, were found equal to 151.6 × 10^6 € and 14.6 € t^{-1} of wet MSW, respectively. For an average annual inflation of 2.7%, the same costs are expected to have been nominally increased in 2013 to I = €197.8m and OC = 19.1 € t^{-1} of MSW, in acceptable agreement with typical literature values (Friege and Fendel, 2011, Whiting et al., 2013). The revenues for the proposed WTE plant are expected from electricity sale and gate fees. According to Greek Law 3851/2010, the price at which a WTE plant can sell electricity depends on the renewable fraction of this electricity, which can be sold at 87.9 € MWh^{-1}, while the rest (fossil fraction) at the system's marginal price (SMP). The SMP is defined as the instant lowest selling price formed by the electricity bid between suppliers and consumers. For 2013, the monthly average SMP varied between 62.8 € MWh^{-1} in December and 32.3 € MWh^{-1} in June, with a year average of 41.5 € MWh^{-1} (LAGIE, 2014). Despite expected variations, the SMP for the analysis herein was taken equal to 32 € MWh^{-1}, i.e. slightly below the minimum of 2013.

The renewable fraction of MSW included food waste, paper/cardboard and, by assumption, 75% ww of Leather–Wood–Fabric–Tyres (Table 1). The renewable LHV was calculated according to the wet mass fractions of Table 1, and the specific LHV values of these fractions, from the same table, and it was found equal to 4.45 kJ kg^{-1}, i.e. the 37.8% of the LHV at the inlet (including the auxiliary diesel fuel at a proportion of 1 kg of diesel per tonne of wet MSW), in agreement with typical values in Europe (Fellner et al., 2007). Thus, by considering the selling price of renewable electricity at 87.9 € kWh^{-1} and the SMP at €32.0, the selling price of the electricity generated by the power plant was calculated at 37.8% × 87.9 + 62.2% × 32 = 53.2 € MWh^{-1}.

Gate fees for WTE plants in the EU can vary from below 70 to above 130 € t^{-1}, depending on the plant's nominal capacity and other parameters (EUNOMIA, 2001). Based on the aforementioned correlations for the investment and the annual operation costs and the electricity price, and taking into account that a private investment can be subsidised by up to 40% (Greek Law 4146/2013), Table 3 presents a preliminary feasibility analysis of the examined WTE plant, for gate fees at 90 € t^{-1}. Thus, for 90 € t^{-1} gate fees, the POT in the order of 5 years, calculated on annual net profits, after taxes. POT on earnings before taxes and depreciation (EBTD) drops to about 2.5 years. The corresponding internal rates of return (IRR) were calculated at 13.3% (on annual net profits) or 24.1% (on EBTD), denoting that such an investment could be economically sound and viable, for gate fees, within the range currently applied in EU-27.

In this context, Figure 3 presents the dependence of IRR on the imposed gate fees. For gate fees of 80 € t^{-1}, the IRR is still above 10% on net profits, and exceeds 20% on EBTD, while POT on net profits can still be below 6 years.

Sensitivity analysis

Figure 4 provides an elementary sensitivity analysis of the economic feasibility results of Table 3. Among the three selected parameters (investment costs as calculated by the aforementioned correlations, annual operating costs, still as calculated by the aforementioned correlations, and SMP), the economic sustainability of the examined WTE plant in EMT, is more sensitive against the actual height of the initial investment. In this context, Figure 3 shows that if the initial investment of the plant is 20% higher than the one considered in Table 3, then the required gate fee for 5 years POT on net profits should be raised to 115 € t^{-1}, i.e. almost 30% higher compared with the 90 € t^{-1} gate fee assumed in Table 3. Nevertheless, it should be stated at this point that even this value of imposed gate fee is still within the European range for mass burning WTE plants.

On the other hand, the described investment appears to be much less sensitive to the variation of annual operation costs and on the SMP. Thus, the increase of the annual operation costs by 20%, compared with the value used for the calculations of Table 3, the required gates fees for POT equal to 5 years do not have to be increased by more than 5%, whereas the decrease of SNP by 20% (i.e. to 25.6 € MWh^{-1}) can be counterbalanced by a less than

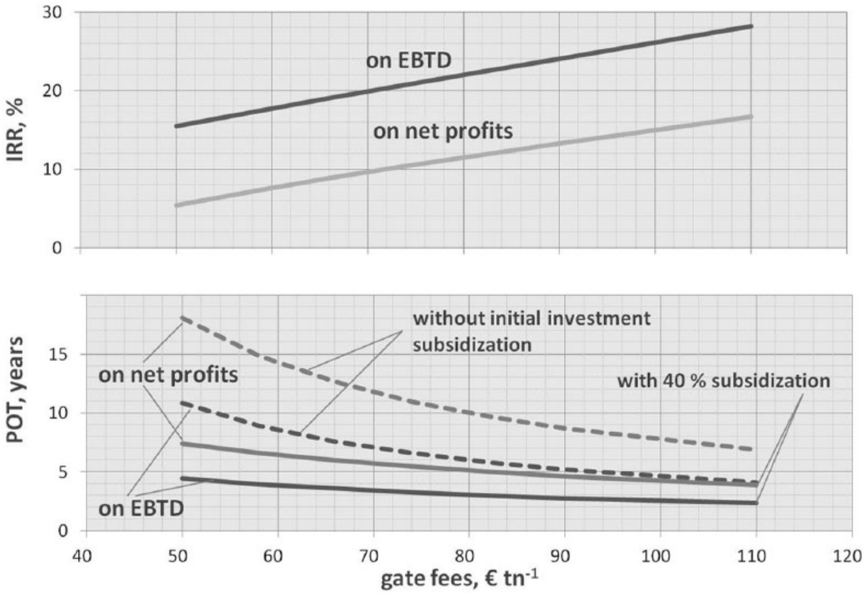

Figure 3. IRR and POT dependence on gate fees, within the gate fee range from 50 to 110 € t^{-1} MSW (dashed lines correspond to POT values without state subsidisation of the initial investment).
EBTD: earnings before taxes and depreciation; IRR: internal rates of return; POT: pay out time.

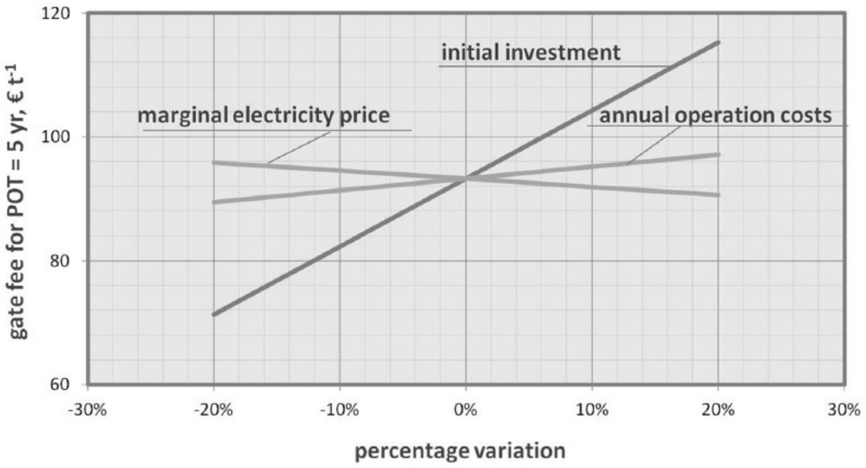

Figure 4. Gate fee variation, in order the POT on net profits to be equal to 5 years, in the case of the initial investment cost, the annual operation cost and the marginal electricity price varies by ±20%, with respect to the corresponding values used for the feasibility analysis of Table 3.
POT: pay out time.

5% increase at the imposed gate fees, so that the investment could still achieve POTs of the order of 5 years. For the latest, it should be mentioned that the SNP assumed for the year 2013 was lower than the lowest monthly average recorded in this year. It should also be noticed that the recorded SNP values tended to constantly increase in 2013, reaching the historically higher value of 65.1 € MWh^{-1} in January 2014. Assuming this value for our analysis, the required gate fees for POT = 5 years drops to 75 € t^{-1}, quite close to the minimum recorded values in EU-27.

Conclusions

The work attempted a preliminary techno-economic feasibility study of a potential plant for mass burning of the total potential of MSW in the region of EMT to generate solely electricity (the option of heat cogeneration was not examined). The total production of MSW in EMT was measured in 2008 and was found equal to 0.277 m t y^{-1} of wet MSW. Correlating this measured value with the MSW in the whole country, and linearly projecting the latest to 2038 (the end of the assumed 25 y lifetime of such a plant installed in 2013), a rough picture of the escalation of MSW potential in EMT was achieved. Setting the nominal capacity at 0.4 m t y^{-1} of wet MSW (50 t y^{-1}, for 8000 h annual operation), the plant is expected to operate at ±20% of its nominal capacity, in the range of its lifetime.

The performed analysis and the techno-economic feasibility assessment were based on an actual plant technology and design, which is commercially available and already applied for MSW capacities comparable with that of EMT (in Brescia, Italy). Based on MSW composition, component elemental analysis (Table 1) and bibliographic correlations for the estimation of HHV (Komilis et al., 2012), a thermodynamic analysis of the full load operation of the plant was performed. According to this analysis, the nominal electrical power output of the plant would be 32.5 MW (in agreement with the similar Brescia plant, which operates since 1998) and the total annual electricity production, at full load, would be about 260 GWh. The overall efficiency of the plant was of the order of 20.5% (on the LHV of the MSW and the auxiliary diesel fuel, the latest at a portion of 1 kg of diesel per 1 t of wet MSW), and the R1 coefficient was calculated at 0.67 and above the limit for energy recovery set by EU Directive 2008/98/EC. The renewable fraction of the LHV at the inlet of the plant was calculated at 37.9% of the total LHV of MSW and the auxiliary diesel fuel. Thus, and according to the Greek Law 3851/2010, the price at which this specific potential plant could sell its electrical production could be 53.2 € MWh^{-1}, the average marginal system price of electricity is 32 € MWh^{-1}.

Based on literature correlations (Tsilemou and Panagiotakopoulos, 2006) and adjusting to 2013, the initial investment cost of such a plant is of the order of €190m and the annual operation costs of about 20 € t^{-1} of wet MSW. According to these correlations and the calculated selling price for electricity, the POT of such an investment is expected to be of the order of 6 years, for 40% initial investment subsidisation and 90 € t^{-1} of wet MSW gate fees. This gate fee value lies within the range of gate fee values currently applied in EU-27 and clearly allows the economic viability of a MSW mass burning to electricity solution in EMT. Finally, the gate fees required for economic viability (assumed at 5 years POT, calculated on net profits) were found sensitive on the actual height of the initial investment, whereas the expected considerable increase of SMP in the forthcoming years further enforces the prospects of this viability, even at gate fees as low as 75 € t^{-1} (which would be among the lowest gate fees for mass burning in EU-27).

The presented analysis was based on the composition and the elemental analysis of the regional MSW (DIAAMATH, 2013; Komilis et al., 2012), which determined the LHV of the feed, the value of R1 coefficient (not including the heat cogeneration option) and the renewable fraction of the generated electricity, the latest crucially affecting the price at which this electricity can be sold. Moreover, the economic analysis included 40% subsidisation of the initial investment (Greek Law 4146/2013) and SMP estimation based also on Greek statistical data series (LAGIE, 2014). Thus, the obtained results and conclusions are country specific, and to the extent that the local MSW deviates from the Greek average (Table 1) they are also region specific. On the other hand, the LHV of the wet MSW in the EMT region (11.7 MJ kg^{-1}; Table 1) is slightly above the European average and close to the lower limit of the corresponding LHV range (Ozbay and Durmusoglu, 2013; Sommer and Ragossnig, 2011), with LHV crucially affecting the economics of WTE mass burning plants (Montejo et al., 2011). Moreover, the equations used for the estimation of the initial investment and the operation costs (equations (2) and (3) – Tsilemou and Panagiotakopoulos, 2006) were developed from cost data of WTE facilities in Europe, whereas the electrical efficiency of similar plants are of the same magnitude as the examined one or even higher (Brinck et al., 2011; Friege and Fendel, 2011; Gohlke, 2009; Murer et al., 2011; Panepinto and Genon, 2014). Thus, provided that the wet MSW LHV are similar to the ones found herein (or higher) and for similar electricity prices and investment subsidisation, the results obtained in the present study could stand for other European countries as well.

Acknowledgement

Antonio Bonomo from A2A, the operator company of the Brescia plant, is highly acknowledged for providing information regarding the suggested technology and the process's flow-diagram.

Declaration of conflicting interests

The authors declare that there is no conflict of interest.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

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