ENVIRONMENTAL CONSEQUENCES OF MALTESE MSW INCINERATION

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Abstract. The intensity of Municipal Solid Waste (MSW) generation by human and economic activities causes environmental impacts, particularly critical in small insular countries, such as Malta. Thus, an investigation of the potential of Maltese MSW incineration with energy recovery was performed in this work focused on thermodynamic and land use aspects. The electricity potential of an MSW incinerator with associated electrical power plant to be built in Malta can be estimated as 5% of the total energy consumed in 2010 in the archipelago; alternatively, in a CHP configuration, it can also supply all the thermal energy required in 2010 for Multi-Effect Desalination. During its lifespan the plant can reduce deposition in landfills by at least 270,000 m^2 (0.09% of the archipelago total area), diminishing also the potential for water and soil contamination. Last but not least, it can contribute to decrease the dependence on imported fossil fuels.

Introduction

The scarcity of energy and drinkable water sources is a real problem in the sustainability strategy of small Islands, namely those that are 100% dependent on fossil fuels. In parallel, the intensity of the MSW generated by human and economic activity also poses difficulties, by affecting land use and causing environmental impacts. This is particularly critical in the case where landfilling is the main End-of-Life practice. This situation has made the Islands of Malta of particular interest as a case study, especially considering that (a) 64% of total gross inland primary energy in 2008 was consumed by the electricity sector; and (b) the water supply depends on desalination and circa 54% of the drinkable water is obtained by reverse osmosis. Other critical facts are: (i) MSW generation in Malta increased 48% between 1998 and 2008, partially due to the increased of the tourism economy; (ii) 87.3% of the MSW produced in that period was sent to landfills; (iii) data recently released shows that the MSW generation tends to stabilize or even to decrease slightly but still is one of the highest in the EU, as depicted in Figure 1 [1].

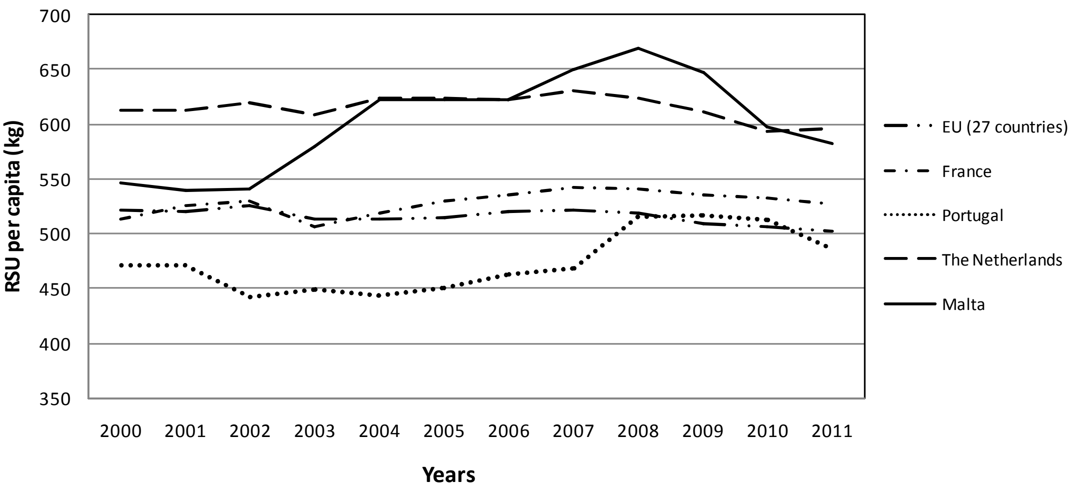

Figure 1. Municipal solid waste generated per year and per capita in various EU countries

The Maltese case study

Malta is one of the smallest countries in the world, a small archipelago, constituted by three main Islands, Malta, Gozo and Comino, located 93 km south of Sicily and 288 km north of Africa, with a total area around 316 km^2. In 2009 there were 412.966 inhabitants in Malta, which made it the most densely populated country in Europe: 1,307 inhabitants per square meter. Natural resources are limited, as the Maltese archipelago has no rivers, forests or mountains. The Mediterranean climate, characterized by mild winters and dry, hot summers, defines its weather, with air temperature generally between 9.5°C and 33°C. The hottest period of the year runs from mid-July to mid-September and the coldest months are January and February.

Methodology

The analysis presented herein was divided into four phases. First, a literature review and a data collection were conducted to gather information on MSW composition and generation. High heat values (HHV) from international literature and moisture from the collected data were used to estimate its LHV. In a second phase, the waste combustion model (stoichiometry of C, H, S) was used to estimate the air throughput in accordance with operational (temperature) and UE regulations (oxygen in the flue gas). Then, the potential for electricity generation and water treatment was assessed by the use of steam thermodynamics, electing two different plant options and limiting the thermal desalination technology to multi stage distillation (MED). Finally, the land use savings are estimated, comparing actual landfill practice with the features of the proposed incineration plant.

Maltese MSW characteristics

Conceptually, Municipal Solid Waste (MSW) can be considered a renewable resource, given that its generation is intrinsically linked to human activity, it renews itself continuously, and it is a potential source of important raw-materials and energy. The importance of the fraction of biogenic waste is a key factor in this consideration. A household solid waste (HSW) survey carried out in Malta, Gozo and Comino in 2002 provides weekly composition data for every quarter of the year. HSW corresponded to circa 70% of the waste generated in that year. The composition of the restaurants and hotels waste was estimated using data of a pilot project performed by the National Statistics Office in 2004 that identified primary and secondary packaging, biodegradable matter and other waste fractions in hotels and restaurants' rooms and hotel' swill rooms. This information must be complemented with data from other countries, namely that of an Irish non-household waste characterization survey, which detailed the various Hotels and Restaurants fractions and identified which of them corresponded to packages or to non-packages. For commercial and industrial waste the composition was taken from an EU Joint Research Centre study. The relevant data are shown in Table 1.

Table 1 – Maltese MSW composition and HHV standards

Fraction/Source	Household [% w/w]	Household [kTon/year$_{2002}$]	Restaurants & Hotels [% w/w]	Restaurants & Hotels [ktonne/year$_{2002}$]	Commercial Industrial [% w/w]	Commercial Industrial [ktonne/year$_{2002}$]	HHV [kJ/kg]
Plastic Containers	4,93%	6,646	4,63%	956	22,1%	5,657	-32,564
Plastic Film	4,96%	6,688	3,35%	691	0,0%	0	-32,200
Paper	9,13%	12,307	9,74%	2,011	31,6%	8,089	-15,800
Cardboard/Cartons	5,72%	7,718	10,81%	2,232	0,0%	0	-18,463
Food Remains	57,90%	7,8071	40,44%	8,349	19,7%	5,043	-5,512
Glass Bottles	3,87%	5,218	11,67%	2,408	15,2%	3,891	-140
Iron Cans	3,56%	4,799	3,38%	697	5,8%	1,485	-698
Aluminium Cans	0,25%	334	0,99%	205	0,6%	154	-698
Textiles	3,16%	4,264	2,58%	532	1,0%	256	-17,245
Hazardous	2,08%	2,799	0%	0	0,0%	0	-12,791
Others	4,45%	5,999	4,72%	975	4,0%	1,024	-6,978
Vegetable Oils	0%	0	7,69%	1,588	0,0%	0	-38,290

The Table summarizes the composition of the three waste streams that compose the Maltese MSW. The commercial and industrial waste figures were calculated using reports and studies from other municipalities/countries, some of them with similar geographical characteristics (e.g. Cyprus). Common materials were clustered to provide complete data for the LVH estimate. In 2002, the Household, Hotels & Restaurants and Commercial/ industrial waste streams amounted respectively to 134,844, 20,644 and 25,597 tonnes. The last column of the Table depicts the HHV of the different material fractions used in the estimations, obtained from the literature [2]. The contribution of each material fraction for the final HHV of a given stream was calculated by the product of the corresponding weight % and HHV. The sum of the contributions of all fractions, considered as-discarded (prior to mixing with other components in the refuse), resulted in the overall HHV [3].

Next, the LHV (that accounts for the energy recoverable from MSW combustion), was calculated with the same rationale presented in above for the HHV, to be - 8,726 kJ/kg of MSW.

MSW generation

The forecast of the maximum yearly waste to be generated during the lifespan of an incineration plant is essential to determine its capacity. In fact, the increase in waste generation in the future years may lead to inadequate capacity and, consequently, to the need of an expansion, which is not economically and environmentally desirable. Three simplified scenarios were assumed for the MSW projections, all based on an incinerator operation time of 8,000 hours per year (Table 2).

Table 2– Scenarios for waste generation

Data bases	Criterion	Estimated capacity [tonne/hour]
Last MSW data (2009)	5% excess capacity	32.5
Historical data (1997 to 2009)	Trend line (plot)	31.5
Average MSW per capita (1997 to 2009)	Population projection (EUROSTAT)	32.0

Then, considering that the 32.5 tonne/hour capacity obtained in scenario 1 (with 5% excess capacity) will cover all the predictions, for 8,000 hours of operation, the future incinerator would have to treat a maximum of 259.8 ktonnes/year up to 2030 (assuming that operations will start in 2015 and a 15 years lifespan). From hereafter this value will be used in all design calculations.

MSW combustion

The analysis of the energy involved in the MSW combustion considers the complete combustion of the three basic elements - carbon (C), hydrogen (H), and sulphur (S) -, using typical physical and elemental compositions from the literature. The oxidizing atmosphere is promoted by air injection, assuming its composition to be 21% (molar) oxygen and 79% (molar) nitrogen. To determine the limit amount of air in the combustion it is necessary to perform an energy balance, taking into account the requirements of pertinent European Directives. These are: (i) the volume ratio between oxygen and the flue gas must be equal or higher than 6%; (ii) the temperature of the flue gas must be maintained between a minimum of 850 ºC, to avoid dioxins formation, and a maximum of 1050 ºC, to avoid the degradation of the refractory material by ash fusion. The energy balance in the incinerator enunciates that the variation of the flue gas enthalpy is caused by the heat released during the combustion (LHV).

Then, the overall enthalpy variation is assessed by introducing the thermodynamic concept of specific heat at constant pressure, or constant heat capacity (Cp) [4]. A third degree polynomial relationship between Cp and temperature, described in the literature, was used to estimate the final temperature of each gas through a trial-and-error method and an iterative process. About 52.78% excess of the theoretical air satisfies all the previously mentioned criteria and maximizes the potential for energy recovery; thus, recirculation of the flue gas was not deemed necessary. Concurrently, 915.5 ºC and 7.86 MJ/kg were taken, respectively, as the final flue gas temperature and the overall enthalpy variation in further calculations.

Contribution of energy recovery for the Maltese electrical sector

Energy recovery arises from the need to cool the flue gas from 915.47 ºC to 250 ºC before its treatment in mechanical equipments that operate at lower temperatures. In the calculations, the flue gas represents the heat source (boiler) where the sub-saturated water is evaporated and superheated before passing through the backpressure turbine.

The electrical potential is analyzed in the light of the Rankine cycle, driven by the ideal enthalpies of each thermodynamic state (turbine, boiler, condenser and pump), based on state proprieties (temperature, pressure and entropy). The isentropic efficiency, from the second thermodynamic law, is next applied to assess the actual enthalpies (turbine and pump), necessary to estimate the real electrical power. The estimation of net electrical power was performed for two different steam operational conditions, 4.0 MPa/ 440 ºC and 5.2 MPa/ 440 ºC, which are applied in real incineration plants. In both cases, the operational pressure and temperature of the condenser were considered to be 0.01 MPa and 45.8ºC.

Both the inefficiency of the turbo-alternator that converts mechanical into electrical energy (32%) and the consumption of electrical energy on-site (70 kW/tonne of MSW) were also taken into account in the final estimation. From the results obtained, it can be concluded that the annual potential corresponds to about 82.0 GWh/year (for 8,000 operation hours). Depending on the operational conditions, it is also equivalent to approximately 3.7% to 3.8% of the total energy produced in 2009 (2,167 GWh/year). Finally, it corresponds to slightly more than the total energy consumed by the water desalination process (reverse osmosis) in that year 79.4 (GWh/year) [5].

Contributions of energy recovery for electrical and water treatment (CHP)

Part of the thermal energy from MSW combustion can be used for electrical power production and the remaining used to desalinate seawater, taking advantage of the energy to evaporate the water from brine. The distillation is initiated at 70 to 80 ºC due to the low pressure over the MED cells to sustain the evaporation mechanism, as the heat losses and the boiling point elevation (brine) influence the evaporation process [6]. In a MED plant, the performance ratio, also called Gain Output Ratio (GOR), relates the water production to the steam consumed. The typical GOR value is 12 kg of distillate per kilogram of steam consumed; moreover, the power consumption is minimized, about 2 kWh/m^3 [6].To satisfy MED requirements the steam specification after expansion in the turbine must be at 0.035 MPa and 72.68 ºC [7]. Two different types of turbines were considered: (a) backpressure, in which the superheated steam is initially expanded in the turbine, and then condensation is performed by the MED plant and (b) condensing turbine which has a steam extraction ($\hat{h}_{5a}$) before complete expansion. The extracted steam (additional outlet nozzle) feeds the MED plant and the remaining steam (turbine) follows to the condenser system after expansion to 0.01 MPa.

The main results obtained, using an already published methodology [6], are presented in Table 3. An acceptable value for PES (≥ 10%) is only achieved for a steam extraction equal or greater than 90% and 5.2MPa of operational pressure.

a

Table 3 – Results for electrical power generation and water desalination (CHP)

Property	**4 MPa Backpressure**	**5.2 MPa Backpressure**	**5.2 MPa Condensing** (steam extraction≥ 90**%)**	**Units**
Net electric power	8.46	8.85	9.01	MW
Primary energy savings index (PES)	13.5%	14.6%	11.1%	-
Electric power produced	10.7	11.1	11.3	MW
Electric power consumed in the plant	2.28	2.28	2.28	MW
Turbo-alternator efficiency	97%	97%	97%	-
Mechanical energy	11.1	11.5	11.6	MW
Thermal energy available	31.2	30.8	27.7	MW
Gain output ratio	12	12	12	kg_{water}/kg_{steam}
Flow-rate of water desalinated per hour	606.8	610.2	529.2	tonne/h
Volume of water desalinated per year	4,854,285	4,881,859	4,393,670	m^3/year
Final electrical power (after MED)	7.25	7.63	7.91	MW

For the two backpressure configurations, the PES index shows that when MED is combined with electrical power plant, 13.5% to 14.6% savings of primary energy can be achieved, respecting the limit established by the European Directive. The drinkable water produced is about 30% of the total water desalinated in the RO plants in 2009 (16,645,743 m^3). The combined capacity for electricity production from the backpressure turbine is achieved, allowing for 2,765 and 2,948 litres of avoided fuel oil, respectively. Despite a lower power for water desalination if compared with the backpressure turbine for both steam operational conditions, the condensing turbine permits modulating the water production according to the yearly energy and water demands.

Environmental analysis – Land use

In Europe, the diversification of waste treatments, integrating Ed-of-Life (EoL) with energy recovery, such as incineration and biogas production, reduced significantly the number of landfills over the years. In islands like Malta, where land is scarce, the land use criteria must deserve special consideration in Municipal Solid Waste Management. At present, incineration is only applied in Malta to burn the waste from abattoirs and hospitals [8].

Concerns regarding air quality have so far prevented full dissemination of this MSW technology. However, recent stringent air pollution regulations and the intense use of incineration in Europe and in the United States have slowly changed those concerns. In terms of land use, incineration plants do not require more land than that established in the design; consequently there is no continuous impact along their lifespan. According to recent data, 100,000 m^2 of land (including landscaping and auxiliary buildings) are enough to treat in a Waste to Energy (WtE) plant one million tonnes of MSW/year, whereas the same amount of MSW sent to landfills would require 100,000 m^2 **per year** [9, 10]. The goal of this analysis is to compare, for the MSW throughput determined, the land necessary for a landfill and a WtE plant, taking into account the Maltese reality, to finally calculate the land savings that can be accrued by using the latter treatment.

The land required for the WtE plant was estimated considering the area of actual plants in Europe, and an expertise based preliminary design that includes the area for an auxiliary landfill. The calculation of the land necessary for the landfill site, with the necessary peripheral infrastructures, was done by using Equations 1 and 2, without considering the specific limitations of available land (geographical aspects) in Malta [8, 11].

$$A = 1.15 \times [(M_{msw} / d_{MSW}) + C \times (M_{msw} / d_{MSW}) + k \times (M_{msw} / d_{MSW}) - B \times (M_{msw} / d_{MSW})] / H_i \quad (1)$$

$$M_{msw} = n \times \dot{m}_{msw} \quad (2)$$

In the equations, M_{msw}, $\dot{m}_{msw}$, d_{MSW} and H_i, represent, respectively, the MSW treated globally during the incinerator life span years (n), the annual MSW throughput, and the density and the maximum landfill height. C, k and B are factors characteristic of the landfill. All results presented below are based on a treatment capacity of 260,200 tonnes per year and a plant life span of 20 years.

The results obtained for the landfill show that the land area required for the next 20 years is around 396,073 m^2 considering H_i = 20 meters, d_{MSW} = 0.85 tonnes/m^3; C (cover factor)= 0.15, k (factor related to the linear and cover systems) = 0.125 and B (10 years settlement factor of biodegradable waste) = 0.1 [12]. The factor k was defined on the assumption of a 1.5 m thick liner system, including the leachate collection layer, and a 1.0 m thick cover system, including a gas collection layer. The estimate of the WtE plant area was based on previous studies for the Maltese archipelago that recommend a land area of 2.5 to 3.5 ha for plants with capacities ranging from 60,000 to 600,000 tonnes [8, 13]. By simple interpolation, for the envisaged capacity, an area of 28,700 m^2 would be required for the incinerator plant.

Depending on the combustion temperatures during the various incineration stages, metals and inorganic compounds (e.g. salts) are totally or partly evaporated. Solid residues are produced in the form of fly ash and bottom ash but also, to a lesser extent, as residues from flue gas treatment. Lastly, the wastewater treatment in the filter produces a filter cake residue. The bottom ash can be deposited in a non-hazardous landfill but the other substances have to be sent to a hazardous waste landfill. In principle, this auxiliary landfill will be located at the site of the plant itself. A report on the implementation of Waste to Energy in Malta refers that 25% of the total MSW becomes fly and bottom ash, and that 2% of the area is necessary for the filter cake [8]. Concurrently, according to data validated in a Portuguese WtE plant [14], at the end of the process, 20% (by volume) of the initial MSW will be inert incinerator bottom ash, circa 1.5% will be scrap iron (iron and aluminium) and 8-8.5% will be effluent gas treatment system ash. Then, it can be calculated that the area necessary for the auxiliary landfill will be about 97,000 m^2. That means that the incineration plant will require a total area around 126,000 m^2.

Ideally, however, both the bottom ash and the scrap can be sold, not occupying floor space. Obviously, the remaining fly ash will occupy space. Then, recycling of metallic scrap and bottom ash for construction purposes could reduce the final deposable waste to values around 8%. This practice has the potential to reduce the landfill area to 28,000 m^2 and the total area required for the plant (incinerator and auxiliary landfill) to 57,000 m^2. The results obtained are synthesized in table 4.

Table 4 - Land necessary to treat the MSW generated in the next 20 years (5.2x10^{12} kg)

EoL treatment	Necessary area	Necessary area with scrap and bottom ash recycling	Unit
Incineration (CHP)	126,0000	57,000	m^2
Landfill	396,000	396,000	m^2
Land saved	270,000	339,000	m^2
Percentage of land saved	68.2	85.6	%

Thus, the minimum land savings will be about 270,000 m^2 (or 339,000 m^2, if the scrap and bottom ash can be recycled). This corresponds to 0.09% (or 0.11%), of the total area of the Maltese archipelago, clearly a very significant figure.

Conclusion

Globally, the present work allows the conclusion that the incineration of the MSW generated in Malta can help reduce deposition in landfills, therefore decreasing the pressure on land use and the potential for water and soil contamination. Its electricity potential can be estimated as 3.7 to 3.8 % of the total energy produced in 2010 in the archipelago; alternatively, in a CHP configuration, the plant could supply the energy required to desalinate all the water consumed in that year. Additionally, by integrating energy recovery, it can diminish the amount of primary energy (fuel-oil) consumed in the two existing power plants (Delimara and Marsa) and in the seawater desalination treatment. Also during its useful life the incinerator has the potential for a minimum land savings of about 270,000 m^2. Finally, as incineration generated electricity can be considered as deriving from a renewable source (namely considering the high fraction of biogenic waste in Maltese MSW), it can help meet the 20% renewable energy target imposed by Directive 2009/28/EC.

The installation of a MSW incinerator with energy recovery plant can thus help solve some of the main difficulties currently facing the Maltese Republic: the management of waste, energy, water and land.

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