WASTES: Solutions, Treatments and Opportunities
1st International Conference
September 12th – 14th 2011

POTENTIAL FOR ENERGY RECOVERY FROM MALTESE MSW: A THERMODYNAMIC ANALYSIS

F.J.C. Pirotta[1], C.A. Bernardo[2] and E.C. Ferreira[3]
1 Institute for Polymers and Composites / I3N. Minho University, School of Engineering, 4800-058 Guimarães, Portugal. pg13990@alunos.uminho.pt
2 Institute for Polymers and Composites / I3N. Minho University, School of Engineering, 4800-058 Guimarães, Portugal. cbernardo@dep.uminho.pt
3 IBB, Institute for Biotechnology & Bioengineering / CEB. Minho University, School of Engineering, 4710-057 Braga, Portugal. ecferreira@deb.uminho.pt

ABSTRACT
An investigation of the Maltese Municipal Solid Waste (MSW) potential for energy recovery is carried in this work. In a first step, MSW composition data was collected to evaluate the waste combustion enthalpy by a weighted average of each fraction, using the corresponding Low Heat Value (LHV). Results indicate that each kilogram of Maltese MSW releases circa 8,726 kJ of energy when combusted. Data from 1997 to 2009 allowed the conclusion that an incinerator with a capacity of 32.5 tonnes per hour can treat the waste expectably generated in Malta during the plant life span. In a second step, MSW elemental analysis was used to evaluate (i) the necessary stoichiometric air (152.4%) and (ii) the temperature of the flue gas (915.5 ºC), respecting the 6% ratio ($v_{oxygen}/v_{fluegas}$) imposed by EU regulations. Finally, the thermodynamics of the steam cycle was applied to study the possible contribution of energy recovery for electrical power generation (PG) and co-generation (CHP). The thermal energy was analyzed assuming its use in desalination (multi effect distillation, MED), by means of the so-called gain output ratio (GOR) index. The final results lead to a potential power of 10 MW (PG) or a minimum of 7.25 and 4.85 millions m^3/year of desalinated water MW (CHP).

Keywords: Islands of Malta; Municipal Solid Waste, Incineration, Energy recovery; Power; Water desalination.

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 when landfilling is the only 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) Malta has the highest MSW mass per area landfilled in the EU (900 tonnes/km^2); (ii) MSW generation increased 48% between 1998 and 2008; (iii) 87.3% of the MSW produced in that period was landfilled; and (iv) data recently released shows a tendency of MSW stabilization for the next years. Malta is economically dependent of tourism activity, which exacerbates the problem of electricity and water demand as well as waste generation during summer.
Thus, incineration of MSW with energy recovery can be an important management option, contributing to reduce the fossil fuels dependence while concomitantly reducing the volume of the MSW landfilled and diversifying water treatment, taking advantage of the remaining thermal energy.

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.

The main economic sectors in Malta are (i) tourism; (ii) financial services; (iii) public services; (iv) construction and quarrying; (v) agriculture and fisheries. The public sector generated 21.4% of the jobs. The private sector, of which the flagship is the service sub-sector (tourism; manufacture and wholesale and retail trade; repairs) is responsible for 73.2% of the overall employment. The remaining jobs are due to statutory bodies.

METHODOLOGY OF THE ANALYSIS

As the key-objective of the research is to evaluate the energy obtainable from the Maltese MSW, the analysis was divided into three phases. First (1), 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 (2) 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). Finally, 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). The gain output ratio (GOR) was applied to estimate the potential for water desalination in a CHP plant. The combination of heat and power was studied considering a backpressure turbine and a condensing turbine with steam extraction.

Maltese MSW characteristics and generation

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 hotels and restaurants' 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 hotels' 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. In the case of commercial and industrial waste the composition was taken from an EU Joint Research Centre study. The relevant data is shown in Table 1

Table 1 – Maltese MSW composition

Fraction/Source	Household [% w/w]	Household [ktonne/$year_{2002}$]	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 make up 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 [1]. 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 [2].

Eq. 1 was used to evaluate the LHV (that accounts for the energy recoverable from MSW combustion), with the same rationale presented in the paragraph above for the HHV. In the equation, λ represents the latent heat of water vaporization, %W the moisture content (w/w) and %H the mass percentage of hydrogen (elemental composition).

$$\text{LHV (kJ/kg)} = \text{HHV} - \lambda \times [9 \times (\%H) + (\%W)] \quad (1)$$

The final LHV of the Maltese MSW was estimated as (-)8,726 kJ/kg of waste, as shown in Table 2.

Table 2 – Moisture and LHV from Maltese MSW

Composition	**Moisture as-fired [%, w/w]**	**Household, Restaurants & Hotels and Commercial /Industrial LHV [kJ/kg]**
Plastic Containers	13.80%	-2,254
Plastic Films	13.80%	-1,219
Paper	24.30%	-1,736
Cardboard/Cartons	24.30%	-913
Food Remains	63.60%	-1,400
Glass Bottles	3%	-3.3
Iron Cans	6.60%	-16
Aluminium Cans	6.60%	-1.6
Textiles	23.80%	-429
Hazardous	12.80%	-177
Others	8%	-273
Vegetable Oils	59.00%	-304
Total	43.5%	-8,726

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 3).

Table 3 – Scenarios for waste generation

Scenario	**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 ($\Sigma\Delta H_{fg}$) is caused by the heat released during the combustion (LHV). Eq. 2, where H_{losses} is the thermal energy lost, ζ represents the percentage of energy lost as a function of the total energy released, and $\dot{m}_{msw}$ is the MSW throughput (e.g., 32.5 tonnes/hour), summarizes the energy balance. The overall flue gas enthalpy can be evaluated by the sum of the individual enthalpies (O_2, N_2, H_2O, CO_2, SO_2) [2].

$$\Sigma\Delta H_{fg} = LHV \times \dot{m}_{msw} - H_{losses} = \Sigma\Delta H_{fg} = \Delta H_{O2}+\Delta H_{N2}+\Delta H_{H2O}+\Delta H_{CO2}+\Delta H_{SO2} = LHV \times \dot{m}_{msw} - \zeta \times LHV \times \dot{m}_{msw} = LHV \times \dot{m}_{msw}(1-\zeta) \quad (2)$$

Then, the overall enthalpy variation (ΔH) is assessed by introducing the thermodynamic concept of specific heat at constant pressure, or constant heat capacity (Cp) [3]. A third degree polynomial relationship between Cp and temperature, described in the literature, was used to estimate the final temperature of each gas (by solving Eq. 2), through a trial-and-error method and an iterative process. About 52.8% 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 7,864 kJ/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 the 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, determined 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 the net electrical power was performed for two different steam operational conditions, 4.0 MPa / 440 ºC and 5.2 MPa / 440 ºC, both 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 [2].

The procedure starts with the evaluation of the steam mass flow rate, $\dot{m}_{ST}$ through Eq. 3, where $\hat{h}_3$ and $\hat{h}_1$ signify the enthalpy of the superheated steam in the turbine inlet and the enthalpy of the sub-cooled steam in the condenser outlet, the $\Delta\hat{H}$ difference represents the specific enthalpy variation and η_{BO} the efficiency of the boiler.

$$[\dot{m}_{msw} \times (\Delta\hat{H}_{915.6} - \Delta\hat{H}_{250}) \times \eta_{BO}] / (\hat{h}_3 - \hat{h}_1) = \dot{m}_{ST} \quad (3)$$

Then the shaft work (turbine), P_{mech}, is estimated by using Equation 4, considering the mass steam flow rate already calculated and the enthalpy at the turbine inlet (h_3) and outlet (h_4).

$$P_{mech} = \dot{m}_{ST} \times (\hat{h}_3 - \hat{h}_{4a}) \quad (4)$$

Both the inefficiency of the turbo-alternator that converts mechanical into electrical energy (3%), and the consumption of electrical energy on-site (70 kW/tonne of MSW) were taken into account in the final estimation. Table 4 presents the results. From the data in the Table, it can be concluded that the annual potential corresponds to about 82.0 GWh/yr (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/yr). Finally, it corresponds to slightly more than the total energy consumed by the water desalination process in that year: 79.4 (GWh/yr) [4].

Table 4 – Results for electrical power generation (PG)

Property	Symbol	Operation conditions (4 MPa)	Operation conditions (5.2 MPa)	Units
Net electric power	$P_{NET,EL}$	10.1	10.4	MW
Overall plant efficiency	n_{NET}	22.5%	23.3%	-
Electric power produced	P_{EL}	12.4	12.7	MW
Electric power consumed in the plant	$P_{EL,com}$	2.28	2.28	MW
Turboalternator efficiency	n_{TA}	97%	97%	-
Mechanical energy	P_{mech}	12.7	13.1	MW
Steam flow rate	$\dot{m}_{SHS}$	50.6	50.9	tonne/h

Alternatively, if one considers the heating value (HV) of the fuel oil for industrial burners (fuel oil number 4) to be between 151.0 and 156.2 MJ per US gallon, (38.9 - 41.3 MJ/litre), and an average power plant efficiency of 32% (as in the existing Delimara and Marsa plants), it is possible to estimate that the corresponding avoided consumption of fuel oil will be between 2,747 and 2,845 litres per hour.

Contribution 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 that should be maintained over the MED cells to sustain the evaporation mechanism, as the heat losses and the boiling point elevation (brine) influence the evaporation process [4]. 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 [5]. To satisfy MED requirements, the steam specification after expansion in the turbine must be at 0.035 MPa and 72.68 ºC [6]. 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 ($\hat{h}_{4a}$, 0.01 MPa and 45.8 ºC). 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 evaluation of the electrical power and the flow rate of water treated when the backpressure turbine is combined with MED follows the same procedure and formulae introduced before. However, for the condensing turbine with steam extraction, the thermal power (upstream and downstream) and electrical power are evaluated through Equations 5, 6 and 7.

$$P_{TH,ext\text{-}ups} = \dot{m}_{ST,ext} \times (\hat{h}_{5a} - \hat{h}_6) \quad (5)$$

$$P_{TH,ext\text{-}dow} = \dot{m}_{ST} \times (\hat{h}_{4a} - \hat{h}_1) \quad (6)$$

$$P_{mech} = \dot{m}_{ST} \times (\hat{h}_3 - \hat{h}_{4a}) + \dot{m}_{ST,ext} (\hat{h}_3 - \hat{h}_{5a}) \quad (7)$$

In the equations above $P_{TH,ext\text{-}ups}$, $\dot{m}_{ST,ext}$, $P_{TH,ext\text{-}dow}$, $\hat{h}_{5a}$, $\hat{h}_6$, and $\hat{h}_1$ are respectively the thermal power and the flow rate of the extracted steam, the thermal power of the sub-cooled steam and the enthalpies at the outlets of the turbine, the MED process and the condenser [8]. Finally, the PES (Primary Energy Savings) index from Directive 2004/8/EC (Eq. 8) was applied to estimate the fuel energy saved by using a CHP plant. The index compares the fuel energy required to run the heating and the power plants, with that required if they were replaced by the co-generation facility. Reference PES values for a new MSW incineration plant, extracted from the Directive, are 25% for separate electricity generation and 80% for separate heat generation. Furthermore, the efficiency reference for separated electricity generation can be further corrected for climate conditions and avoided grid losses.

$$PES = 1 - 1/[(\eta_{EL,CHP}/Ref\ E_\eta) + (\eta_{TH,CHP}/Ref\ H_\eta)] \quad (8)$$

In Eq. 8, $\eta_{EL,CHP}$ and $\eta_{TH,CHP}$ represent, respectively, the calculated electrical and thermal power efficiencies of the CHP plant, and Ref E_η, Ref H_η the corresponding Directive reference values. The main results obtained are presented in Table 5. An acceptable value for PES (≥ 10%) is only achieved for a steam extraction equal or greater than 90% and 5.2MPa of operational pressure.

Table 5 – Results for electrical power generation and water desalination (CHP)

Property	Symbol	(4 MPa) Backpressure	(5.2 MPa) Backpressure	5.2 MPa; Condensing $\dot{m}_{ST,ext}$ = 90% x $\dot{m}_{STCond.}$	Units
Net electric power	$P_{NET,EL}$	8.46	8.85	9.01	MW
Primary energy savings index	PES	13.5%	14.6%	11.1%	-
Electric power produced	PEL	10.7	11.1	11.3	MW
Electric power consumed in the plant	$P_{E,com}$	2.28	2.28	2.28	MW
Turbo-alternator efficiency	n_{TA}	97%	97%	97%	-
Mechanical energy	P_{mech}	11.1	11.5	11.6	MW
Thermal energy available	P_{TH}	31.2	30.8	27.7	MW
Gain output ratio	GOR	12	12	12	Kg_{wter}/kg_{steam}
Flow-rate of water desalinated per hour	V_{WD}	606.8	610.2	529.2	tonne/h
Volume of water desalinated per year	V_{WDY}	4,854,285	4,881,859	4,393,670	m^3/yr
Final electrical power (after MED)	n_{THP}	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. On the other hand, the condensing turbine has a potential for fuel oil savings of about 2,873 litres. 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.

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. 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. Finally, as incineration generated electricity can be considered as deriving from a renewable source, it can help meet the 20% renewable energy target imposed by Directive 2009/28/EC.

References

[1] Meraz AD, Kornhauserb I, Rojas F. A thermochemical concept-based equation to estimate waste combustion enthalpy from elemental composition. Fuel 2003; 82, 1449-1507.
[2] Mastro F, Mistretta, M. Cogeneration from thermal treatment of selected municipal wastes. A stoichiometry model building for the case study of Palermo. Waste Management 2004; 24, 309-317.
[3] Rousseau, RMF, Ronald W. Balance in reactive process. Elementary Principles of Chemical Process. US: John Wiley & Sons, 2000, Third volume.
[4] Zsigraiova Z, Tavares G, Semiao V, Carvalho MG. Integrated waste-to-energy conversion and waste transportation. Energy 2009; 34, 623–635.
[5] Wade, N. M. Distillation plant development and cost update. Desalination 2001; 136, 3-12.
[6] IDE Thermal desalination solution. [Online] http://www.ide-tech. com/files /990b0fa01310a9c82f841f2183e9ebcb/downloadchapter/2010/01/MED%20Brochure.pdf27.