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Review

Energy recovery and impact on land use of Maltese municipal solid waste incineration

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ABSTRACT

An investigation of the potential of Maltese MSW (Municipal solid waste) for energy recovery is carried in this work together with a preliminary assessment of the corresponding economic and land use impacts. MSW composition data was collected to evaluate the waste combustion enthalpy. Data from 1997 to 2010 allowed the conclusion that an incinerator with a capacity of 32,500 kg/h can treat all the waste expectably generated in Malta during next 20 years. The thermodynamics of the steam cycle combined with elemental analysis was applied to study the contribution for PG (power) and CHP (combined heat and power) generation. The thermal energy was analyzed assuming its use in desalination. The best scenario considered corresponds to a potential electric power of 10 MW (PG) or to a maximum 4.8 million m^3/year of desalinated water combined with and 7.25 MW (CHP). It was concluded that incineration and CHP have the greatest potential to maximize revenues, due to the optimal combination of heat production and electricity generation. Finally, a calculation of the savings in land use due to the MSW incineration implementation was performed. Those savings could represent from 13,500 to 17,000 m^2 per year, a decisive benefit for Malta.

1. Introduction

Studies of energy and waste management in SIS (small isolated systems),[1] as is the case of small insular states, deserve special attention, due to the constraints arising from limited availability of land and resources [1]. The commitment to meet the targets of GHG (greenhouse gas) emission Directive, has brought to light hidden problems of these systems, such as the security of the energy/fossil fuels supply, the impact of implementing large scale renewable energy projects and the difficulty of finding and managing landfill sites [1,2].

Recycling and recovering materials from MSW (municipal solid waste) or selective sorting is normally a hard task in small isolated systems. Also, due to limited markets there are usually insufficient alternative energy sources and the price of primary energy transportation is very high. As a result, recent policies have been focused on the possible use of potential endogenous energy sources, namely incineration of MSW with energy recovery and carbon dioxide emission mitigation [3]. Additionally, in many of these SIS, seasonal fluctuations in population, due to the growing tourism industry, induce a strong variation in the waste generated and in energy demand, providing an extra rationale to solve the waste elimination and energy planning problems concurrently.

Europe is the cradle of the modern incineration technique. Thermal technology has been applied for a long time to reduce the volume of municipal solid waste, as well as to recover the combustion energy, to produce electricity and/or heat [4,5]. In an incineration plant, the reduction of MSW is the main objective, the energy recovery being done for sustainability reasons, with the economic optimization as an important side line. As such, it should not be regarded as competing with the production of energy from fossil fuels. In recent years the European hierarchy of waste management put forward by Directive 2008/98/EC, in which incineration plays a significant role, has promoted this EoL (end-of-life) treatment and contributed to the decrease of deposition in landfills. In particular, in small insular states, incineration plants can lead to significant energy recovery, contributing to satisfy the electricity demand or to power water treatment plants or other important facilities.

Air emissions are another important aspect to consider when implementing an MSW incineration project. In fact, such projects

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[1] Directive 2003/54/EC uses two criteria to define a small isolated system: the energy consumed should be less than 3,000 GWh per year (1996), and less than 5% of the annual energy demand should be imported from other systems.

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Nomenclature

B	factor related to the settlement of biodegradable waste in landfills
Bbl	barrel of oil
C	cover factor
d_{MSW}	density of waste
e	excess of air over stoichiometry
GOR	Gain output ratio
HHV	MSW high heat value (kJ/kg)
H_i	Maximum landfill height (m)
I_{CHP}	Investment cost for incineration with CHP facility (€)
I_E	Investment cost for the electricity facility (€)
K	factor related to the landfills linear and cover systems
LHV	MSW low heat value (kJ/kg)
MED	multi-effect distillation
MSW	municipal solid waste
M_{MSW}	MSW treated globally during the incinerator life span (kg)
$\dot{m}_{(A)msw}$	MSW throughput (kg/year)
$\dot{m}_{msw}$	MSW throughput (kg/s)
MSF	multi stage flash
$\dot{m}_{ST}$	throughput of generated steam (kg/s)
$\dot{m}_{ST,ext}$	throughput of the extracted steam (kg/s)
N	landfill life span (years)
O&M	operation and maintenance
PES	Primary energy savings
RO	reverse osmosis
$V_{air,teo}$	theoretical volume of air (m^3)
V_{CO2}	volume of carbon dioxide (m^3)
V_{fg}	volume of flue gas (m^3)
V_{H2O}	volume of water (m^3)
$V_{N2,air}$	volume of nitrogen from air (m^3)
$V_{N2,MSW}$	nitrogen content in the MSW (m^3)
V_{SO2}	volume of sulfur dioxide (m^3)
WtE	waste to energy
ΔH_{CO2}	enthalpy of CO_2 in flue gas (kJ/s)
ΔH_{H2O}	enthalpy of H_2O in flue gas (kJ/s)
ΔH_{N2}	enthalpy of N_2 in flue gas (kJ/s)
ΔH_{O2}	enthalpy of O_2 in flue gas (kJ/s)
ΔH_{SO2}	enthalpy of SO_2 in flue gas (kJ/s)
ζ	energy lost as a function of the total released
$\Sigma\Delta H_{fg}$	variation of the flue gas enthalpy (kJ/s)

can lead to a net reduction in GHG emissions, due to both the avoidance of methane emissions from landfills and the substitution of fossil fuels, resulting from the recovered energy [6]. The degree to which such reductions can be achieved depends on both the MSW ratio of biogenic to fossil carbon and on the energy transformation efficiency.

The combustion, energy recovery, and gas treatment concepts embody the principle of waste to energy, which evolved due to environmental pressures on society and the economy. European Directives play a major role in regulating this sustainable waste management development.[2] This legal framework makes Europe the largest disseminator of the incineration process, with the highest level of regulation, and also the promoter of the more advanced and risk minimizing technologies.

Conceptually, 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 [7,8]. The fraction of biogenic waste is a key factor in this consideration. As a consequence, for some years now, the waste characteristics (both generation rate and composition) have been researched in order to help decision-makers model environmental waste policies according to the more appropriate technological solutions.

The purpose of the present paper is to discuss the benefits that MSW incineration with energy recovery could bring to a small insular state, the Republic of Malta. We expand similar insular context studies [3,8] by calculating land use/saving and including a cost-benefit analysis. This will be done by studying the MSW incineration as a renewable source of energy for power generation, and the related economic and land use aspects. In a first step, the waste composition was determined and its low heat value estimated, to appraise the total heat potential. In a second step, the analysis of the combustion process was carried out, in order to evaluate the potential of the recovered energy for electricity production and thermal water treatment. Then, an economic analysis was performed, to monetize the different costs of investment. Finally, the avoided land use was calculated, by comparing current landfill and incineration practices.

2. Case study background

Malta, like other small insular states in Europe, faces serious MSW treatment problems that are exacerbated by its specific characteristics. On the other hand, those same extreme characteristics make Malta a particularly interesting case study. The Republic of Malta, a member of the European Union since 2004, consists of three main islands, Malta, Gozo and Comino. Three other uninhabited small islands, Filfla, Cominotto and St. Paul, are part of a natural protected area. Geographically, Malta is located in the Mediterranean, 93 km south of Sicily and 288 km north of Africa (Fig. 1). The area of the archipelago, which has no rivers, forests or mountains, totalizes only 316 km^2. The highest regions are in the Southwest, where limestone rocky formations and coastal cliffs that do not exceed 250 m above sea level can be found [10]. Mild winters (12–18 °C) and dry, hot summers (30–35 °C), typical of the Mediterranean climate, define the weather in Malta [11].

According to the Maltese National Statistics Office 2010 projections, the archipelago has 414,372 inhabitants, leading to the highest population density in Europe, 1311 inhabitants per square meter. This compares with circa 1,300,000 inbound tourists that visited Malta in 2010. The public sector generates 21.4% of the jobs, whereas the private sector, of which the flagship is the service subsector, is responsible for 73.2% of the overall employment. Tourism related activities represent a major share of this sub-sector [12].

Electric energy is produced in two power plants, fueled by imported fossil fuels (mostly oil). As a consequence, the electricity sector has a high impact in the global carbon dioxide emissions and in the economy. In 2008, the total Maltese CO_2 emissions amounted to 2.9×10^9 kg, 68.5% of which were due to that sector, the transport sector being responsible for only 17.9%. Tourism enhances electricity consumption, mainly through the use of air conditioning systems and electrical heating appliances, major drivers for the grid overload, inasmuch as there is no district heating system. Currently, the government plans to increase the renewable sources component of the energy mix, mostly through off-shore wind generation,

[2] Amongst them, Directive 2000/76/EC that regulates MSW incineration, Directive 2004/8/EC that promotes cogeneration, and Directive 89/369/EEC that regulates the prevention and control of air pollution.

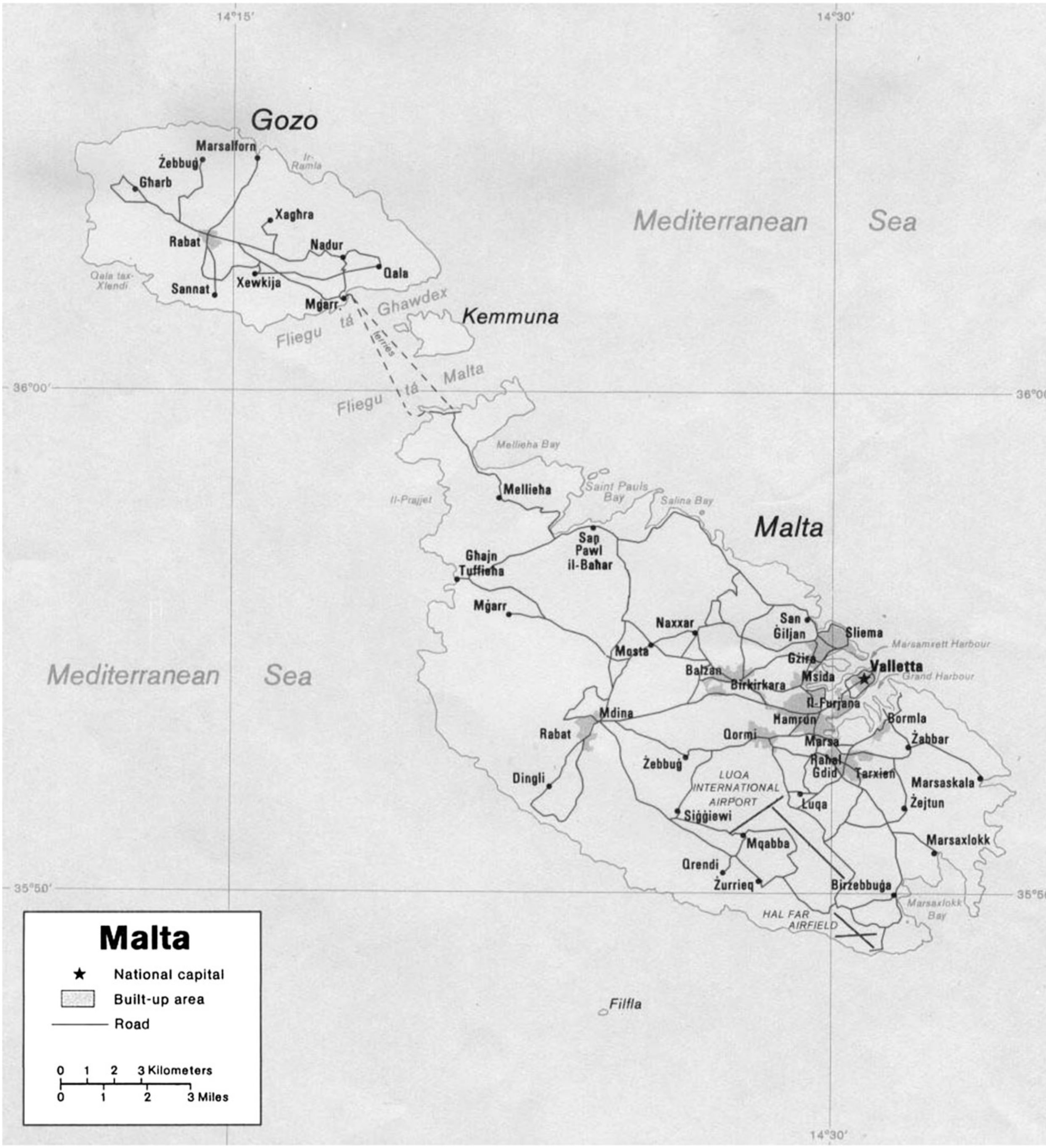

Fig. 1. Geographical situation of Malta [9].

as in-land installation is highly restricted by a number of factors, namely land scarcity. However, even the off-shore projects face environmental and fishing restriction problems.

Water supply in Malta is strongly dependent on desalination by RO (reverse osmosis), as rainfall is rather low, approximately 600 mm per year [8]. Three major desalination plants (Pembroke, Lapsi and Cirkewwa) produce most of the drinking water, with global specific electricity consumption around 4.77 kWh/m^3 of permeated water [13]. This makes the water treatment plants the largest energy users in the country.

Last but not least is MSW management. Despite having an efficient collection process, the system is limited by the high amount of waste generated per capita and the scarcity of land available for landfills. In fact, Malta has the highest ratio of waste produced per unit area, far higher than other EU countries, as highlighted in Fig. 2. Other countries, with similar geographical features, produce higher amounts of MSW per capita than Malta, but none so much MSW per unit land area (in 2010, this was 778.6×10^3 kg/km^2, 14 times the EU average). Further, in such a small, densely occupied, country the almost exclusive use of landfills as EoL treatment brings unique consequences to land availability. Up to very recently these indicators have increased; for instance, between 1998 and 2010 the MSW generated per capita grew 26%, of which circa 82% were landfilled.

The facts presented above and the recent Maltese government projects to build an incineration plant motivated this study, based

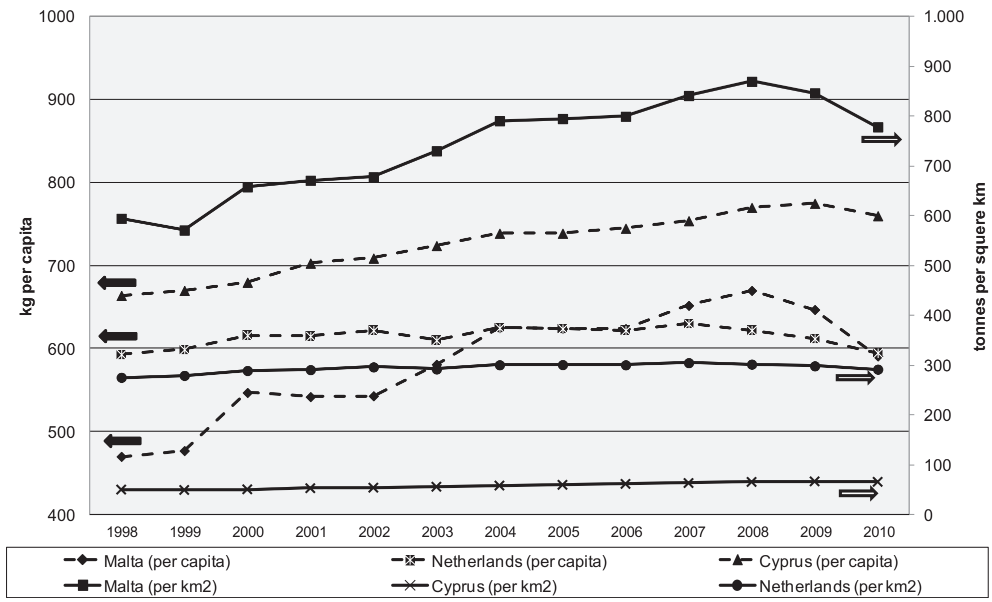

Fig. 2. Intensity of municipal solid waste production – per capita and per km^2.

on the last available MSW data and combustion and thermodynamic concepts on incineration with energy recovery.

3. Analysis procedure

The scheme depicted in Fig. 3 highlights the methodology used in the present work, detailing each step, from the MSW analysis to the energy analysis and finally to the simplified economic and environmental analyses. From the scheme it is evident that it is essential to know the average Maltese MSW composition in order to understand its nature and the efficiency of waste separation as a whole. Moreover, that composition is necessary to study the combustion process, as it is used as an input in the heat recovery calculation and in the economic analysis.

The overall analysis is developed in 9 parts. The first three parts focus on the characterization of Maltese MSW, namely i) its physical composition, including data collection and validation; ii) an estimate of the low heat value, using elemental analysis data obtained in the literature; and iii) the calculation of the future stream of MSW generation. This data, validated in a visit to a local waste managing company, was essential to predict MSW treatment capacity and also for the combustion and energy analyses. In the fourth and fifth parts, complete combustion calculations based on gas and steam thermodynamic concepts take place to determine the operational flue gas temperature and the recoverable energy for electricity and heat production, respectively. In the sixth, seventh and eight parts an economic analysis is performed, to estimate the net cost of energy incineration, considering investment, operational and maintenance costs, as well as revenues from electricity and heat sales. Investment, operational and maintenance costs functions developed for incineration plants in Europe were used to perform these estimates. The ninth and final part corresponds to the environmental analysis, which is centered in the land use feature. The actual practice of intense land use for landfills was compared with the estimated land that would be necessary if an incineration plant was installed in Malta to treat the same amount of MSW.

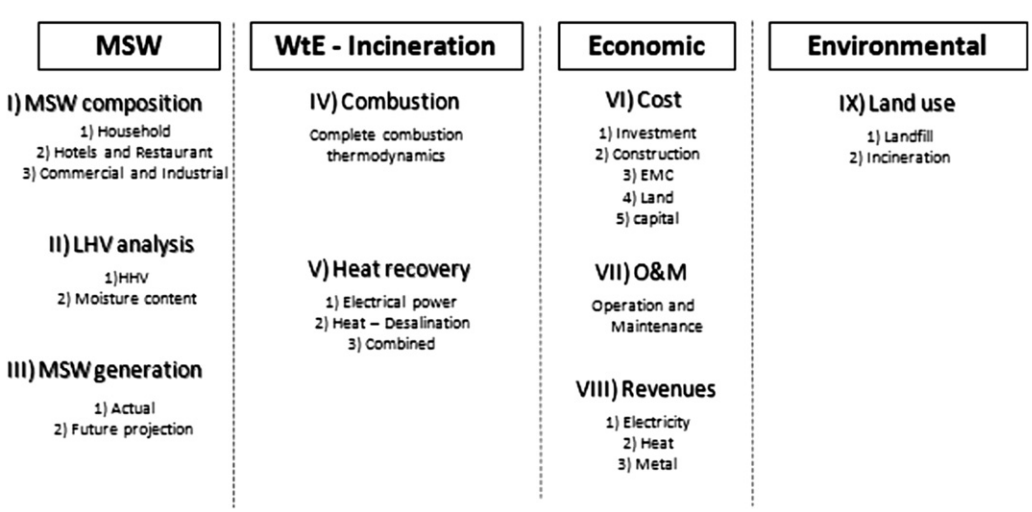

Fig. 3. Schematic representation of the present work methodology.

3.1. MSW analysis

The Maltese MSW analysis includes data from household, hotels and restaurants waste, as well as commercial and industrial waste. The data was collected from the NSO (National Statistics Office) 2002 and 2003 surveys [14,15]. The waste from the commercial and industrial streams was determined using literature data on the composition of the same streams in similar countries, like Ireland and Cyprus [16,17]. Fig. 4 summarizes the calculated composition of the Maltese MSW.

Household solid waste represents about 70% of the total waste generated between 2002 and 2010, which makes it determinant in the final MSW composition, namely in what concerns its organic fraction. The surveys revealed that organic waste (food) is the MSW largest fraction. Usually, in a densely populated island context, this is justified by (i) tourism activity during summer, (ii) precipitation during winter that increases the moisture content, and (iii) the near complete absence of home composting. "Others" correspond to the inerts fraction (ash, rock and dirt). The hazardous waste is, in this case, composed by batteries, electrical lamps and fluorescent tubes [14]. According to the EU Incineration Directive these materials cannot be incinerated jointly with MSW (non-hazardous waste) due to the toxic elements released [18]. In the present study, however, they were considered in the LHV (low heating value) estimate using literature values [19], since they could not be singled out from the household solid waste data.

In the NSO survey, no laboratorial ultimate analysis was performed to determine the elemental and moisture compositions; therefore literature sources on MSW moisture content, elemental analysis and high heating value [19] were used as an acceptable alternative. The LHV values were estimated next, by discounting the energy released by moisture evaporation and by evaporation of the water formed by hydrogen oxidation. Table 1 summarizes the data utilized in the calculations and the results obtained for the LHV estimation.

The prediction of the waste to be generated in future years is essential to determine the capacity of any incineration plant. However, to the authors' knowledge, there are no published studies forecasting the evolution of the Maltese MSW. In any case, the amount of waste generated in previous years is known (for instance, in 2010 it was 245×10^6 kg). Hence, using that data and two additional criteria, the future MSW generation could be predicted in three scenarios. The first scenario considers the yearly operation time of the incinerator. Based on values supplied by the LIPOR energy recovery plant,[3] this time was estimated to be 8000 h. Considering the 2010 MSW data, this leads to a 30,600 kg/h capacity. Admitting 5% excess capacity to cover unexpected variations [20], a final 32,100 kg/h value is obtained. The second scenario makes use of historical MSW data between 1997 and 2009 to plot the tendency curve and estimate the future waste generation, as shown in Fig. 5.

Plotting the data and fitting a trend-line in Fig. 5 allows the conclusion that the MSW will probably stabilize between 248 and 250×10^6 kg/year (31,000 and 31,250 kg/h, respectively) in the next 20 years. Then, the ideal capacity from this projection was taken as 31,250 kg per hour.

The last scenario was established using the MSW generated per capita, an indicator normally applied to support future estimations. In the Maltese case, this indicator showed minor fluctuations in the few last years, pointing to a stable value of 600 kg. Its average for the period 2000–2010 was 602.9 kg of MSW per person. These data were taken together with European Union projections on the Maltese population (growth rate) [21], which is expected to peak at 431,610 inhabitants in 2030. The calculation leads to a yearly MSW generation in the 20 years period mentioned above of 260.222×10^6 kg (or 32,500 kg per hour, for 8000 h of operation/year).

Considering the three scenarios, it can be concluded that the 32,500 kg/h capacity obtained in the third scenario will cover all the predictions, that is, a yearly MSW incineration capacity up to 2030 of 260.2×10^6 kg. This value will be used in the next design calculations.

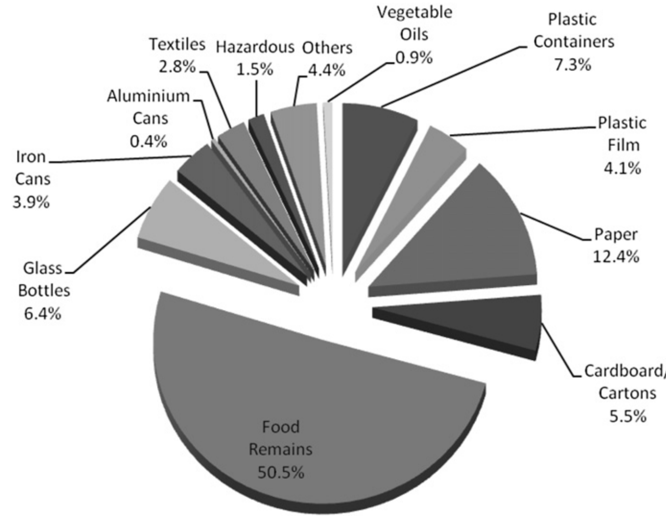

Fig. 4. Material composition of Maltese MSW.

3.2. Combustion and energy recovery

One of the aims of the present analysis is to address the combustion process, evaluating the air requirements and the flue gas temperature necessary to attain complete combustion. For this, data from the literature and/or based on experience and the targets imposed by the EU Directives were used. The technology considered was the mass burn, namely the grate firing technology, applied for un-subdivided solids until satisfactory burnout. This technology requires low level processing of MSW, thus reducing treatment costs and the area necessary for handling.

The energy and mass conservation principles applied to the MSW characteristics, as defined in the previous section, were utilized to estimate (i) the input air; (ii) the output volume of flue gas generated, and (iii) the heat generated. The MSW combustion energy analysis [22] considers the complete combustion of the three basic elements – carbon (C), hydrogen (H) and sulfur (S). Hence, the calculations begin by estimating the stoichiometric oxygen that feeds the combustion chamber, using typical physical and elemental compositions from the literature [19,23].

In the derivation, the following requirements of the European Incineration Directive [18] were considered: (i) the volume ratio of oxygen in the flue gas must be equal to or higher than 6% [24], and (ii) the temperature of the flue gas must be maintained between a minimum of 850 °C – to avoid dioxins formation [19] – and a maximum of 1050 °C – to avoid degradation of the refractory material by ash fusion [3,26].

First, the volume of flue gas (V_{fg}) with excess air (e) is evaluated by Equation (1), taken from reference [24]. It should be noted that the nitrogen from the MSW and air is not oxidized, being released in the molecular form.

[3] LIPOR is the Inter-municipal waste management service of the great Porto area, in the north of Portugal (http://www.lipor.pt/default.asp?SqlPage=pgVEner_EN&cor=5).

Table 1
Average physical and elemental composition of Maltese MSW.

	Moisture (weight %)	C (weight %)	H (weight %)	O (weight %)	N (weight %)	S (weight %)	Ash (weight %)	LHV (MJ/Kg)
	13.80	60.00	7.20	22.80	0.00	0.00	10.00	2.25
	13.80	67.21	9.72	15.82	0.46	0.07	6.72	1.22
	24.30	43.50	6.00	44.00	0.30	0.20	6.00	1.74
	24.30	49.60	6.40	35.70	0.72	0.24	7.34	0.91
	63.60	48.00	6.40	37.60	2.60	0.40	5.00	1.40
	3.00	0.50	0.10	0.40	0.10	0.00	98.90	0.00
	6.60	4.50	0.60	4.30	0.10	0.00	90.50	0.02
	6.60	4.50	0.60	4.30	0.10	0.00	90.50	0.00
	23.80	55.00	6.60	31.20	4.60	0.20	2.50	0.43
	12.80	29.04	5.18	6.12	0.18	0.02	59.46	0.18
	8.00	26.30	3.00	2.00	0.50	0.20	68.00	0.27
	59.00	73.14	11.54	14.82	0.43	0.07	0.00	0.30
Average	*40.2*	*24.21*	*3.20*	*15.59*	*0.68*	*0.12*	*15.95*	*8.73*

$$V_{fg} = V_{CO_2} + V_{H_2O} + V_{SO_2} + V_{N_2,MSW} + \left[0.79V_{air,theo}(1+e) + 0.21eV_{air,theo}\right] \quad (1)$$

The energy balance in the incinerator, assuming that the variation of the flue gas enthalpy ($\Sigma\Delta H_{fg}$) is caused by the heat released during the combustion (LHV), can be represented by Equation (2), also taken from Ref. [24].

$$\Sigma\Delta H_{fg} = \Delta H_{O_2} + \Delta H_{N_2} + \Delta H_{H_2O} + \Delta H_{CO_2} + \Delta H_{SO_2} = \text{LHV}\times\dot{m}_{MSW} - \zeta\text{LHV}\times\dot{m}_{MSW} = \text{LHV}\times\dot{m}_{MSW}(1-\zeta) \quad (2)$$

Next, a third degree polynomial relationship between Cp and temperature, described in the literature [3], is used for each gas to determine the final temperature of the flue gas, by solving Equation (2) using the EXCEL Solver [25]. An iterative process is then used to estimate the energy released to the water on cooling (boiler).

Considering the average annual temperature in Malta to be 18 °C and an incinerator capacity of 32.5 × 10^3 kg per hour, it is possible to evaluate the throughput (mass and number of moles per hour) of each component, as depicted in Table 2.

Table 3 presents the temperature of the flue gas determined for four different values of excess air. In the calculations it was also considered that 90% of the total energy released from the combustion was responsible for the enthalpy variation, the remaining 10% being heat losses [3,26].

It can be concluded that about 52.78% excess of the theoretical air satisfies all the previously mentioned criteria while still maximizing the potential for energy recovery. As a consequence, the recirculation of the flue gas was not considered necessary [23]. Consequently, in further calculations, the final temperature of the flue gas was taken as 915.47 °C.

The heat released during the combustion of the MSW (fuel) can then be used in a steam cycle with the possibility of producing power, heat or a combination of both. For practical reasons, the Rankine cycle is normally used in power or CHP (combined heat and power) plants to prevent problems with wet steam. The isentropic efficiency, from the second thermodynamic law, can then be applied to estimate the real electrical and thermal power. For that, it was additionally assumed that the pressure drops in the boiler and in the condenser are negligible and may be neglected in the calculations.

Established values applied in real situations were considered for the inlet (4.0 MPa; 440 °C), and for the outlet (0.01 MPa; 45.8 °C) of the steam condensing turbine to estimate the potential for power production. The procedure starts with the evaluation of the steam

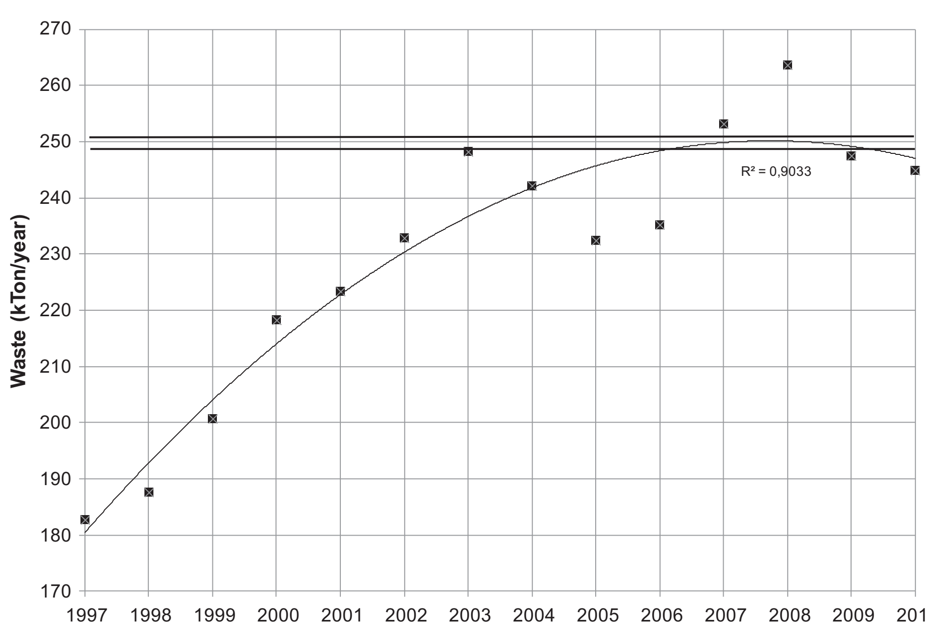

Fig. 5. Historical and projected MSW generation.

Table 2
Throughput of the main elements in the combustion process.

Throughput	Total moisture (H_2O)	Total carbon (C)	Total hydrogen (H_2)	Total oxygen (O_2)	Total nitrogen (N_2)	Total sulfur (S)	Ash
Mass (10^3 kg/h)	13.08	7.87	1.04	5.07	0.22	0.04	5.19

mass flow rate; then, the shaft work is estimated. The efficiency of the turbo-alternator that converts mechanical into electrical energy and the consumption of electrical energy on-site were calculated using the formulas developed by Zsigraiova et al. [3] and Mastro et al. [24]. The final estimation of the net electrical power, as well as the turbo-alternator efficiency, is presented in Table 4. The overall plant efficiency is calculated in order to emphasize the remaining thermal energy that is eliminated in the condenser.

The production of energy by incineration can partially reduce the amount of oil that is currently consumed in the Maltese power plants. Assuming that the heating value of the fuel oil for industrial burners (fuel oil number 4) is 41,200 MJ/m^3 [27] and the overall efficiency of Maltese plants is 32%, it is possible to estimate that the 10.08 MW of the condensing turbine electrical power will correspond to about 17.3 barrels per hour[4] of avoided fuel oil.

Alternatively, the heat recovered could be used for thermal use, namely to desalinate seawater, via MED (multi-effect distillation). Use of MED leads to savings in capital cost, lower electrical consumption (higher efficiency), and lower operation temperature compared with the MSF (multi stage flash) technology. In the case of Malta, another advantage is the current use of the MED technology to desalinate the seawater that feeds the Delimara Power Plant.

For the thermal calculation, a typical GOR (gain output ratio) value of 12 kg of distillate per kilogram of steam consumed [28] was used. The aim is to assess the amount of water that could be treated if all thermal energy generated was used in a low temperature MED plant, considering the above GOR value and the minimum steam requirements for the operation of the plant. To satisfy these requirements, a simple steam condensing cycle operating at 0.035 MPa and 72.68 °C was considered. The estimated value for water desalination capacity is presented in Table 5.

A simplified analysis was again made, considering that the actual average energy consumed for each cubic meter of water desalinated in the current RO plants is 4.77 kWh/m^3 and will be an estimated 2 kWh/m^3 in the proposed MED plant. Then, bearing again in mind the efficiency of the Maltese electrical power plants (32%), it is possible to calculate that this technology will bring a reduction in oil consumption of circa 0.75 L/m^3 of treated water [29]. Finally, for circa 6.5 million m^3 of water desalinated per year (Table 5) that could be treated in a thermal plant, the avoided fuel oil would be 3.86 barrels per hour.

In the combined system, the steam is primarily used for power generation taking advantage of the high quality energy to produce shaft work, and the remaining thermal energy is applied in industrial processes, such as the MED desalination. In the case of a backpressure turbine, the MED process can substitute the condenser in the Rankine cycle. However, in the case of a condensing turbine, the steam extraction feeds the MED system and the sub-cooled steam remaining in the turbine is condensed. In the former case, the evaluation of the electrical power and the flow rate of water treated follow the same procedure mentioned before for the steam condensing turbine [3,24].

The amount of primary energy savings provided by cogeneration was estimated using the so-called PES (primary energy savings) index from Directive 2004/8/EC [30]. This index represents “the fuel energy saved by using a CHP plant compared to the energy required to run separately the heating plant and the power plant that the cogeneration facility replaces” [3]. Tables 6 and 7 summarize the results obtained for both the backpressure and the condensing turbine plant configurations.

Table 3
Temperature of the flue gas for different values of excess air.

Oxygen in the flue gas, V_{O2}/V_{fg} (%)	Excess of air, e (%)	Temperature, T (°C)	Enthalpy variation, $-\Delta H$ (kJ/kg)
6.00	*52.8*	915.5	7853.6
6.50	59.2	890.7	7853.6
7.00	66.0	865.6	7853.6
7.50	73.3	840.2	7853.6

Using the same rationale, the combination of the backpressure turbine and MED system could avoid the consumption of 17.2 barrels of fuel oil per hour if about 4.8 million m^3 of water were treated per year by the MED system instead of the RO. For the condensing turbine with steam extraction, these figures will be 17.9 barrels/hour and about 4.4 million m^3 per year, respectively.

Any of the three heat recovery scenarios studied shows that incineration of the MSW generated in Malta could give an important contribution to mitigate its inherent energy problem. Even the simple condensing turbine for electrical power production could be used to increase the electrical supply or to power the installed RO plants, contributing to significant primary energy savings.

If all thermal energy was used in a MED plant, about 39% of the total potable water consumed in the archipelago nowadays (about 16.6 million m^3/year) could be generated. On the other hand, a single thermal source is a limited application in terms of energy decentralization/diversification. Moreover, it may lead to the closure of the installed RO facilities. CHP plants constitute the ideal scenario, by permitting to generate electrical power and to desalinate seawater concurrently. These processes could be seasonably modulated. In the case of Malta, the CHP could improve energy savings during summer when water and electrical power consumption increase due to tourism. The water produced by the thermal process could help meet the water demand, without increasing electrical consumption, and the plant would still enhance the Maltese electrical energy supply.

Moreover, the installation of the condensing turbine with steam extraction could permit modulating the flow rate of water treatment, guarantying a higher electrical power production. Focusing on the PES index, it can also be concluded from Table 7 that the

Table 4
Output of the steam condensing turbine (4 MPa).

Property	Value	Units
Net electric power	*10.08*	*MW*
Overall plant efficiency	22.53	%
Electric power produced	12.35	MW
Electric power consumed in the plant	2.28	MW
Turbo-alternator efficiency	97	%
Mechanical energy	12.73	MW
Steam flow rate	50.64	10^3 kg/h

[4] 1 oil barrel is equivalent to approximately 159 L.

Table 5
Potential for desalination.

Property	Value	Units
Gain output ratio	12	kg_{dist}/kg_{steam}
Volume of water desalinated per year	6,511,800	m^3/yr

energy savings are quite above the 10%, minimum imposed by the European Directive 2009/28/EC [31].

3.3. Economic analysis – MSW incineration cost

Incineration of MSW is considered an expensive waste treatment when compared with other end-of-life techniques, mainly due to its investment and O&M (operation and maintenance) costs. The present section is thus focused on the private cost of implementing an incineration plant with energy recovery. A simplified electricity price analysis (ignoring inflation and economic effects on the investment, maintenance and operation) is performed, considering the MSW treatment cost under two perspectives: (1) the net MSW treatment cost, and (2) the electricity and heat prices. The former, takes into account the revenues from the electricity and heat generated, based on the actual prices of electricity (Maltese reference) and heat (UK reference). The latter, considers that those revenues should offset (eliminate) the net MSW treatment cost.

Taking the price of 0.72 €/kg[5] for thin fuel oil in Malta, the cost related to the avoided oil could represent at least 9.4 million Euros per year, depending on the plant configuration. However, the economic analysis will focus instead on the direct private cost of the plant.

From an economical perspective, it is necessary to differentiate the net specific treatment cost of MSW from the gate fee. The gate fee is not a cost, but a market price that depends on the local competition, amount of unused capacity, limitations to the intake of specific materials, strategic objectives of the facility operator and others (e.g., competition with alternative methods, such as landfills) [4,20].

The economic analysis was developed for all plant configurations studied before. However, the investments that could be necessary to implement the electricity and heat distribution networks have not been included. The revenues considered are also restricted to the sales of electricity, heat and recovered metals.

The estimation of the investment and O&M costs of an incineration with energy recovery plant (electrical and CHP) is usually based on the type of cost functions presented in Table 8 [32].

In the case of the incineration plant with heat use, the investment and O&M costs are estimated by using a scale factor for the facility, combined with information on costs of pure heat decoupling (steam extraction for thermal use) and CHP, from the Reference Document (BREF) on the Best Available Techniques for Waste Incineration [4]. Additional costs were calculated using typical indexes from the BREF document. The annual proportional cost for maintenance specified by the designer (long stops) was estimated using the LIPOR reference, where the annualized cost is about 5 million of Euros, for 380×10^6 kg of MSW incinerated per year. It was admitted that this value does not vary, either with facility size or plant option. The annualized cost of the MSW treatment was estimated based on 20 years of plant economic life and an interest rate of 6% per year.

The results for all plant options are presented in Table 9. The estimated costs of the two CHP configurations are the same, as the cost function is only dependent on plant capacity. Therefore, the difference in the net specific MSW treatment cost arises only from the revenues of electricity and heat.

According to the data in Table 9, MSW incineration coupled with an electrical or a CHP power plant would lead to the lower net specific treatment cost. The former due to the smaller investment and O&M cost, the latter due to the higher revenues from electricity and heat sales. The incineration facility connected with a thermal power plant (heat decoupling) has the highest net specific treatment cost, as the revenues are restricted to heat sales and the heat price is low. Hence, this option is considered to be the least advantageous. Albeit power plants and CHP plants have the same net specific treatment cost, the CHP configurations have the greatest potential to maximize revenues. This is due to the optimal combination of heat production and electricity generation (the former has a very low impact on the latter). This is thus considered the best option to meet the electricity and heat and cooling demand for long term planning in Malta. As stated before, it also has the possibility to respond to the expected increases in water demand through the MED desalination technology.

In all cases, the annual recovery savings derived from sales of electricity, heat and recyclables are significant, varying from 9.1 to 14.8 million Euros/year, depending on the plant configuration. This as a profound societal significance, as it allows the price charged for the MSW treatment to be much lower.

3.4. Environmental analysis – land use

In Europe, the diversification of waste treatments, integrating 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 MSW management.

Table 6
Backpressure turbine and MED.

Property	(4 MPa)	Units
Net electric power	8.46	MW
Primary energy savings index	20.6	%
Electric power produced	10.74	MW
Electric power consumed in the plant	2.28	MW
Turbo-alternator efficiency	97	%
Mechanical energy	11.07	MW
Thermal energy available	31.18	MW
Gain output ratio	12	kg_{dist}/kg_{steam}
Flowrate of water desalinated	606.8	10^3 kg/h
Volume of water desalinated	4854.3	10^3 m^3/yr

Table 7
Condensing turbine (steam extraction) and MED.

Property	$\dot{m}_{ST,ext} = 75\% \times \dot{m}_{ST}$	$\dot{m}_{ST,ext} = 90\% \times \dot{m}_{ST}$	Units
	(4 MPa)	(4 MPa)	
Net electric power	8.87	8.62	MW
Primary energy savings	12.48	17.55	%
Electric power produced	11.14	10.90	MW
Electric power consumed	2.28	2.28	MW
Turbo-alternator efficiency	97	97	%
Mechanical energy	11.49	11.24	MW
Thermal energy available	23.39	28.06	MW
Flow rate of water desalinated	455.09	546.1	10^3 kg/h
Volume of water desalinated	3640.71	4368.9	10^3 m^3/yr
Final electrical power (after MED)	7.96	7.53	MW

[5] As from Enemalta website: www.enemalta.com.mt/index.aspx?cat=2&art=7.

Table 8
Cost function for an electrical and a CHP plant [32].

Facility type	Investment cost (£[a])	O&M cost (£[a])	Range of facility capacity (10^9 kg/year)
Incineration (CHP)	$I_{CHP} = 9346 \times (\dot{m}_{MSW})^{0.754}$	$O\&M_{CHP} = 1372 \times (\dot{m}_{MSW})^{-0.333}$	120–380
Incineration (electrical)	$I_E = 17{,}778 \times (\dot{m}_{MSW})^{0.676}$	$O\&M_E = 1572 \times (\dot{m}_{MSW})^{-0.361}$	120–380

[a] Average exchange rate (2010): 1.17€/£.

Table 10
Land necessary to treat the MSW generated in the next 20 years (5.2×10^{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	%

At present, incineration is only applied in Malta to burn the waste from abattoirs and hospitals [10]. Population concerns regarding air quality have so far prevented the dissemination of this MSW technology. However, the recent stringent regulations for air pollution and the intense use of incineration in Europe and in the United States have slowly changed the government and population perceptions. In fact, the benefits of MSW incineration go beyond the energy recovered (that is, the avoided fuel oil consumption), as it can also decrease the amount of MSW landfilled, consequently avoiding occupation of usable land.

Incineration plants do not require more land than that established in the design; consequently there is no continuous land impact along their lifespan. According to recent data, 100,000 m^2 of land (landscaping and auxiliary buildings) are enough to treat in a WtE (waste to energy) plant about 10^3 million kg of MSW per year, whereas the same amount of MSW landfilled would require 100,000 m^2 *each* year [33,34].

The goal of this analysis is to estimate, 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 EoL 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 (3) and (4), without considering the specific limitations of available land (geographical aspects) in Malta [10,35].

$$A = 1.15 \frac{M_{MSW}}{d_{MSW}} \frac{(1 + C + k - B)}{H_i} \quad (3)$$

$$M_{MSW} = n \times \dot{m}_{(A)MSW} \quad (4)$$

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 260.2×10^6 kg per year and a plant life span of 20 years.

Table 9
Cost analysis for the various power plant configurations.

Description	Elec. power plant	CHP[a] plant,$_{BKP}$	CHP[b] plant,$_{ExT}$	Thermal plant	Unit
Specific treatment cost	82	104	104	98	€/10^3 kg
Specific revenue	35	57	56	40	€/10^3 kg
Net specific treatment cost	*47*	*47*	*48*	*58*	€/10^3 kg
Annual recovery savings[c]	9,107,000	14,831,400	14,571,200	10,408,000	€/year

[a] Back pressure turbine.
[b] Condensing turbine with extraction.
[c] For 260.2 10^9 kg/year.

The results obtained for the landfill show that the land area required for the next 20 years is around 396,073 m^2 considering $H_i = 20$ m, $d_{MSW} = 850$ kg/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) $= 0.1$ [36]. 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 25,000–35,000 m^2 for plants with capacities ranging from 60 to 600×10^6 kg [4,10]. 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 [10]. 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 [10]. Concurrently, according to LIPOR validated data, 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 aluminum), and 8–8.5% will be effluent gas treatment system ash. Then, it can then 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 disposable 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 10.

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.

4. Conclusions

If a MSW incineration plant is built in Malta with an associated electrical power plant, its electricity potential can be estimated as 5% 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.

Thus, the use of the energy generated by the MSW combustion would also represent a reduction of the primary energy dependence, even though the avoided fuel oil consumption is not too significant. In any case, the CHP plant has the biggest potential of all configurations to save fuel, making full use of the MED (multi-effect distillation) technology to desalinate water for general consumption. The MED plant could contribute to satisfy the increased water demand that occurs in Malta during summer (namely due to tourism activity). In fact, in this period, it could supply, more efficiently, a significant part of the water that is currently produced by the desalination plants using the RO technology. In conclusion, the electrical and thermal power generated by the incineration plant could help Malta save fuel oil and increase its energy supply.

Specifically, the expected results, dependent on the type of plant installed and the end-use of the produced energy, are:

- If a power plant with 10.1–10.4 MW capacity is installed, the total energy generated will correspond to 2.4–2.5% of the total yearly energy demand in the reference scenario for 2020.
- If a dedicated 44.7 MW thermal plant is installed, it can provide 42.3% of the energy needed for the heating and cooling systems in the 2020 reference scenario; alternatively, the energy could be used to provide at least 40% of the total 2010 desalinized water demand.
- If a 44.7 MW (8.5–8.9 MW electrical power) CHP/backpressure turbine and MED plant is installed, it can provide 2–2.1% of the electrical energy needed yearly in the 2020 reference scenario. The remaining 30.8–31.2 MW of thermal power represents 29% of the total required for the heating and cooling systems in that year; alternatively, the thermal energy could be used to provide at least 30% of the total 2010 desalinized water demand.
- If a 44.7 MW (9.0 MW electrical and 28.1 MW thermal power) CHP/condensing turbine and MED plant is installed, it can provide about 2.1% of the electrical energy required yearly in the 2020 reference scenario, or 26% of the thermal energy required for the heating and cooling systems in that year; alternatively, the 28.1 MW of thermal energy could be used to provide at least 27.1% of the total 2010 desalinized water demand.

Proper consideration of the investments and revenues, as well as plant configuration, is determinant if the incineration plant is to be self-financing. In fact, the revenues generated by selling electricity and heat can significantly reduce the O&M costs of the plant, with important economical and social consequences. Combination of incineration and CHP provides the best economic solution, leading to the greatest specific revenues, a low net specific MSW treatment cost and the highest annual recovery savings. Furthermore, it has the largest potential to absorb fluctuations in electrical and heat prices. Additionally, the present work allows the conclusion that incineration of Maltese MSW can help reduce deposition in landfills, therefore leading to significant savings in land area during the plant lifespan, and decreasing the potential for water and soil contamination. 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.

In synthesis, the present study addresses, and proposes a partial solution for some of the main difficulties that have to be overcome by the Maltese Republic: the management of waste, energy, land, and water.

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