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Integrated waste-to-energy conversion and waste transportation within island communities

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ABSTRACT

Usually in islands both primary energy sources and drinking water are missing. Additionally, municipal solid waste (MSW) must be managed avoiding exclusive use of landfills, which limits sustainable development. Power generation from MSW incineration contributes significantly to replacing energy produced from fossil fuels and to reduce overall emissions. A solution based on thermodynamics, environmental and economic analyses and 3D-GIS modelling for the afore-mentioned problems for Cape Verde is proposed. This model integrates waste transportation optimisation and incineration with energy recovery combining production of heat and power (CHP), the heat being used for drinking water production. The results show that extraction condensing steam turbines are more suitable when power production is a priority (5.0 MW with 4000 m^3/d of drinking water), whereas back-pressure turbines yield 5540–6650 m^3/d of drinking water with an additional power production of 3.3–4.7 MW. The environmental and economic assessment performed shows the feasibility of the proposed CHP solution, which brings a considerable reduction in net air emissions (1.6 kt), including a significant decrease in the greenhouse gas emissions (131 $ktCO_2$), and that the revenue from energy sales (€15 million) has potential to balance the incineration cost. Moreover, when terrain relief is accounted for in the route optimisation for minimum fuel consumption, savings up to 11% are obtained.

1. Introduction

Waste management is an issue in every country as waste is generated by daily human activities in all economic sectors and is generally an unavoidable by-product. Waste generation without recycling or energy recovery reflects a loss of materials and energy and imposes economic and environmental costs on society for its collection, treatment and final disposal. On the other hand, municipal solid waste (MSW) represents a significantly valuable source of recoverable materials and, even after recycling, constitutes a valuable potential energy resource.

However, there still subsists the need for a critical review of waste treatment options with a view to the achievement of a more intensive waste recovery that will allow for the reduction in waste generation or, at least, its stabilisation. Despite significant progress reported in waste recovery and recycling [1–3], the aimed stabilisation of waste generation is far from being achieved.

Waste management in isolated communities, such are islands, has its particular features that influence significantly the choices of the acceptable management options [4]. In fact, policy makers' attention in island communities has recently been focused on the possibility of making use of any potential endogenous energy resources, including waste-to-energy conversion, because of the following idiosyncratic aspects of island economies: the limited availability of land reduces in practice the disposal of waste by landfill to a large extent; recycling and recovery of materials is problematic due to both the absence of a market for recycled materials and the distance from the mainland; insufficient energy resources and the restrictive prices of primary energy transportation together with the fact that expensive imported fuels cause negative environmental impact and do not contribute to energy security of the islands, leading to a strong dependence on fossil fuels (usually diesel) in electricity and drinking water production, with high price of small scale, fossil fuel-based technologies. Additionally, seasonal demographic fluctuations in the population due to the growing tourism sector breaks down the desired steadiness of waste generation and energy production, imposing higher pressure to solve adequately waste elimination and energy planning problems.

The long-term development of island communities has to comply with the need to take into account alternative ways to

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Nomenclature

α	flue gas recirculation rate (%)
$\bar{c}_{p,SW}$	mean specific heat of seawater (kJ/(kg K))
Δi_{FG}	change in the flue gas enthalpy (kJ/kg$_{MSW}$)
ΔT_{SW}	temperature gradient of the brine in the first stage of a desalination unit (°C)
η_{EL}	electric efficiency of the plant (%)
$\eta^{A}_{EL,CHP}$, $\eta^{A}_{TH,CHP}$	electrical and heat efficiency of the CHP calculated on the annual basis (%)
$\eta_{EL,REF}$, $\eta_{TH,REF}$	harmonised reference efficiency for separate production of electricity and heat (%)
η_{HE}	efficiency of thermal exchange (%)
η_{NET}	overall efficiency of the plant (%)
η_{T-A}	efficiency of the alternator (%)
$i_{1,w}$ ($i_{1,w,BP}$/$i_{1,w,EXT}$)	enthalpy of the saturated water leaving the condenser at 10 kPa (30 kPa/0.2 MPa) and 45.81 °C (69.1 °C/120.23 °C) (kJ/kg)
i_3	enthalpy of the superheated steam (440 °C/4 MPa) (kJ/kg)
$i_{4'}$	steam enthalpy after real expansion in the turbine (kJ/kg)
$i_{4',BP}$/$i_{4',EXT}$	steam enthalpy after real expansion in the turbine (subcooled/superheated steam) (kJ/kg)
$i_{4',K}$	steam enthalpy after real expansion in the turbine (down to steam extraction) (kJ/kg)
l_{F-G}	latent heat (kJ/kg)
L_{actual}	actual amount of combustion air per unit of MSW (m^3/kg$_{MSW}$)
m	excess air
m_{MSW}	MSW flow rate (kg/s)
m_{ST}	generated steam mass flow rate (kg/s)
$m_{ST,DOWN}$	remaining steam mass flow rate after the steam extraction (kg/s)
$m_{ST,EXT}$	extracted steam mass flow rate (kg/s)
m_{SW}	seawater mass flow rate (kg/s)
P_{MECH}($P_{MECH,CHP}$)	the real mechanical power generated by turbine during steam expansion (CHP) (MW)
P_{EL}($P_{EL,CHP}$)	the real electric power at the alternator outputs (CHP) (MW)
$P_{EL,CONSUM}$	the electric energy consumed on-site (MW)
P_{NET}($P_{NET,CHP}$)	the net electric power to the grid (CHP) (MW)
$P^{BP}_{TH,CHP}/P^{EXT}_{TH,CHP}$	thermal energy of the condensing/extracted steam (MW)
PES	primary energy saving index (%)
q_{FG}	change in the flue gas enthalpy between the boiler inlet and outlet (kJ/kg$_{MSW}$)
Q_{MSW}	total heat content of the waste (MW)
$Q(LHV)_{MSW}$	heating value of the waste (low heat value) (kJ/kg$_{MSW}$)
T_{FG}	temperature of the flue gas leaving the furnace (°C)
V_{FG}	actual flue gas amount per unit of MSW (under excess air conditions) (m^3/kg$_{MSW}$)
V_{SW}	seawater flow rate per day (m^3/d)
$x_{4'}$	subcooled steam quality after real expansion in the turbine
X_{O_2}	oxygen content in the wet flue gas (vol%)

traditional fuels in order to reduce their dependence on energy imports. Therefore, locally available energy resources, as well as MSW, are essential for their sustainable development.

As far as waste treatment technology is concerned, due to the serious and urgent problems mentioned above (shortages of the primary energy resources), very often combined with local social and cultural conditions and habits (waste disposal to open landfills, incipient consciousness for the need to separate waste, etc.), there still subsist limitations to the implementation of some of the MSW treatment techniques as these cannot respond rapidly and efficiently.

The process of thermal treatment of MSW by incineration combined with energy recovery can bring reasonable and sustainable solutions when integrated within an overall waste management system. In fact, such process represents a double gain: it constitutes simultaneously a considerable potential for reduction in reactivity of any residual landfilled material and the potential energy resource providing the excess of the recovered energy for further exploitation [5–7].

In addition, there is another important aspect related to the implementation of energy recovery from MSW. During incineration of MSW, a net reduction in emissions of greenhouse gases (GHG) can be achieved. This reduction is due to both avoiding methane emissions from landfills and to the substitution of fossil fuels by waste in energy production [8]. The degree to which emissions reduction can be reached depends both on the ratio of biogenic to fossil carbon in the waste and on the achieved efficiency of energy transformation.

From the above discussion it can be concluded that waste management and energy systems are strongly linked: there is a need for waste elimination with energy recovery on one side and, on the other, the demand for fuels for electricity production is also affecting the planning of future waste management. This makes their simultaneous analysis compelling mandatory.

Another related problem to be considered is the growing demand for drinking water production, which is an energy intensive process requiring a stable energy supply. MSW is a locally generated and permanently available energy resource mostly used, so far, only for power generation or in combination with the supply of district heating [4,5,7]. As a matter of fact, examples of its application for water treatment purposes are not known, except one plant in the Netherlands recovering brackish water [9].

The transportation of waste is another important issue, which constitutes an inseparable part of an integrated MSW management system, present at each stage of the waste treatment from its collection up to the final disposal. The economic and environmental problems associated with waste transportation include energy and fuel consumption, and significant amounts of emitted pollutants. Furthermore, as a cost intensive activity, it is necessary to justify such an investment in terms of environmental and technological feasibility and economic optimisation, ensuring that the required degree of efficiency is achieved. Therefore, the optimisation of the routing network for waste collection and transportation has to be considered as demonstrated elsewhere [10,11]. However, such optimal routes are usually searched according to the shortest distance travelled, or time spent. On the other hand, the optimisation based on fuel consumption minimisation expresses more appropriately the actual situation [12–14] as the shortest distance travelled may actually correspond to higher fuel consumption. Since fuel consumption of vehicles is influenced by the engine load, in turn dependent on the longitudinal slope of the roads, this parameter has to be considered during optimisation as proposed by Tavares et al. [14]. Such an approach can bring an important contribution to the improvement of MSW management systems resulting in significant savings, both economically and environmentally.

In this work, an innovative integrated approach to improving the energy efficiency of MSW management in islands or isolated regions is proposed through the combination of MSW recovery by incineration, as an alternative source of energy, with the reduction of both the cost of waste transportation to the incinerator site and the transportation-related emissions. Within this frame, the viability of extracting energy from MSW more efficiently is assessed herein, namely by cogeneration linked with drinking water production, and to simultaneously minimise fuel consumption of waste transportation vehicles by applying geographic information system (GIS) tools with a three-dimensional modelling of the road network. This analysis is accompanied by a brief environmental and economic assessment of the impact of the proposed solution.

2. Case study

As a case study, the problem of MSW treatment in Cape Verde was selected. Cape Verde is an island republic located on an archipelago in the Macaronesia eco-region of the North Atlantic Ocean, 500 km off the western coast of Africa. It consists of 10 islands with a land area of 4033 km^2 as depicted in Fig. 1. Situated in the tropical zone, Cape Verde has a temperate, warm and windy climate with dry summer and irregular rainfall.

The population of less than a half million is spread over 9 islands. The largest and the most populated island is Santiago, where the capital Praia is also situated. Presently about 55% of the total population of Cape Verde live on the island of Santiago, and almost 25% of all inhabitants live in the capital. It is expected that by 2020 the population of Santiago will rise to 58% of the total and to 30% in Praia. The annual growth rate of 2.4% is related to better work opportunities after independence of the country gained in 1975 [15].

From the economic point of view it is a developing country experiencing constant growth. It does not have its own fuel resources and there is also a shortage of drinking water. Diesel-based technologies cover more than 90% of present demands for power and water production. Although there is potential for wind and solar energy exploitation, its penetration in the energy system is not yet significant.

A great challenge for Cape Verde is the establishment of an integrated and well functioning waste management system to guarantee proper treatment and disposal of MSW. Waste amount has been increasing very significantly as a result of urban pressure, demographic growth and tourism. Despite efforts for action at governmental and municipal levels [16,17], there is still evident lack of urban development plans. The rural exodus and inter-island settlement of migrants is not controlled. Existing waste management is characterised by insufficient collection and the collected waste is mostly disposed in uncontrolled open landfills with subsequent burning for reduction of volume, hence without any material or energy recovery. It results in a direct negative impact on the environment and health of the population and also affects tourism development.

The waste collection and transportation system of Santiago Island with its six municipalities is divided into two regions: the capital Praia region, including its urban and rural areas, and the remaining zones of Santiago. Each municipality is responsible for waste collection and transportation to landfill on its territory, this constituting the final and only treatment method of the collected waste. In general, the existing MSW collection system of Praia and the remaining part of Santiago Island is a combination of small returnable containers and high-capacity containers collected by compacting vehicles and trucks. While the waste collection from returnable bins is mostly done on a daily basis, the large containers are collected and emptied twice a week or even sporadically, depending on the place and means of transportation.

Prospectively, there is a project in progress for the thermal treatment of MSW by incineration located some 8 km from the centre of Praia. It is expected that the plant capacity will allow for the treatment of all waste collected from all the municipalities of Santiago Island. This is the scenario taken into consideration in the present study.

3. Methodology

To contribute to a substantial improvement of this situation, the present research is focused on waste streams at the island of Santiago. The work can be defined as having as a main objective the project of an incineration plant treating MSW from its six administrative districts with energy recovery, otherwise directly disposed to several mostly open uncontrolled landfills, combined with the reduction of the cost of waste transport to the place of treatment through the minimisation of vehicle fuel consumption.

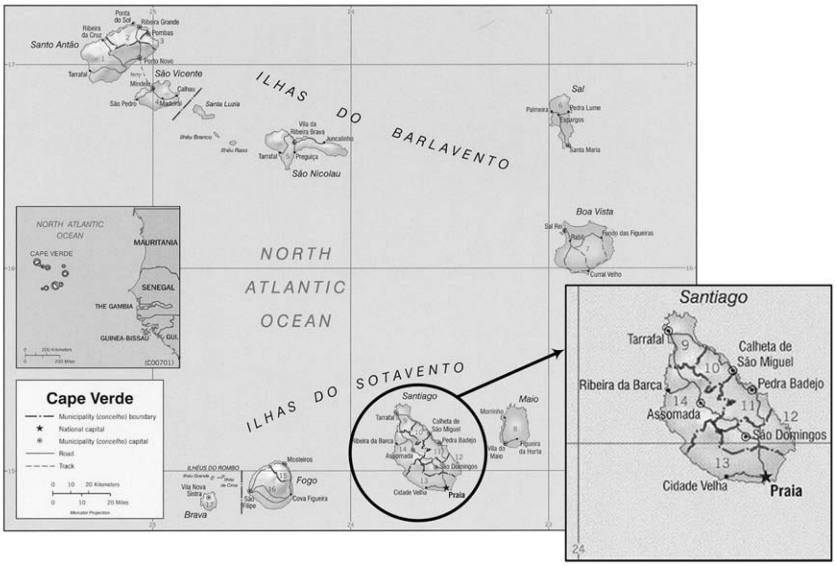

Fig. 1. Situation map of Cape Verde. Detailed map of the island of Santiago.

Expected benefits in the form of waste elimination, substitution of imported fuel as well as the reduction of fuel consumption for MSW transportation are demonstrated in Fig. 2.

This section consists of 5 parts. The first 3 deal with the introduction of a model allowing for the analysis of energy from waste. Part 1 presents an analysis of MSW composition, and estimation of MSW heating value, based on the MSW composition, as low heat value (LHV), in order to determine the total heat input to the proposed incineration plant. The incineration process in terms of required amount of air, excess air to guarantee complete combustion and to comply with the existing constraints under the EU directives on MSW incineration is analysed in Part 2. The determination of the expected energy recovery and the corresponding overall efficiencies for two specified plant configurations accompanied by the analysis of the obtained results is given in Part 3. In Part 4 a brief assessment of the environmental and economic performance for the proposed solution is performed. Finally, Part 5 deals with the application of GIS 3D modelling to determine the optimal routing network that minimises the fuel consumption for transporting the collected MSW from the capital Praia and the remaining municipalities of Santiago Island to an incineration plant located at the municipality of Praia.

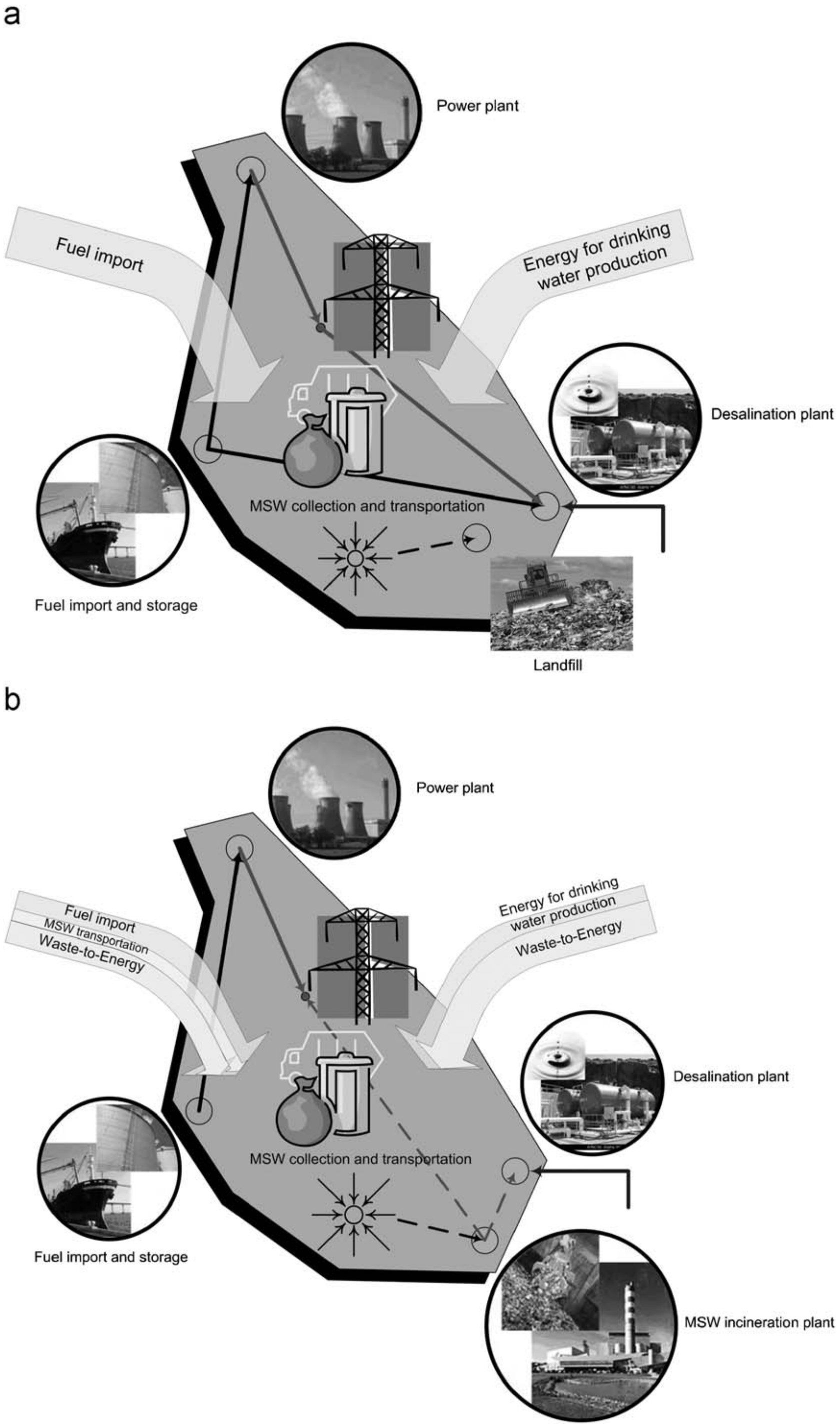

Fig. 2. The energy streams at the island of Santiago: (a) at present and (b) after the construction of the MSW incineration plant and the optimisation of the MSW transportation vehicle routing.

3.1. MSW generation and composition

Knowledge of average MSW physical composition is important to understand the nature of treated waste. Table 1 shows composition of the collected unsorted MSW split in material fractions [18].

The chemical composition of the waste is also very important, as the proximate analysis (ash, volatiles, moisture) and the ultimate (elemental) analysis can be used to assess how the waste will burn in the incinerator and the emissions which are likely to result.

Since the elemental composition of the studied MSW was not available, it was estimated using existing literature sources [19] that are also shown in Table 1.

With regard to heating value, it is estimated for each MSW fraction in the form of LHV using formulas presented by Meraz et al. [19] and Magrinho and Semiao [20]. The final value for the mixture is calculated as a weighted average from LHV of the individual MSW material fractions.

As demonstrated in Table 1, the mean MSW composition is quite different from data usually found in literature. In fact, the analysed MSW comprises much more glass and metals than usual. This can be explained by the fact that there are no mechanisms of recycling to deal with the significant amount of glass or metal packaging material entering the country by import of goods.

Thus, it seems imperative to study the possibility of a partial recovery of glass and metals from the MSW, which are not biodegradable. Moreover, as glass and metals are not combustible components of MSW they do not contribute to overall heat content. Rather, these consume a part of the heat released in the incineration process. Selective collection of waste is not established, and therefore has not been a focus of this study. Furthermore, in order to dimension the system under study, the amount of waste available has to be determined.

As already mentioned above, at present, the administrative districts of the island of Santiago treat the collected waste in each local territory individually. Based on projections for population growth [15] and waste production presented in a study by the Ministry of Infrastructure and Residence [18], the assumed data on the collected waste for the reference year 2008 are given in Table 2. The total amount of waste available for incineration was estimated to be of 75 kt/yr, which results in a capacity for the incineration plant of 10 t/h. In future, as a response to the expecting growth in MSW generation, the expansion of the plant capacity by building additional line(s) can be considered.

3.2. Combustion process

Incinerators primarily used to reduce waste mass have nowadays systems for energy recovery. Modern incinerators can be designed to receive different types of waste using various types of combustion technologies, and are characterised by emissions abatement and pollution prevention systems. In the present work a mass-burn incineration of the unsorted waste in a grate-type incinerator was considered. The mass-burn incineration is one of the most developed and widely deployed forms of MSW thermal treatment. Currently, grate and fluidised bed furnaces are commonly used for waste incineration. The present trend is to utilise grate systems for the combustion of untreated waste, and fluidised beds for the combustion of refused derived fuel (RDF).

In order to evaluate the MSW combustion from the point of compliance with the requirements on the operational conditions and potential recoverable energy, the parameters that have to be determined are analysed below, according to their role in the constructed model.

In such model, the estimation of the total required amount of air for the combustion is based on the assumption of complete oxidation of the combustible components such as carbon, hydrogen and sulphur (C, H, S) of the waste to final products. A part of the combustion air (secondary air) is supplied to the

Table 1
Average physical and elemental composition of MSW (as collected) at Santiago.

Fraction	Composition	Moisture[a] W (wt%)	Elemental analysis (dry basis)[a]						LHV[b] (MJ/kg)
	Wet basis (wt%)		C (wt%)	H	O	N	S	Ash	
Organic (mixed)	27	70	48.0	6.4	37.6	2.6	0.4	5.0	4.04
Paper (mixed)	25	6	43.5	6.0	44.0	0.3	0.2	6.0	14.40
Plastics (mixed)	23	2	60.0	7.2	22.8	0.0	0.0	10.0	25.00
Glass	15	2	0.5	0.1	0.4	0.1	0.0	98.9	0.00
Metals	10	3	4.5	0.6	4.3	0.1	0.0	90.5	0.00
Total	100	21.5	28.1	3.6	19.0	0.3	0.1	27.4	10.40

[a] Values estimated using existing literature sources [19].
[b] Values estimated for each MSW fraction using formulas presented in [19,20].

Table 2
Projection of population and MSW collected from the municipalities of the island of Santiago for the reference year 2008 [18].

Municipality	Population (no. inhabitants)	MSW collected (t/d)	MSW collected (kt/yr)
Praia	134,400	120	37
Santa Catarina	57,900	60	19
Santa Cruz	38,300	25	8
Sao Domingos	14,200	12	4
Tarrafal	22,700	11	3
Calheta	17,400	12	4
Santiago	284,900	240	75

post-combustion chamber to assist mixing of the flue gas rising from the bed and to deliver oxygen to complete combustion.

Due to the nature of untreated MSW mass burning at grate type furnaces, where waste forms a packed bed on the grate, the incinerators normally operate with considerable excess air, with values ranging from 70% up to 100%. Excess air is required to ensure that combustion is complete and that the concentration of carbon monoxide (CO) is minimised. Therefore, the resulting oxygen concentration in the flue gas will be significant, typically ranging from 7% to 10% [21,22].

Furthermore, the amount of excess air will influence the level of the combustion temperature (the temperature of the combustion products) and the composition of the flue gas being, therefore, an important factor in the control of the combustion temperature and in determining the size and design of the heat recovery unit as well as the entire flue gas cleaning system.

The course of the combustion process has to satisfy environmental requirements, since it determines the level of emissions formed during the process. In 2000 the European Parliament adopted a directive on the incineration of waste (2000/76/EC [23]) with stringent regulations on waste incineration, which defines minimum requirements on the plant operation as well as emission limits.

However, due to the nature of MSW, the formation of some pollutants cannot be prevented or completely controlled and the use of additional end-of-pipe equipment is needed.

In order to find the proper value of excess air *m*, while keeping in mind the requirements defined in the above-mentioned EU directive, the following constraints were set for the calculation procedure:

- Minimum temperature of the flue gas set to more than 850 °C to assure elimination of dioxins.
- Maximum temperature of the flue gas set to less than 1050 °C, as above this temperature ash fusion is likely to occur leading to a build-up of slag on the lining refractory material.

In relation to the determination of the flue gas temperature, the heat balance has to be respected taking into consideration the losses. These include heat losses through the walls to the surrounding environment, losses by incomplete combustion represented by the level of carbon in the ash, by the heat trapped in the bottom ash and a part of the heat consumed to heat waste up to reach the ignition temperature. It was assumed that the losses represent 10% of the total thermal energy entering the furnace through the waste [21].

Finally, the sought excess air has to guarantee that the flue gas temperature will remain inside the limits defined in terms of safe destruction of dioxins and furans (minimum) and, at the same time, will eliminate the high thermal stresses of the refractory lining (maximum). In the case that the flue gas temperature is still high for the given oxygen content, an option with the flue gas recirculation is analysed. It is considered that the flue gas is extracted from the gas stream leaving the boiler.

The results obtained by applying the model to treat the MSW from the island of Santiago are presented in Table 3. It can be seen from this table that, in order to comply with all the set constraints, 1.88 of excess air is required (i.e. additional 88% of the combustion air in comparison with the stochiometric conditions), corresponding to 8.8% of O_2 in the flue gas resulting in a flue gas temperature value around 1050 °C.

When the possibility of the flue gas recirculation was analysed, the maximum recirculation rate of some 3.3% has been estimated for the case of 6% of O_2 concentration in the flue gas providing the temperature of 1050 °C.

Table 3
Results of the combustion process analysis.

X_{O_2} (%)	m (-)[a]	Without recirculation		With recirculation		
		T_{FG} (°C)	Δi_{FG} (kJ/kg)	α (%)	T_{FG} (°C)	Δi_{FG} (kJ/kg)
6.0	1.49	1242.6	9392.5	3.29	1051.9	8058.9
6.5	1.54	1208.9	9392.6	2.91	1047.7	8244.4
7.0	1.61	1174.8	9392.6	2.44	1049.2	8486.8
7.5	1.67	1140.2	9392.6	1.96	1049.2	8732.8
8.0	1.75	1105.2	9392.5	1.38	1052.3	9018.4
8.5	1.83	1070.0	9392.5	0.70	1052.6	9290.9
8.8	1.88	1048.2	9392.5	–	1048.2	9392.5

X_{O_2}—Oxygen content in the wet flue gas, m—excess air, T_{FG}—temperature of the flue gas leaving the furnace, Δi_{FG}—change in the flue gas enthalpy, α—flue gas recirculation rate.

[a] (-)—dimensionless.

Usually a proportion of approximately 10–20% by volume of the flue gas can be recirculated [22]. As the 3.3% resulting recirculating rate of the flue gas is not significant, and the required temperatures can be satisfied by controlling the excess air, the results obtained with no recirculation of flue gas were used for the further calculation.

3.3. Energy recovery

As mentioned earlier, Cape Verde experiences shortages both in electricity supply and in drinking water. Therefore, energy recovery by cogeneration offers an effective possibility to contribute a solution to both problems. Taking this fact into consideration, two possible plant configurations are assessed: power production only, and combined heat and power production using heat for seawater desalination.

The energy recovery from combustion is based on the employment of a steam turbine fed by a heat recovery steam generator. The generated superheated steam is considered to be utilised in an actual Rankine power cycle:

- in the case that only power is produced with a simple steam condensing turbine, or
- in the case of cogeneration:
    - ○ a back-pressure turbine linked with a seawater desalination unit, or
    - ○ a condensing turbine with steam extraction for seawater desalination.

The designed operation conditions for the plant under study are provided in Table 4.

3.3.1. Power generation

Leaving the combustion chamber, the flue gas passes through a boiler, which serves as a heat recovery unit for superheated steam generation. The potential recoverable energy, which can be transferred to the steam, is given by the change in the enthalpy of the flue gas between the boiler entering and leaving sections.

The flow rate of the produced steam $\dot{m}_{ST}$ is calculated from the heat balance for the boiler, given by Eq. (1), taking into account requirements on the flue gas temperature as well as the desired values of the steam parameters, as given in Table 4

$$\dot{m}_{MSW} q_{FG} \frac{\eta_{HE}}{100} = \dot{m}_{ST}(i_3 - i_{1,w}). \tag{1}$$

The flue gas is rapidly cooled in the boiler from its entering temperature to some 250 °C [21] before entering the flue gas

Table 4
Designed operating conditions.

Parameter	
MSW flow rate (t/h)	10
Flue gas temperature at the boiler outlet (°C)	250
Efficiency of heat transfer in the boiler (%)	98
Superheated steam temperature (°C)	440
Superheated steam pressure (MPa)	4
Condensing pressure (kPa)	10
Back pressure: MED/MSF (kPa)	30/200
Extraction pressure: MED/MSF (kPa)	30/200
Thermodynamic efficiency of a steam turbine (%)	80
Annual plant availability (%)	90
Reference efficiency for separate power production[a] (%)	25
Reference efficiency for separate heat production[a] (%)	80
Average annual ambient temperature (°C)	25
Seawater water flow rate (m^3/d)	2000

[a] Values adopted from the Directive 2004/8/EC and the Commission decision 2007/74/EC [28,29].

cleaning equipment (in this case comprising a semi-dry scrubber followed by a bag house filter).

3.3.2. *Work of the turbine*

The thermal energy recovered in the form of superheated steam during the waste combustion is utilised in a steam turbine. Considering an actual Rankine cycle, the work done by the turbine can be analysed as follows.

The second law of Thermodynamics limits the efficiency of converting the thermal energy of the steam to mechanical energy. Thus, considering the turbine efficiency during the steam expansion to be 80% and additional mechanical losses, the mechanical energy available on the shaft of the turbine can be calculated as follows:

$$P_{MECH} = \dot{m}_{ST}(i_3 - i'_4). \tag{2}$$

The mechanical energy generated by the steam in the turbine is then converted into electricity.

Due to friction losses in the electric generator and dissipation in the windings the electric output is reduced as

$$P_{EL} = P_{MECH}\frac{\eta_{T-A}}{100}. \tag{3}$$

The thermal treatment process also consumes energy. For MSW incineration it is assumed that around 14% of the electrical power generated is consumed on-site, with a specific consumption around 70 kWh/t of waste incinerated [24]. This is required for operating the cranes and moving grates, fans and pumps, and flue gas treatment equipment.

Then, the electricity output available for exporting is expressed by

$$P_{NET} = P_{EL} - P_{EL,CONSUM}. \tag{4}$$

3.3.3. *Combined heat and power production—cogeneration*

In the case of cogeneration, the utilisation of the steam enthalpy after its expansion (or a partial expansion) in the turbine is considered, otherwise it would be lost in the condenser unit. This recovered heat serves for drinking water production applying thermal seawater desalination technologies.

The parameters of the extracted steam (pressure, temperature and flow rate) are determined by the requirements on the process heat, i.e. by the required temperature and flow rate of the process medium (seawater). A short insight to the applicable thermal desalination technologies is given below.

3.3.4. *Process heat utilisation*

Thermal desalination technologies have been mostly used for desalination of seawater. They are based on distillation process by heating saline water and then collecting the condensed vapour to produce pure water. Commercially available thermal desalination technologies are multi-effect distillation (MED) and multi-stage flash (MSF) [25,26].

MED takes place in a series of vessels called effects and uses the principle of condensation and evaporation at reduced ambient pressure organised in several steps in sequence. It allows the saline water to undergo boiling without the need to supply additional heat after the first effect (with maximum brine temperature limited to 70–80 °C). Operating at low temperature MED has advantages of minimised corrosion and scaling risk, low energy consumption and low operating costs [27].

MSF is a process where the saline water is heated by steam and then passes through a series of stages where reduced pressure leads to immediate boiling (flash) without the need to supply additional heat (operating at limited maximum brine temperature to 120 °C) [27].

The present study analyses the application of both above-mentioned thermal desalination technologies to be linked with the proposed MSW incineration plant.

3.3.5. *Combined heat and power (CHP) plant configuration*

The schemes of the proposed integrated MSW incineration plant are presented in Figs. 3a and b. To satisfy the requirements of the desalination technologies, the outlet steam pressure for the back-pressure turbine was chosen to be 30 kPa with temperature 69 °C and 200 kPa with 144 °C for MED and MSF, respectively. The same conditions were considered for the extracted steam from the extraction condensing turbine for MED and MSF, respectively.

In the back-pressure turbine all the generated steam $\dot{m}_{ST}$ expands up to desired pressure and then condenses in the first stage of the desalination unit transferring the heat to the brine.

The available thermal energy of the subcooled steam after expansion is given by

$$\begin{aligned} P^{BP}_{TH,CHP} &= \dot{m}_{ST}(i'_{4,BP} - i_{1,w,BP}) \\ &= \dot{m}_{ST}[(i_{1,w,BP} + x'_4 l_{F-G}) - i_{1,w,BP}]. \end{aligned} \tag{5}$$

As far as the case of steam extraction is concerned, the required flow rate of the extracted steam can be calculated from

$$\dot{m}_{ST,EXT} = \frac{\dot{m}_{SW}\bar{c}_{p,SW}\Delta T_{SW}}{(i'_{4,EXT} - i_{1,w,EXT})\frac{\eta_{HE}}{100}}. \tag{6}$$

The corresponding thermal energy of the extracted steam is

$$P^{EXT}_{TH,CHP} = \dot{m}_{ST,EXT}(i'_{4,EXT} - i_{1,w,EXT}). \tag{7a}$$

In the case of the subcooled steam, the thermal energy can be expressed as

$$P^{EXT}_{TH,CHP} = \dot{m}_{ST,EXT}[(i_{1,w,EXT} + x'_4 l_{F-G}) - i_{1,w,EXT}]. \tag{7b}$$

The conversion to mechanical power in the CHP plant is determined comprising two parts upstream to and downstream from the point of the steam extraction

$$P_{MECH,CHP} = \dot{m}_{ST}(i_3 - i'_{4,EXT}) + \dot{m}_{ST,DOWN}(i'_{4,EXT} - i'_{4,K}). \tag{8}$$

Finally, in both cases referred, applying Eqs. (3) and (4) the total power $P_{EL,CHP}$ and the net power $P_{NET,CHP}$ can be calculated, including the additional consumption on-site.

3.3.6. *Efficiency of cogeneration*

In order to evaluate the performance of a CHP plant, both the desired outputs, i.e. electrical power and useful heat, must be taken into consideration. A performance criterion for cogeneration

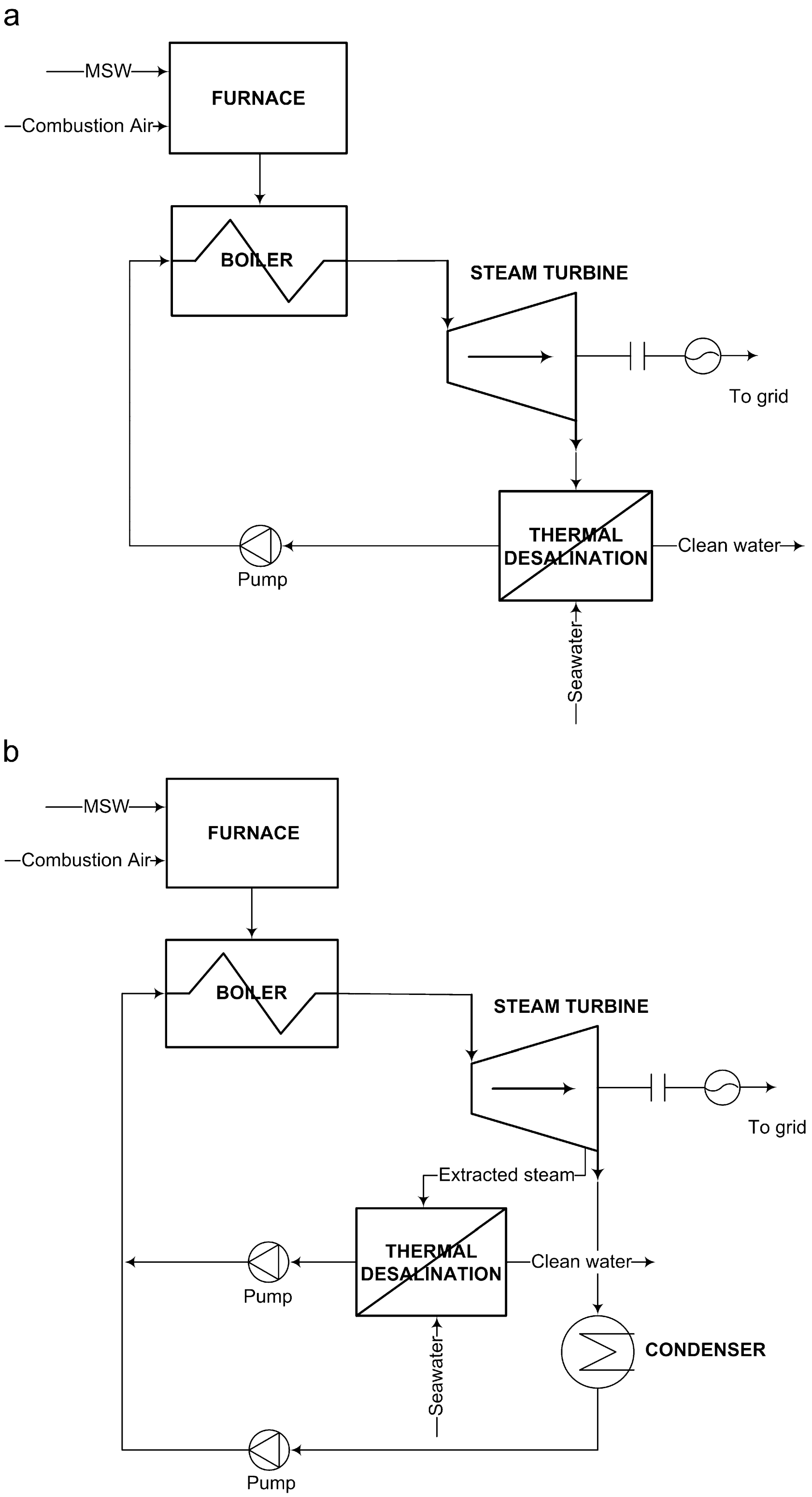

Fig. 3. The schemes of the CHP configurations: (a) the MSW incineration plant linked with a back-pressure steam turbine and (b) the MSW incineration plant linked with an extraction condensing steam turbine.

plants, known as the primary energy savings (PES) [28], is applied and is expressed by

$$PES = \left[1 - \frac{1}{\frac{\eta^{A}_{EL,CHP}}{\eta_{EL,REF}} + \frac{\eta^{A}_{TH,CHP}}{\eta_{TH,REF}}}\right]100. \qquad (9)$$

PES represents the fuel energy saved by using CHP plant when compared to the fuel energy required to run separately the heating plant and the power plant that the cogeneration facility replaces. For the purpose of determining the efficiency of cogeneration according to the above-mentioned directive, the EC recently established harmonised efficiency reference values for separate production of electricity and heat, $\eta_{EL,REF}$ and $\eta_{TH,REF}$ [29]. These reference values take into account the used technology, the year of construction and the types of fuel. According to this, the efficiency reference values for the case of a new MSW incineration plant were selected from the Directive, and are specified in Table 4. Furthermore, the efficiency reference for separated electricity production is later corrected for climate conditions and avoided grid losses.

3.4. *Environmental and economic assessment*

As the community of the island of Santiago continues to grow, the local authorities are constantly challenged by the need to provide an adequate waste management capable of responding to the urgent problems, and, at the same time, to establish a sustainable and systematic treatment of waste. The proposed solution has potential to contribute to this development in several ways demonstrating its beneficial environmental, social and economical dimensions. It may increase employment (assuming the creation of some 35–40 new jobs for the referred size of the plant) and to improve overall standard of living conditions in the community through reduction in air and groundwater pollution, and providing higher accessibility to and availability of two important resources, electricity and drinking water. This can also contribute to stabilisation of their market prices. It is worth mentioning that in Cape Verde, besides the public, most industrial plants are consumers of electricity, since electricity is the energy used for seawater desalination. At the capital Praia the energy needs are significant and growing every year by some 15%, whereby as much as 16% of the energy produced is needed for the production of drinking water by desalination [30].

Also of importance is the public perception of the proposed waste incineration plant and concern over its impact on the community. Although this aspect is hard to quantify, candidness, sincerity, good information and explanation are the means to gain the public support. Nevertheless, it is not expected that the impact of the plant is in anyway negative.

The objective of the assessment presented in this section focused on the estimation of the performance of the proposed MSW incineration plant in terms of environmental burdens, energy balance and economic costs, which can form a good basis for the further decision making. For this purpose the life cycle inventory (LCI) methodology together with the IWM-2 model tool for solid waste management were applied [24].

The functional unit of the LCI was defined in terms of the input to the system under study, the MSW incineration plant with energy recovery, i.e. 75,000 t of the treated MSW for 1 year. In relation to the system boundaries, these have been set to include waste incineration, energy recovery and emission abatement system (flue gas cleaning). Thus, the MSW is taken as the input to the system. Together with the waste, additional energy (electricity, auxiliary fuels) and other materials (limestone, etc.), enter the defined system. In the IMW-2 model indirect energy consumption as well as emissions and waste associated with production of this energy are included. No recycling activities (ferrous metals and bottom ash) were considered for the time being. The outputs are energy produced from waste, airborne emissions and solid residues (bottom ash and fly ash) to be deposited to the respective landfills. Emissions to water are not analysed due to the considered flue gas cleaning system (semi-dry) to be installed allowing for reuse of the released water in the system. Conventional diesel-based energy production that is actually used is assumed to be displaced by the energy recovered from MSW at the island of Santiago. Then, the avoided emissions and resulted solid waste associated with the production of the displaced energy are included in the calculation of air emissions and final residual waste deposited to landfill.

To evaluate MSW incineration in light of resultant GHG, the global warming potential (GWP) methodology [31] was used. It is based on the expression of the emitted GHG in the form of CO_2 equivalent over a 100-year time horizon. MSW, being partially global warming neutral, due to its composition including normally higher fraction of biogenic carbon (from the organic part of waste) than that of fossil origin (plastics, etc.), can result in a net reduction of GHG emissions. Although the combustion of the biogenic part of waste helps to reduce the generation of greenhouse gases, particularly CO_2, consumption of auxiliary fuels during the combustion process should be taken into account.

Moreover, besides avoiding energy production from the fossil fuel (diesel) and hence reducing GHG emissions from its combustion, waste incineration would also divert waste from its disposal to landfill and thus it will avoid generation of landfill gas. Landfill gas, as a result of the anaerobic decomposition of biodegradable fractions of MSW, has a significant global environmental effect since it consists mainly of methane (CH_4) ($GWP = 21$, i.e. the global warming effect of CH_4 is 21-times higher than that of CO_2) and CO_2 ($GWP = 1$). The composition of the gas released varies during the active life of a landfill site due to the type of waste contained and different anaerobic reactions, but usually CH_4 comprises 50–55%, most of the remaining volume being occupied by CO_2. Landfill gas production is expected to average around 200 Nm^3/t of biodegradable waste [24].

In line with the environmental analysis the economic assessment is carried out to demonstrate the feasibility of the proposed system. In general, the economic cost of incineration is considered to be high due to the capital investment required to set up a plant, mainly for the flue gas cleaning equipment installed to guarantee compliance with the strict directives on emissions [23]. As the comparable type of plant does not yet exist in Cape Verde, the capital and operational costs were estimated based on those in Europe for an incineration plant of comparable size. Moreover, the local conditions were taken into consideration (a World Bank loan, payback 30 years, interest 2.5%, salaries). Revenue from sales of the energy recovered from waste can counterbalance the plant expenditure. In order to estimate this revenue a market price for electricity of 12 ECV (the local currency)/kWh (0.109 €/kWh) was assumed. The same price has been applied for sales of the generated steam.

Keeping the objective of covering the MSW incinerator expenses rather than generating profit two scenarios are investigated. *Scenario* 1 assumes only capital and operational costs to define the cost of incineration resulting in 70 €/t of MSW treated, while *Scenario* 2 considers the expected average revenue from the generated energy sales during the calculation of the incineration cost resulting in 20 €/t of MSW treated.

3.5. *Optimisation of MSW transportation*

The efficiency of an integrated management system that is able to solve problems related to vehicles circulation in road networks can be measured through its capacity to obtain optimised routes. For a system of MSW transportation, this consists of generating an optimal route for a given vehicle so that the value of the selected cost criterion is minimised.

When assessing the optimal routing, the shortest travelled distance has been the most commonly used optimisation criterion [10,11]. However, engine performance and efficiency are also influenced by the roads slope, resulting in a variation of the engine power requirement and, thus, yielding different fuel consumptions and released emissions [13,14]. Therefore, it appears to be compelling to take the effect of the road slope into account when determining the fuel consumption of trucks transporting MSW.

Related to this it should be mentioned that Santiago is a very mountainous island and is characterised by areas with considerable variations of the relief of the terrain resulting in significant gradients of the path roads. The highest point is Pico d'Antonia situated at 1394 m over the sea level, located at the central part of the island. These facts make evident the need to consider the road networks gradients to calculate the optimised fuel consumption of the waste transportation fleet. For that, the model developed by Tavares et al. [14] is applied in this study establishing optimal routes for waste transportation with the minimum fuel consumption. In order to allow for the comparison and to demonstrate the effect of the road inclination on fuel consumption the optimisation calculations for the MSW transportation vehicle routing are done considering both the shortest distance and the lowest fuel consumption criteria.

At this moment there is neither an incineration plant nor transfer stations at Santiago and the collected waste is directly deposited to the local landfills. Therefore, the incineration plant location used in the work is the one planned by the Cape Verde government and mentioned earlier in Section 2 and transportation of the waste from all six municipalities directly to the incineration plant is assumed.

In relation to the vehicles used for waste transportation, trucks of 12 t capacity are considered and the average vehicle speed is assumed to be 30 km/h.

Considering these figures and those displayed in Table 2 for the waste collection, the number of trips for day required is straightforward: for Praia, as the projection of waste collected is 120 t/d, it is necessary to perform 10 trips to the incineration plant. The transportation frequency is 6 days per week.

The obtained waste transportation routes optimised for the shortest distance are shown in Fig. 4a and those optimised for the lowest fuel consumption in Fig. 4b.

4. Discussion of results

The thermodynamic model presented in this study was developed with the aim to evaluate the potential to incinerate MSW for energy recovery simply for electricity production or for a combined production of electricity and heat with application for isolated communities.

Table 5 shows the results obtained for the simple condensing steam cycle, where electricity production sent to grid reaches 4.7 MW at the overall plant efficiency 16.1%.

Table 6 exhibits the results for the CHP configuration with a back-pressure turbine, where all the steam leaving the turbine is used as process steam in a thermal desalination plant instead of being cooled down in a condenser. It is evident that significant savings in primary energy can be achieved for the MED thermal desalination technology analysed as its PES value is 24.9%, being quite above 10%, which is the lower limit established by Directive 2004/8/EC [28] for CHP units to be recognised for high-efficiency cogeneration production. Savings of 11.1% were obtained for MSF technology. The desalination units can produce up to 6650 and 5540 m^3 of drinking water per day by the MED and MSF technologies, respectively. Related to electricity production, in both previous cases, there is a certain penalty in comparison with the simple condensing steam cycle (see Table 5) and this is due to the back-pressure conditions. Comparing MED and MSF, the linkage with the MSF desalination gives lower electricity output

Table 5
Production of electricity in a simple condensing steam cycle.

Q_{MSW} (MW)	m_{ST} (t/h)	P_{EL} (MW)	η_{EL} (%)	$P_{EL,CONSUM}$ (MW)	P_{NET} (MW)	η_{NET} (%)
29	23.1	5.4	18.5	0.7	4.7	16.1

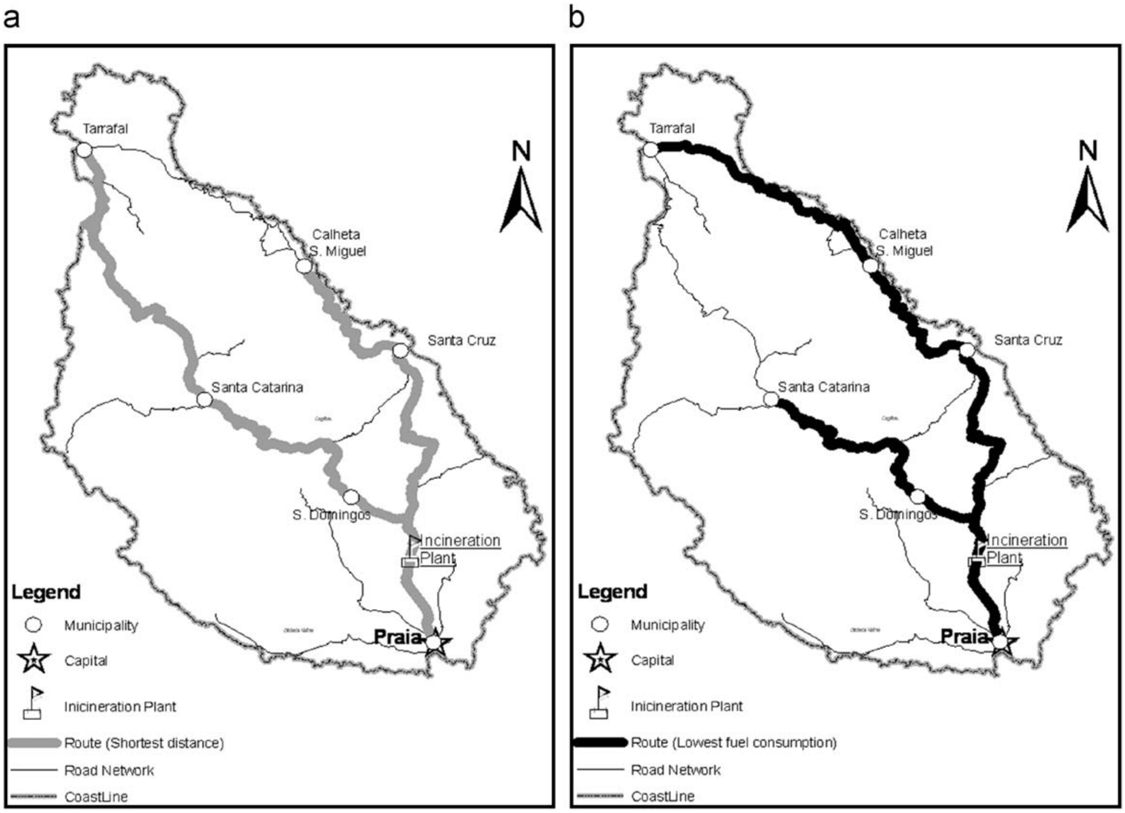

Fig. 4. A spatial distribution of the municipalities and the location of the incineration plant with the optimised waste transportation routes: (a) the transportation routes optimised for the shortest distance and (b) the transportation routes optimised for the lowest fuel consumption.

for the same energy input since this technology has a higher thermal demand.

Table 7 shows the results obtained for the CHP configuration with a condensing turbine, where the process steam is extracted from the turbine in a certain stage to satisfy the requirements of the desalination plant. For desalination plant capacity of 4000 m^3 of dinking water per day, the CHP does not bring savings in primary energy (PES equal 3.8%) when using MSF. In contrast, PES reaches 11.2% when the MED is employed. Therefore, to ensure the overall optimisation of the plant, the capacity of the desalination plant has to be optimised as well. If the desalination unit capacity is increased to 5000 m^3/d, the CHP can bring savings of some 16.9% when integrating MED and 8.7% when integrating MSF. It should be noted that if the extraction condensing turbine expands all the steam for electricity generation (which means that heat is not used for desalination), this corresponds to the case presented earlier (see Table 5). On the other hand, if all the heat is extracted for desalination this corresponds to the back-pressure turbine case study displayed in Table 6.

Electricity production is once more penalised in both MED and MSF cases in comparison with the simple electricity production given in Table 5. However, such penalty is smaller than that in the case of the back-pressure turbine. Again comparing MED and MSF, the use of MSF desalination yields lower electricity output for the same energy input.

The back-pressure architecture of the plant allows full exploitation of the thermal energy of the steam leaving the turbine, which means that the power output is not a priority and the plant is designed for the maximisation of the desalination unit capacity. This is also in line with the fact that back-pressure cycles are used mainly for constant heat output applications.

The extraction condensing turbine allows for greater operating flexibility due to the partial independence of the power output from the steam generation. Thus, it can be implemented in cases when the demand for electricity has to be satisfied.

Due to this higher flexibility of the extraction condensing turbine, it seems better to combine MSF with it in the CHP, rather than with back-pressure turbine, as MSF requires higher parameters of the heating steam.

MED seems to be more suitable for combination with a back-pressure turbine as it requires lower parameters of the process steam. In this case the higher capital investments to the heat exchanger can be compensated by higher drinking water and power production.

Based on the results obtained from the analysis of the plant from an energy recovery potential perspective, two representative cases were selected for the environmental-economic assessment: (1) power case—power generation from MSW and (2) CHP case—cogeneration (employing a back-pressure turbine) supplying heat for seawater desalination by the MED technology.

As shown in Table 8, the amount of energy generated from the waste in the form of electricity or electricity and steam combined with the energy entered to the system results in a net energy production. It is evident that in both cases as the energy recovered, some 34.8 and 137 GWh (including process steam) for the power and CHP case, respectively, exceeds the energy consumed within the system (5.3 GWh), there can be an export of the excess production, 29.5 GWh for the power and 131.8 GWh for the CHP. This yields a yearly thermal energy generation by the system of 391 and 1747 TJ for the power and for the CHP case, respectively.

With regard to airborne emissions it can be said that, in general, a significant net reduction can be achieved for all relevant pollutants (PM_{10}, CO, NO_x, SO_x, HCl or heavy metals) as demonstrated in Table 9. For GHG emissions, when recovering energy from the MSW only as electricity the emissions increased by 57 kt of CO_2 equivalent, whereas the CHP plant gives the possibility to a considerable decrease resulting in a net reduction by 33 kt of CO_2 equivalent. It is estimated that for the analysed cases landfill diversion rates from 70% up to 72% of the input

Table 6
Performance of CHP with a back-pressure turbine steam cycle.

Desalination technology	m_{SW} (t/h)	V_{SW} (m^3/d)	$P_{EL,CHP}$ (MW)	$P_{EL,CONSUM}$ (MW)	$P_{NET,CHP}$ (MW)	$P_{TH,CHP}$ (MW)	PES (%)
MED	277	6650	4.7	0.7	4.0	14.3	24.9
MSF	230	5540	3.3	0.7	2.6	14.5	11.1

Table 8
Energy balance.

Parameter	Electricity	CHP
Overall efficiency (%)	16.1	63.0
Energy produced (GWh)	−34.8	−137.0
Energy consumed on-site (GWh)	5.3	5.3
Net energy (total energy consumption/production) (GWh)	−29.5	−131.8
Thermal energy (TJ)	−391.0	−1746.8

Negative numbers represent generation or savings.

Table 9
Net emissions to air.

Emissions to air	Electricity	CHP
Air pollutants		
PM_{10}-particulates (t)	−11.1	−49.5
CO (t)	−6.6	−29.3
NO_x (t)	−57.7	−257.8
SO_x (t)	−274.3	−1223.5
HCl (t)	−0.3	−1.3
HF (t)	0.0	0.0
Dioxins/furans (t)	0.0	0.0
Heavy metals (Cd, Hg, Ni, As, Pb, Cr, Cu, Mn) (t)	−0.1	−0.7
Total (t)	−350.1	−1562.1
Global warming potential (GWP)		
GHG emissions (t_{CO_2}eq)	57,000	−33,000
Final solid waste to landfill (t)	22,900	21,200
Landfill diversion rate (LDR) (%)	70	72
Avoided GHG emissions from MSW landfilling (t_{CO_2}eq)	−95,239	−98,316

Negative numbers represent savings.

Table 7
Performance of CHP with a condensing steam cycle with steam extraction.

Desalination technology	m_{SW} (t/h)	V_{SW} (m^3/d)	$m_{ST,EXT}$ (t/h)	$m_{ST,DOWN}$ (t/h)	$P_{EL,CHP}$ (MW)	$P_{EL,CONSUM}$ (MW)	$P_{NET,CHP}$ (MW)	$P_{TH,CHP}$ (MW)	PES (%)
MED	166	4000	14.0	9.2	5.0	0.7	4.3	8.6	11.2
	208	5000	17.4	5.7	4.9	0.7	4.2	10.8	16.9
	250	6000	20.8	2.3	4.7	0.7	4.0	12.9	22.0
MSF	166	4000	16.6	6.4	3.9	0.7	3.2	10.4	3.8
	208	5000	20.8	2.3	3.5	0.7	2.8	13.0	8.7

waste can be achieved (see Table 9), which represents additional reduction in GHG emissions by 95–98 kt of CO_2 equivalent.

The economic analysis shows that, for the given incineration cost of 70 €/t_{MSW} (*Scenario* 1), the resulted revenue (€3.8 million) does not cover all the plant expenses (€5.3 million) for the power generation case as presented in Table 10. On the contrary, the CHP shows significant savings (€9.8 million). The negative total cost is obtained due to a quite high price of electricity, even it has been set as a conservative value (assumed to be constant during the plant life time).

In *Scenario* 2 (incineration cost of 20 €/t_{MSW}), the total cost expresses a double gain (€2.3 million and €13.5 million for the power and CHP cases, respectively): firstly, from energy sales and, secondly, from avoiding the production of the same amount of energy using conventional technologies.

As far as the optimisation of the MSW transportation vehicle routing is concerned, as demonstrated in Figs. 4a and b, a different route is only generated for waste transportation from the Tarrafal municipality when the optimisation criterion was switched from the shortest distance to the lowest fuel consumption. In fact, while the route passing the central hilly part of the island is chosen by the model when optimisation for the shortest distance is performed (see Fig. 4a), the major part of the route optimised for the minimum fuel consumption follows the eastern coastal line having a moderate variability of the elevation, and thus, the roads with lower gradients. The numerical results presented in Table 11 for this case show that the value of fuel consumption was reduced by some 11% (from 58.4 to 52.1 kg/trip or 18.2 to 16.3 t/yr), which implies a similar percentage reduction in vehicles emissions, while the distance travelled was slightly longer (from 124 to 125 km/trip or 38,752 to 39,018 km/yr).

Overall, considering MSW transportation vehicles circulation from all the municipalities of Santiago, the fuel consumption decreased by 4.3% per total daily trip (from 147.8 to 141.5 kg) representing 1.9% savings in fuel per year (from 102.2 to 100.2 t).

Table 10
Cost balance.

Cost items	Scenario 1		Scenario 2	
	Electricity	CHP	Electricity	CHP
Incineration cost (€/t_{MSW})	70.0	70.0	20.0	20.0
Expenditure (€ million)	5.3	5.3	1.5	1.5
Revenue (energy sales) (€ million)	−3.8	−15.0	−3.8	−15.0
Total cost (€ million)	0.7	−9.8	−2.3	−13.5

Negative numbers represent savings.

As discussed above, although savings in fuel consumption were observed they were not particularly significant (some 1.9% on the annual basis), which is due to the fact that the actual road network for this specific case of Santiago Island does not allow for more alternative roads to be considered.

5. Conclusions

Many island communities often face problems of insufficient energy resources resulting in high transportation prices of imported fuels. In addition, shortage of such vital important commodity as drinking water can occur. The long-term development of island communities generally requires the need to take into account alternative ways to traditional fuels in order to reduce their dependence on energy imports. Therefore, locally available energy resources are essential for their sustainable development, which is also a case of generated MSW that can be thermally treated by incineration combined with energy recovery. Cape Verde is one of the countries facing these problems.

The results obtained in this study show that application of MSW incineration as a treatment alternative for the solid waste in Cape Verde is feasible and, in addition to providing the elimination of waste, represents also a considerable potential energy resource. The recovered energy can be further utilised for power generation or even in a more effective way in a combined production of power and heat, where the heat is used in thermal units for drinking water production by seawater desalination.

CHP with back-pressure steam turbines can desalinate 5540 m^3/d of seawater with MSF technology and 6650 m^3/d with MED with an additional power production of 3.3 and 4.7 MW, respectively. For both cases, PES is quite above the minimum 10% required to be considered as a highly efficient CHP process.

CHP with extraction condensing steam turbines are able to produce more electricity (4.9 MW for MED), at the expense of reducing the amount of heat for seawater desalination.

The environmental and economic assessment of two selected configurations of the MSW incineration plant showed the feasibility of the proposed CHP solution resulting in a considerable reduction in net emissions to air (1.6 kt), significantly decreasing the net GHG emissions (131 kt of CO_2 equivalent) and, at the same time, demonstrating the potential to compensate the high incineration cost due to the revenue from energy sales (€15 million).

Moreover, although savings in fuel consumption were not substantial in the case under the study (total savings of 1.9% for year), it can be concluded that both the terrain relief and the route optimisation through fuel consumption minimisation may be important factors for the management of waste transportation

Table 11
Results for the optimised waste transportation routes from the Santiago municipalities to the incineration plant.

Municipality	Number of trips		Optimisation criterion							
	(trips/d)	(trips/yr)	Distance				Fuel consumption			
			Total distance		Total fuel consumption		Total distance		Total fuel consumption	
			(km/trip)	(km/yr)	(g/trip)	(kg/yr)	(km/trip)	(km/yr)	(g/trip)	(kg/yr)
Praia	10	3120	16	51,012	5070	15,818	16	51,012	5070	15,818
Santa Catarina	5	1560	61	95,222	28,923	45,120	61	95,222	28,923	45,120
Santa Cruz	2	624	44	27,325	18,315	11,429	44	27,325	18,315	11,429
Sao Domingos	1	312	16	4833	6495	2026	16	4833	6495	2026
Tarrafal	1	312	124	38,752	58,432	18,231	125	39,018	52,121	16,262
Calheta	1	312	74	23,057	30,587	9543	74	23,057	30,587	9543
Santiago	20	6240	335	240,201	147,822	102,167	336	240,467	141,511	100,198

vehicles and, therefore, for overall energy planning. In fact, when terrain relief made a difference, as in the case of waste transportation from Tarrafal to the incineration plant, 11% of savings were achieved through the route optimisation for the minimum fuel consumption taking road slope into account.

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