# COST-BENEFIT ANALYSIS OF A WASTE TO ENERGY PLANT FOR MONTEVIDEO; AND WASTE TO ENERGY IN SMALL ISLANDS

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# EXECUTIVE SUMMARY

This thesis consists of two parts. The first is a cost-benefit analysis by the author of a waste to energy (WTE) plant in Montevideo, Uruguay; the second part is a description of WTE projects in various islands, some of which have succeeded and some are in various phases of implementation.

**Part 1: Cost-Benefit Analysis of a WTE Plant for Montevideo**

In May-September 2011, the Earth Engineering Center of Columbia University investigated the waste management system of Montevideo, Uruguay. The first part of this thesis describes the contribution of the author to this study. The results of this study showed that building a WTE plant in Montevideo would help the city and Uruguay advance in sustainable waste management, as Montevideo has a fairly good waste management system that can warrantee the daily delivery of certain amount of wastes to the WTE plant.

The study showed that the best-suited thermal treatment technology for Montevideo is grate combustion of as received waste. The reasons are that it is the most proven waste-to-energy technology in the world, has demonstrated high plant availability (>90%), and is easy to learn how to operate.

The scenario examined in this thesis was the construction of a WTE plant consisting of two parallel furnaces each combusting 40 tons of waste per hour, at 90% plant availability (8,000 hours per year), that is, a total of 640,000 tons of solid wastes per year.

Montevideo, in 2010, landfilled around 850,000 tons of waste. Therefore, the WTE plant will be able to handle 75% of the waste landfilled in 2010. The site selected for the plant is within the property of the existing landfill that serves Montevideo. The capital investment required to build the facility was estimated at US$420 million, and the operating costs at US$22 million per year.

The WTE plant will export to the grid 0.6 MWh of electricity per ton of waste incinerated, that is, 380 GWh of electricity per year. This electricity generation will translate into approximately US$35million revenues per year for the plant.

The next most important revenue source for the plant will be the gate fee, which currently is US$16/ton, in average, for waste disposal in Montevideo’s landfill. Other revenue sources for the WTE plant could be sale of metals recovered, and carbon credits.

According to the financial analysis presented in this study, if the government owns the plant, in order to maintain the current gate fee of US$16/ton, and recover the capital investment over the payback period of 23 years, the cost of capital for this plant should

be lower than 3.1% including revenues from carbon credits. If the cost of capital for the government is 6%, then, in order to recover the capital investment over the 23 years, the gate fee must be increased to at least US$25/ton, including the revenues from carbon credits. An option for improving the economics of the plant would be for the government to obtain a grant or a low rate loan from an international organization.

If the plant is privately owned, the cost of capital will most likely be higher than for the government. The financial analysis showed that for a cost of capital of at least 10%, without subsidies or grants, the gate fee should be US$50/ton. Also, if the gate fee is to be maintained at the current US$16/ton, the subsidy or grant needed is at least 40% of the capital cost. It is believed that both of these scenarios are unlikely and, therefore the project will not be feasible under private ownership.

However, if the city can reduce appreciably the current very high MSW collection and transportation costs, such reduction could be transferred to the WTE plant, and the economics would improve.

Moreover, when building a WTE plant, there are other obstacles to overcome besides the financing of the plant. In particular, in Montevideo, two other challenges that must be taken into account are public opposition, and the large scavengers' population.

## Part 2: Waste-to-energy in small Islands

Rapid economic development and also population growth of urban centers in developing island nations have resulted in the generation of large amounts of MSW that in the past were dumped at uninhabited areas indiscriminately. Also, islands have very limited space for new, sanitary landfills.

This study examined islands where WTE has been implemented successfully (Bermuda, Martinique, St. Barth) and others (Jamaica, Mauritius, Rhodes) where WTE has been considered and is in various stages of implementation.

The study showed that the per capita generation of MSW increases as GDP per capita increases. Also, it is usually recommended to improve the waste management system one step at a time, that is, to go from non-sanitary landfills, to sanitary landfills, and then to waste to energy. It is interesting to note that the three islands examined in this study went directly from dumps to WTE. This phenomenon can be partly attributed to the scarcity of land for new landfills, but may also be due to the desire to develop a local and renewable energy source.

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# PART 1: COST-BENEFIT ANALYSIS OF MONTEVIDEO WTE

## 1. INTRODUCTION

The Oriental Republic of Uruguay (Uruguay) is situated in South America. Its capital city, Montevideo, concentrates 41% of the country's population in 0.3% of its surface area. Montevideo also concentrates most of Uruguay's economic resources, as most of the business transactions take place here (services, industries, and commerce). In terms of waste management, as one would expect, around 52%[1] of the Municipal Solid Waste (MSW) generated in Uruguay is generated in Montevideo.

Wastes that reach the formal systems in Montevideo (which are not all the wastes generated) are currently discarded in a landfill that is transitioning from non-sanitary to sanitary. Moreover, the wastes that do not reach the formal waste management system, and that are not recycled or re-used, are disposed indiscriminately in open fields and water basins, or burned. Therefore, although there is some aerobic composting, and recycling (mostly informal) done in Montevideo, waste management in this city is mainly placed in the lowest two steps of the hierarchy of sustainable waste management (Figure 1).

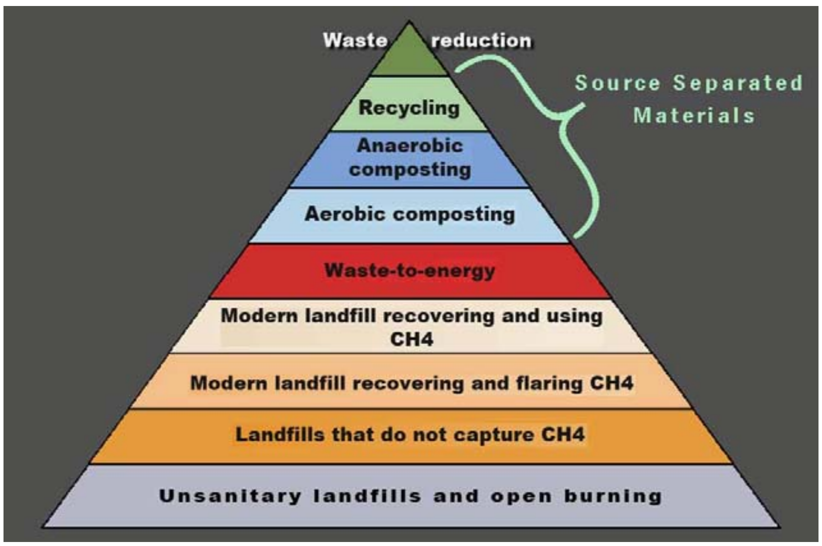


**Figure 1, Hierarchy of sustainable waste management[2]**

Building a waste-to-energy (WTE) facility to treat at least part of the wastes currently landfilled in Montevideo could help the city, and the country, to advance in sustainable waste management.

The objective of this study is to compile and analyze information on the current waste management system of Montevideo and to analyze the operating cash flows, under different scenarios, of a 2-line WTE plant with the capacity of treating 640,000 tons of waste per year. The purpose of this analysis is to obtain general guidelines for the financial feasibility assessment of the plant.

## 2. BACKGROUND ON URUGUAY AND MONTEVIDEO

The Oriental Republic of Uruguay (Uruguay) is located in South America; it borders with Brazil in the north and west, with Argentina in the north and east, and with the Atlantic Ocean in the south (Figure 2). It has a population of 3.24 million (2004)[3] and a GDP of US$48 billion (US$13,700 per capita, taking into account purchasing power parity)[4]. It is one of the smallest countries in South America, with a surface area of 176,000 km$^2$. The economy has been traditionally based in agriculture product exports (beef, soybeans, cellulose, rice, wheat, wood, wool, dairy products) but in recent years, other industries have grown (food processing, electrical machinery, transportation equipment, petroleum products, textiles, chemicals, beverages). Most of the population enjoys sanitation services and potable water. The country has a high literacy rate (98% of the population over 15 years of age can read and write), and there is a relatively even income distribution.


**Figure 2, Location of Uruguay within South America[5]**

Uruguay is politically divided in 19 municipalities, and the municipality of Montevideo is its capital city. Montevideo is located in the south of the country (Figure 3), and it comprises 41% of the country's population in 0.3% of its surface area (Table 1).

**Table 1, Population and surface area[3]**

| Region | Population (million) | Area ($km^2$) |
|---|---|---|
| **Uruguay** | 3.24 | 176,065 |
| **Montevideo** | 1.33 (41% of total) | 530 (0.3% of total) |


**Figure 3, Location of Montevideo within Uruguay[6]**

Montevideo is the largest city in the country. As capital of Uruguay, it is the economic and political center of the country, housing most of its largest companies. It concentrates 77% of the industries in the country, 53% of its electricity and water, 63% of construction, 53% of commerce, restaurants and hotels, 67% of transportation and communications, and 70% of its services[7].

## 3. WASTE MANAGEMENT IN MONTEVIDEO

In Uruguay, each municipality has its own government and manages its waste independently. Therefore, collection, transportation, and disposition of waste, are all responsibility of the municipality. Nevertheless, there are agreements between municipalities regarding waste management. For example, some of the industrial wastes generated in other municipalities are currently disposed in Montevideo's landfill.

## 3.1. MUNICIPAL SOLID WASTE (MSW)

### 3.1.1. MSW GENERATION

The MSW in Montevideo that reaches the landfill is estimated at around 80% of the MSW generated. This is because there are a large number of informal collectors ("clasificadores") who scavenge MSW. They sell part of the waste they collect, either for re-use, for recycling, or as food waste for pig feeding. Most of their non-usable residue goes back to the formal waste management system, but part is either discarded indiscriminately in open fields and water basins, or burnt.

In 2010, 773,834 tons of wastes were disposed in Montevideo's landfill, Felipe Cardozo[8].

### 3.1.2. MSW CHARATERIZATION

The latest characterization study of MSW in Montevideo was carried out in 2003. The values obtained are shown in Table 2 below.

**Table 2, Composition of MSW 2003 and calorific value**

| Material | % In MSW[9] | Calorific value* | | Contribution to calorific value (MJ/kg) |
|---|---|---|---|---|
| | | BTU/lb | Mj/kg | |
| **Plastics** | 1.20% | 14,101 | 32.80 | 0.39 |
| **Plastics (rigid)** | 0.80% | 18,687 | 43.47 | 0.35 |
| **Film** | 9.90% | 14,101 | 32.80 | 3.25 |
| **Plastic bottles** | 2.00% | 18,687 | 43.47 | 0.87 |
| **Glass** | 3.40% | 84 | 0.20 | 0.01 |
| **Textiles** | 2.10% | 7,960 | 18.51 | 0.39 |
| **Ferrous metals** | 1.30% | 0 | 0 | 0 |
| **Non ferrous metals** | 0.20% | 0 | 0 | 0 |
| **Paper** | 8.30% | 6,799 | 15.81 | 1.31 |
| **Cardboard** | 2.20% | 7,042 | 16.38 | 0.36 |
| **Hazardous/toxic** | 0.30% | 0 | 0 | 0 |
| **Organics** | 58.00% | 1,797 | 4.18 | 2.42 |
| **Wood** | 0.60% | 6,640 | 15.44 | 0.09 |
| **Leather, rubber, bones** | 0.60% | 9,195 | 21.39 | 0.13 |
| **Diapers** | 5.20% | 2,199 | 9.81 | 0.51 |
| **Composite materials** | 1.00% | 4,600 | 10.70 | 0.11 |
| **Inert materials** | 2.10% | 0 | 0 | 0 |
| **Other** | 0.80% | 4,600 | 10.70 | 0.09 |
| **Total** | **100.00%** | **4,417** | | **10.27** |

*Value estimated using Handbook of WM, Tchobanoglous[10].

### 3.1.3. MSW COLLECTION

Most of the MSW generated in Montevideo is disposed in containers (Figure 4) that are emptied daily, although in some areas manual collection is still practiced. The municipality or companies under contract to the municipality carry out collection.


**Figure 4, Montevideo MSW container**

Manual collection is done in compacting trucks with a capacity of 14 $m^3$, and containers are emptied using 25 $m^3$ trucks. Waste collection is not very efficient and costs are high (Section 3.5).

## 3.2. INDUSTRIAL WASTE

Industrial waste disposal in Montevideo is not well regulated. While some industries dispose their waste in Montevideo's landfill, most have their own clandestine dumpsters, or, to less extent, burn their waste illegally. The Plan Director[11], a thorough study on waste management in Montevideo's metropolitan area carried out in 2004, estimated that the amount of industrial waste generated in the metropolitan area of Montevideo (which includes parts of two other municipalities) in 2003 was 293,000 tons, most of which was generated in Montevideo. According to information provided by the National Environment Agency (DINAMA), the amount of industrial waste landfilled in Montevideo's landfill in 2009 was 84,451 tons[12], that is, only 28% of the industrial waste generated in the entire metropolitan area in 2003. These numbers illustrate the lack of regulations regarding industrial waste disposal. In the future, if a WTE plant is built, industries that dump or burn their waste illegally could be forced to dispose at the WTE at a gate fee, which would help the economics of the plant and facilitate acceptance of the WTE by community.

Nevertheless, most of the industrial waste currently disposed at Montevideo's landfill could be incinerated in the WTE plant. Table 3 shows the characterization of the waste disposed at Montevideo's landfill in 2009. The items marked "No" are not suitable for incineration due to their low calorific value.

**Table 3, Industrial waste characterization (2009)**

| Type of waste | Amount (tons/yr.) | Percentage |
|---|---:|---:|
| Urban | 18,075 | 21.4% |
| Dust with hydrocarbons | 13,244 | 15.7% |
| Sludge | 10,421 | 12.3% |
| Dust with combustibles | 6,573 | 7.8% |
| Leather | 4,446 | 5.3% |
| Construction – No | 3,501 | 4.1% |
| Hospital | 3,409 | 4.0% |
| Slag – No | 3,285 | 3.9% |
| Grease | 2,187 | 2.6% |
| Food | 1,925 | 2.3% |
| Animal hair | 1,662 | 2.0% |
| Leachate – No | 1,252 | 1.5% |
| Office sweepings | 1,030 | 1.2% |
| Metals – No | 991 | 1.2% |
| Wood | 729 | 0.9% |
| Clay – No | 700 | 0.8% |
| Dust | 572 | 0.7% |
| Medicines | 460 | 0.5% |
| Bones and wool | 419 | 0.5% |
| Ash – No | 303 | 0.4% |
| Paper | 285 | 0.3% |
| Sulfuric acid residue | 257 | 0.3% |
| PVC | 200 | 0.2% |
| Tires | 167 | 0.2% |
| Marble – No | 162 | 0.2% |
| Textiles | 109 | 0.1% |
| Yard | 100 | 0.1% |
| Other | 7,990 | 9.5% |
| **Total** | **84,451** | **100.0%** |

The total of items not suitable for incineration in the WTE plants add 10,196 tons. Therefore, the industrial wastes suitable are about 74,258 tons per year.

Regardless of the WTE plant, Montevideo's landfill does not have special cells for disposing hazardous waste. For this reason, the government has planned to build a safety cell in the landfill for this purpose. The industrial hazardous wastes to be disposed in this cell are wastes generated in the industries in Table 4 below.

**Table 4, Hazardous waste**

| Industry | Amount of waste (Ton/yr.) |
|---|---|
| Auto parts | 450 |
| Chemical | 2,333 |
| Electricity | 128 |
| Metallurgy | 7,700 |
| Painting | 19 |
| Petroleum | 2,000 |
| Plastic | 1,594 |
| Tannery | 29,731 |
| **Total** | **43,955** |

## 3.3. HOSPITAL WASTE

Hospital waste management in Montevideo is private. It is all currently treated in a sterilization plant owned by the company “Aborgama”[13].

Waste is disposed in thick red plastic bags. Sharp objects are disposed in rigid plastic containers. Waste is then transported in 120-liter containers (1 m high by 0.6 m in diameter), with an average weight of 15 kg (max. 25 kg). The plant treats approximately 25,000 containers/month (approximately 4,500 t/y), using two autoclaves that treat the waste for 30 minutes at 150°C. The treated waste is then landfilled in Montevideo’s landfill, which is almost adjacent to the sterilization plant (Figure 11).

All the containers and trucks used by the plant, are washed and disinfected with ozone and peroxide, and all the wastewater produced is treated (it produces approximately 30 $m^3$/y of sludge).

In the future, these wastes could be combusted in a WTE plant, but presently, due to the small amount of these wastes, it may not be worth breaking the contracts with the private companies.

**Figure 5, Medical waste bags and autoclave**

## 3.4. WASTE DISPOSAL SITES

### 3.4.1. THE MONTEVIDEO LANDFILL

The Felipe Cardozo landfill is the only landfill in Montevideo. It receives all the waste generated in Montevideo and some industrial wastes from other municipalities of the metropolitan area of Montevideo. A staff of 50 employees operates it.

The total land area is 121.3 ha, divided as follows:

- Cell 5: 22.7 ha.
- Cells 6 and 7 (Figure 6): 29.5 ha (closed; cell 6 operated 1990-2006; cell 7 operated 1995-2006; the city has plans to collect and flare methane from these cells).
- Cell 8 (Figure 7): 18 ha (this cell has 4 sub-cells, two of which are closed. This is the only cell that is sanitary; a PVC geo-membrane is being used to protect the soil).
- Infrastructure and others (51.1 ha.):
  - New cells (in construction) using 16 ha that they estimate that it will fill in 5 years (Figure 8).
  - New office.
  - Leachate treatment pools (in construction).
  - Weighing zone with two 60-ton weighing scales (in construction - Figure 9).
  - A cooperative for waste separation, which employs around 70 clasificadores.
  - Unused land.

**Figure 6, Standing on cells 6 and 7**

**Figure 7, Cell 8**

**Figure 8, New cells (in construction)**

**Figure 9, Scales (in construction)**

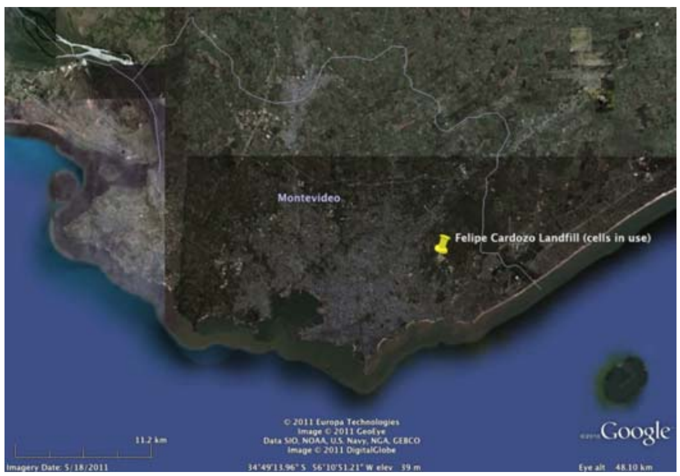


**Figure 10, Location of Felipe Cardozo landfill within Montevideo**


**Figure 11, Felipe Cardozo landfill aerial view**

### 3.4.2. COMPOSTING FACILITY

Montevideo has a composting plant called TRESOR (Figure 12). TRESOR treats waste from markets (vegetable waste) and industries (e.g. gelatin capsules from pharmaceutics, hair from leather industry). In the future, TRESOR wants to include leafs swiped from streets.

Market waste is separated manually in the composting facility, and industrial waste is source-separated. Composting is done aerobically in open windrows in a field; waste is treated separately according to its origin. Vegetables degrade in 3-4 months and other materials take from six months to one year. The capacity of the plant is 10,000 tons per year, and the goal is to increase it to 50,000 tons by 2015. The composting plant has two ponds for collecting and treating leachate. The compost characteristics are: 25% organic matter; Ph: 7.9; C/N = 10.

The gate fee for wastes received is about US$28/$m^3$. The compost product is sold at US$45/$m^3$. However, the plant has problems selling all the compost produced, and is trying to get contracts from industries.

The land size of the property is 42 ha, of which only 20 ha are used (including planned expansion).

**Figure 12, Composting piles**

## 3.5. SOLID WASTE MANAGEMENT COSTS

Solid waste management costs in Montevideo are as follows:

- MSW collection: US$128/ton[14].
- MSW disposal cost (Felipe Cardozo): US$15/ton[14].
- In addition to this MSW, the following wastes are landfilled at Felipe Cardozo:
    - Small amounts of waste (transported in vans or cars). Received any time, disposal is for fee.

- Construction waste. Received through a controlled area, also for free.
- Commercial and industrial waste. It is weighted and may be disposed in the "arriving" area or directly in the cell. The gate fee is about $29 per ton.

## 3.6. INFORMAL RECYCLING

It is estimated[11] that, in Montevideo, clasificadores (Figure 13) collect 40% of the MSW, of which 30% is re-used or recycled, and the remaining 70% is discarded. Of the 70% discarded, approximately 70% (20% of total MSW) goes back to the formal system, and 30% (8% of total MSW) is dumped in open fields or water basins, or burned illegally.

Collected materials are sold for recycling, sold in fairs for reuse or discarded. Collected organics are used for proprietary animal feeding, sold for pig feeding, or discarded.

The tonnage sold and prices obtained for the recyclables sold in 2004 are shown in Table 5.

**Table 5, Tonnages of recyclables sold in 2004[11]**

| Material | Tons recycled | Percentage of total |
|---|---|---|
| Glass | 2,756 | 2% |
| Aluminum | 1,814 | 1% |
| Copper | 1,574 | 1% |
| Bronze | 2,217 | 2% |
| Iron | 23,703 | 16% |
| Paper and cardboard | 53,690 | 36% |
| Plastics | 3,440 | 2% |
| Organics | 58,366 | 40% |
| **Total** | **147,560** | **100%** |

Table 6 shows the prices obtained for some of the recyclable materials in 2011, for materials sold by individuals and by groups of clasificadores.

**Table 6, 2011 prices of recyclable materials sold[15]**

| Material | Individual sale | Group sale |
|---|---|---|
| | US$/ kg (national average 2011) | |
| **Paper** | 0.10 | 0.14 |
| **Cardboard** | 0.07 | 0.10 |
| **PET (white)** | 0.27 | 0.35 |
| **PET (green, other)** | 0.22 | 0.28 |
| **Glass bottle** | 0.23 | 0.29 |
| **Nylon (clean)** | 0.21 | 0.27 |
| **Copper cables** | 3.53 | 3.91 |
| **Aluminum** | 0.78 | 0.86 |
| **Junk** | 0.06 | 0.07 |
| **Organics (2004)** | 0.06 | 0.08 |

Using the tonnage per material collected, as reported by the Plan Director[11], updating prices for the waste materials, and considering that there are about 6,000 families of clasificadores, the author estimated that the average income per family is around US$550 per month. The national minimum wage in Uruguay is US$324[16], since families of clasificadores have, in average, 5 members, and in most of the cases more than one member of the family is dedicated to scavenge, the income per clasificador is likely to be below the minimum wage. This means that in an effort to employ clasificadores, for example, in a materials recovery facility, meeting or even improving their salary expectations may not be difficult.

Montevideo started a pilot program for single-line recycling by installing waste disposal containers of two colors: gray for disposable MSW, and orange for specified recyclable materials. This program has not been as successful as the government would like, because clasificadores scavenge the recyclables, and also some materials from the disposable MSW bins (clothes, toys, food for pig feeding). There are also some containers in the city for glass recycling (Figure 14).

**Figure 13, Clasificador at work**

**Figure 14, Glass recycling container**

### 3.7. WASTE WATER MANAGEMENT

Montevideo has a wastewater pre-treatment plant that has been in operation for 20 years (Figure 15).

The plant has a capacity of 5 $m^3$/sec., it treats between 80% and 90% of the wastewater of Montevideo (approx. 2.5 $m^3$/sec in dry season and 4.5-5 $m^3$/sec in rainy season). Only 30% of the water that reaches the plant is separated (rainwater and wastewater); the rest arrives through a combined collection system.

The plant consists of a series of filters and pools to separate solids from liquids (there is no chemical treatment). The final effluent is discharged into the La Plata River at a distance of 2.3 kilometers from the shore. The solids are transported to the landfill (5-6 $m^3$/day; estimated less than 3,000 tons per year) by truck.

There is a laboratory adjacent to the plant that takes samples from the different bays to monitor the quality of the water.

**Figure 15, Wastewater treatment plant (WWTP) filters and ponds**

A new WWTP is under construction and is scheduled to start operations in 2015. It will have a capacity of 4.5 $m^3$/sec. It will cost US$160 million and it is being financed by The InterAmerican Development Bank (IDB). This plant will have chemical treatment, and will treat the wastewater that the existing plant cannot treat. In particular, it will treat the wastewater of a refinery that is currently discharged directly into the river.

## 4. WTE PLANT CAPACITY

The WTE plant to be considered in this financial analysis is a two-furnace (2 line) facility with the capacity of treating 40 tons/hr. per line, with 90% availability (8,000 hours of operation per year), that is, 640,000 tons/year.

The amount of waste that could be treated in the WTE facility is the waste that is guarantied to reach the formal system, that is, the waste that is currently landfilled.

In summary, the total amount of waste landfilled in 2010 in Montevideo was:

**Table 7, Solid wastes landfilled in Montevideo in 2010**

| Source | Amount | Percentage |
|---|---:|---:|
| Montevideo MSW | 773,834 | 91% |
| Montevideo industrial* | 74,258 | 9% |
| **Total** | **848,092** | **100%** |

* This number could be considerably higher

Therefore, the WTE plant will be able to treat 75% of the waste landfilled in 2010.

Moreover, according to the 2003-2010 projections in the Plan Director[11], the amount of MSW generated in Montevideo in 2010 would be 649,700 tons, which is 16% lower than the 773,834 tons of MSW that were actually landfilled in 2010. The same projections estimate the MSW to increase another 5% from 2010 to 2015, 5% from 2015 to 2020, and 6% from 2020 to 2025.

The amount of waste generated in Montevideo will most probably increase with growing population and increasing GDP per capita. Uruguay's population growth rate is 0.23%, with an urbanization rate of 0.4%[4]. Uruguay's GDP real growth rates of the last three years were 8.5% in 2010, 2.6% in 2009, and 8.6% in 2008[4]. Therefore, the generation rates projected in the Plan Director are conservative, but reasonable.

Applying the estimated waste growth rates of the Plan Director to the current amount of waste landfilled, and assuming the same growth rate for the periods 2025-2030 and 2030-2035 than for 2020-2025 (i.e., 6%), the projected amount of waste that will reach the formal system for these years is:

**Table 8, Projected waste in the formal system**

| Year | Growth rate | Amount of waste (tons/yr.) |
|---|---|---|
| 2010 | | 848,092 |
| 2015 | 5% | 890,497 |
| 2020 | 5% | 935,021 |
| 2025 | 6% | 991,123 |
| 2030 | 6% | 1,050,590 |
| 2035 | 6% | 1,113,625 |

These projections imply that the increase in the amount of waste that reaches the formal system in the 25 years from 2010 to 2035 will be equivalent to 31% of the amount landfilled in 2010, and therefore, that in 2035, the plant will treat 60% of these wastes.

## 5. WTE PLANT TECHNOLOGY

The best-suited technology for the WTE plant analyzed in this financial study is Grate Combustion (also known as Mass Burn). The advantages of this technology are:

- It is the most **proven technology** in the world, since 600 of the over 800 WTE plants in the world are grate combustion.
- **High plant availability**: Grate combustion plants nowadays have 90% availability.
- **Simplicity of operation:** Most of the process is automatized; the only exception is the crane operation.
- **Low personnel requirements:** Grate combustion plants require between 30 and 60 people to operate (depending on the size) and the training of unskilled personnel is fairly easy. In comparison, Felipe Cardozo landfill has 50 employees (Section 3.4.1).

**DESCRIPTION OF GRATE COMBUSTION PROCESS:**

Figure 16 shows the drawing of typical grate combustion WTE plants.

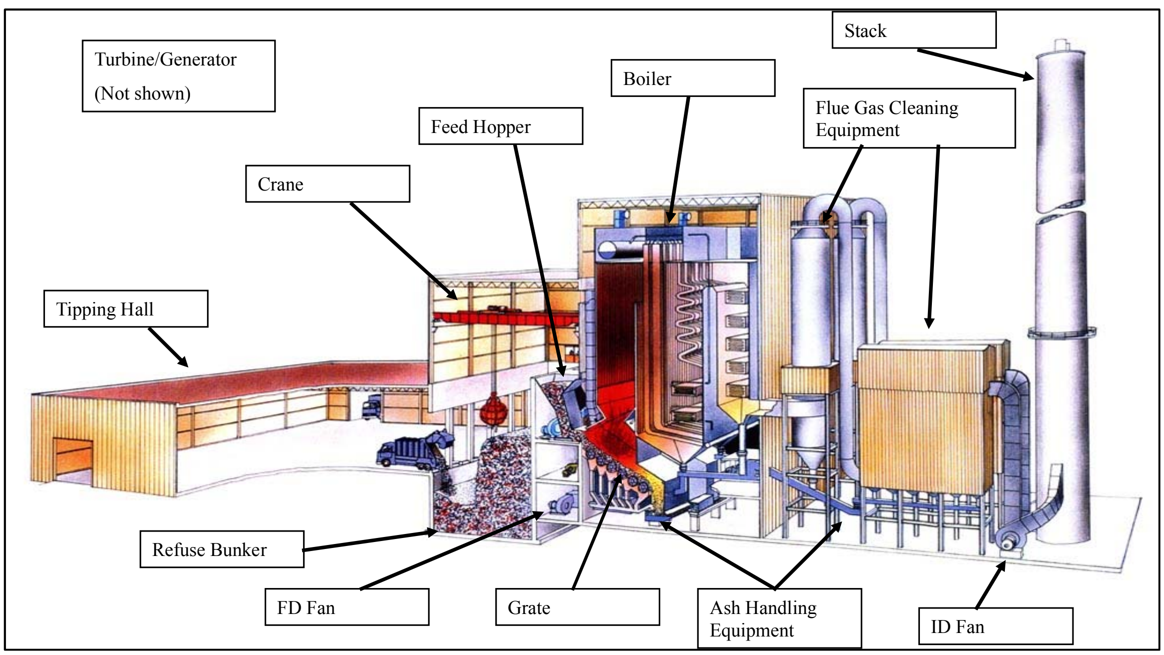


**Figure 16, Grate combustion WTE plant**[17]

In grate combustion plants, trucks enter the receiving area, which is kept closed and at negative pressure to avoid odors leaving the building. MSW bags and other wastes are discharged into the waste bunker, which is typically large enough to hold over a week's feedstock. Overhead claw cranes (capable of holding about 3 tons) load the solids into the feed hopper of the WTE furnace, and a ram feeder at the bottom of the hopper pushes the wastes onto the moving grate that can be inclined or horizontal. The mechanical motion of the grate, and gravity force in the case of an inclined grate, move the wastes through the combustion chamber. The grate is 3-12 meters wide, depending on the furnace capacity, and approximately 8 meters long; the average temperature of the boiler is between 1,000°C and 1,200°C, and in average, the wastes take one hour to pass through the grate. The high temperature oxidation in the combustion chamber reduces objects as large as a suitcase, to ash that is discharged at the lower end of the grate. The furnace height above the grate is about 20 meters so that the combustion gases travel 4 to 8 seconds within the combustion chamber. In many WTE facilities, urea or ammonia is injected into the boiler to lower nitrogen oxides emissions.

Water in tubes in the walls of the boiler becomes superheated steam as heat contained in the combustion gases is transferred. This high-pressure steam drives a turbine that generates electricity. The low-pressure steam from the generator exhaust can be used for district heating. The most efficient WTE facilities are co-generators of electricity (>0.6 MWh) and district heating (> 0.5 MWh per ton of MSW processed).

Gases are cleaned in an Air Pollution Control (APC) system before being released into the atmosphere. APC systems in WTE plants are amongst the most advanced of all high-temperature industrial processes. They consist of urea or ammonia injection (already mentioned), dry or semi-dry scrubbers with calcium hydroxide of $SO_2$ and HCl, injection of activated carbon for adsorbing organic and volatile metal molecules, and fabric filter (baghouse) for the removal of particulate matter.

Emissions from grate combustion WTE facilities nowadays comply with the European pollution standards, which are some of the most stringent in the world (Table 9).

**Table 9, European emission standards**[18]

| Parameters | European Limits (11% $O_2$; mg/$Nm^3$) |
|---|---|
| Fly Ash | 10 |
| TOC | 10 |
| HCL | 10 |
| HF | 1 |
| $SO_2$ | 50 |
| $NO_x$ | 200 |
| Cd+ Ti | 0.05 |
| Hg | 0.05 |
| Sb | 0.5 in total |
| As | |

| | |
|---|---|
| Pb | |
| Co | |
| Cr | |
| Cu | |
| Mn | |
| Ni | |
| V | |
| Dioxins and Furans (TEQ) | 0.1 ng/Nm³ |
| CO | 50 |

Ash from the APC (fly ash) and form the incinerated wastes (bottom ash) are equivalent to 1-2% and 20-25%, respectively, of the wastes incinerated by weight. These ashes are usually mixed and used as landfill cover, as the mix is inert. Bottom ash may have other uses, such as road construction. The problem with giving bottom ash other uses than landfill cover is that if fly ash is not mixed with bottom ash, it has to be stabilized before disposing in a landfill due to its contaminant contents.

## 6. PUBLIC PERCEPTION OF WTE

The international experience has been that the general public many times misconceives the concept of WTE by association with indiscriminate burning, and past incineration practices, when no air pollution controls were in place. Therefore, WTE is many times perceived as a highly polluting, and hazardous to health technology.

Public opposition due to this misconception has been so strong in some places in the world that it has brought WTE projects to failure. In particular, in Montevideo, some years ago, there was an initiative to build a hospital waste incinerator, and the project failed due to public opposition.  For this reason, it is of outmost importance to educate the public in WTE, and inform how the environmental impacts of WTE are lower than the impacts of landfills and many other industrial processes.

This education campaign should start during the planning phases of the project and, if possible, it is recommended to involve citizen group leaders who can better transmit the benefits of WTE, and how, by building such plant, Uruguay would be advancing in sustainable waste management.

Moreover, the facility should have a visitors' center for students and general public to visit and learn about sustainable waste management, and renewable energy.

# 7. WTE PLANT COSTS

## 7.1. CAPITAL COSTS

The capital cost of the plant in Montevideo was estimated at US$420 million. This estimate was done on the basis of similar capacity recently built plants, assuming that the WTE technology has a high quality design with grate-fired furnace, empty vertical passes and a vertical boiler followed by a semi-dry flue gas cleaning and a 75m-80m stack. Since capital costs are very dependent on world steel price indices and on various local factors, the estimate is expected to be within +/- 20% accuracy.

## 7.2. OPERATING COSTS

The estimated operating costs (also within plus or minus 20% accuracy) are of US$22 million per year.

This estimate assumes a staff of 43 employees (25 operative staff, 8 technical staff, 8 administrative staff, 2 executive staff), and it also assumes that ash will be mixed (bottom and fly), and then used as landfill cover at the Montevideo landfill. Moreover, bottom ash and fly ash are equivalent to 20-25% and 2-3%, respectively, of the waste incinerated (by weight). Therefore, the average amount of ash for the proposed plant in Montevideo would be about 150,000 tons/yr.

# 8. WTE PLANT REVENUES

## 8.1. ELECTRICITY SALE

The sale of electricity is one of the most important revenue sources of WTE facilities. The following parts of this section show the estimated electricity generation and price for the proposed facility in Montevideo.

<u>ESTIMATED ELECTRICITY GENERATION</u>

According to section 3.1.2, the calorific value of MSW is 10.27 MJ/kg, that is, 2.85 MWh/ton. Assuming that the heat losses in the furnace, ash, and stack gases are 10%, then the heat in the steam entering the turbine is equivalent to 2.6 MWh per ton of waste. Assuming a temperature of 400°C and pressure of 40 bar, the thermal efficiency of the WTE turbine is estimated at 28%. Therefore 0.7 MWh of electricity will be produced per ton of waste incinerated. However, it is estimated that the plant will consume 15% of this electricity, which implies that 0.6 MWh/ton will be exported to the grid. Since the plant is expected to process 640,000 tons/y, the net electricity output of the proposed plant is estimated at 380 GWh.

ESTIMATED PRICE OF ELECTRICITY

The installed capacity in Uruguay is 2,700 MW (57% hydro, 32% fossil, 9% biomass, 1% wind). The national goal is to reach the level of 50% renewable energy and 25% renewable electricity by 2015. With this goal in mind, the Energy Agency has issued a decree approving 20-year Power Purchasing Agreements (PPA) with biomass energy generators, category under which the WTE could fall.

The price of electricity produced by these kinds of endeavors is around US$92/MWh, which is the price that will be used in this study.

Regarding the sale of by-product steam, since:

- There is no district heating in Montevideo.
- There is no steam commercialization in Montevideo.
- Producing steam for sale implies producing less electricity.

For purposes of this study, it will be assumed that the turbine will produce as much electricity as possible, and the by-product low-pressure steam will be cooled.

## 8.2. GATE FEE

Gate fee is the payment that the WTE plant collects per ton of waste received. This fee is usually also collected by landfills. In the case of MSW, the fee is usually charged to citizens similarly to other services (such as electricity and water) or in the form of taxes, or the government subsidizes it. In the case of industrial waste, it is usually charged as the waste is received.

In Montevideo, only industrial and commercial waste generators pay a gate fee, and fees are subsidized for the reminder of the waste generators. Accordingly with section 3.5, the current disposal costs in Montevideo are US$15/ton for MSW, and US$29/ton for industrial and commercial waste.

WTE gate fees are usually higher than landfill gate fees, because waste disposal in WTE plants is more expensive due to its superiority in sustainable waste management, which translates into higher capital costs. However, in the long run, WTE plants have shown to be more economical than landfills, especially in places with land scarcity.

For MSW in countries where waste services are subsidized, as it is the case of Uruguay, the government has to decide whether to continue subsidizing the increased gate fee, or to start charging citizens for the service (fully or partially). If the second alternative is selected, then the willingness of the citizens to pay has to be studied (e.g. through surveys) to guarantee the plant income, to avoid incentivizing illegal dumping or burning, and to prevent public opposition to the WTE plant.

Regarding industrial wastes, it is recommended not to increase the gate fee, as doing so may encourage illegal dumping or burning. Moreover, as mentioned before, to help the plant income and to improve waste management in Montevideo, it is recommended to reinforce penalties for illegal dumping and burning of industrial wastes.

## 8.3. CARBON CREDITS

Combusting MSW in WTE plants instead of landfilling it, decreases carbon emissions in approximately 0.5 to 1 ton of carbon dioxide equivalent (depending on the type of landfill, and the efficiency of landfill gas recovery systems) due to the following factors:

- MSW typically contains about 30% carbon, two thirds of which are of biogenic origin (paper, wood, food wastes, etc.).
- Using MSW as fuel reduces the amount of fossil fuel used (anthropogenic origin).
- Diverting MSW from landfills reduces the amount of methane emitted by landfills, and one molecule of methane emitted to the atmosphere is equivalent to 21 molecules of carbon dioxide.

Uruguay, as a non-Annex I country of the Kyoto protocol, could qualify to issue carbon credits (Certified Emission Reductions – CERs) from the $CO_2e$ emissions avoided by the WTE plant through the Clean Development Mechanism (CDM). CERs are currently trading between US$12 and US$20.

In Montevideo, since the business as usual scenario for the waste would be to be disposed in Felipe Cardozo landfill, which does not recover landfill gas, 1 ton of $CO_2e$ would be avoided per ton of waste incinerated. Therefore, the WTE plant in Montevideo could receive an additional income from carbon credits of between US$12 and US$20 per ton of waste, depending on the price of CERs. In this study, a price of US$12 will be assumed.

## 8.4. METALS SALE

The portion of ferrous and non-ferrous metals can be recovered from the bottom ash of the WTE plant is about 50% and 8%, respectively[19]. According to section 3.1.2, the percentages of ferrous and non-ferrous metals in Montevideo's MSW are 1.30% and 0.20%, respectively. Therefore, the amount of ferrous and non-ferrous metals recoverable is equivalent to 0.65% and 0.02% of the waste processed by the WTE plant.

The prices of recycled aluminum and copper in Uruguay are around US$0.8/kg and US$3.7/kg, respectively (Table 6). Since aluminum is much more abundant in waste than copper, and because there are other non-ferrous metals present in MSW, for purposes of this study, it will be assumed that the non-ferrous metals recovered from the WTE plant can be sold at an average of US$1/kg.

According to the construction materials price list of the Ministry of Transport and Public Works[16], the prices of steel and iron bars are US$2.6/kg and US$2.5/kg, respectively. Since recycled ferrous metals are less expensive than virgin metal, for purposes of this study, it will be assumed that the ferrous metals recovered from the WTE plant can be sold at one fourth the price of steel and iron bars, that is US$0.6/kg.

## 9. FINANCIAL ANALYSIS

The financing capital structure of a project (percentage of debt, percentage of private and/or public capital, and percentage of subsidies and/or grants, among others), and the cost of capital for each part of the structure are defined by the business model selected for the plant. Therefore, the usual approach would be to design a business model, and then develop the financial analysis.

However, the author finds difficult to select a business model for the specific case of Montevideo, because there are no WTE plants in Uruguay, and therefore no evidence on how a WTE plant could be financed in Montevideo. With this in mind, the author believes that the best approach is to develop a simple financial analysis, without assuming any business model.

This means that the financial model takes into account all the operational costs and revenues of the plant, but does not take into account possible financing costs such as interests or dividends. Moreover, the model does not consider changes in prices or costs of the different inputs (electricity, salaries, etc.), due to inflation or any other factor; and also, the model is in US dollars, which is not the currency of most of the cash flows. Therefore, the results should be interpreted only as very general guidelines for the financial feasibility assessment of the plant.

The model consists of a combination of calculations of Net Present Value (NPV) and Interest Rate of Return (IRR) of the net operating cash flows (revenues minus expenses). NPV is the calculation of the present value of the net cash flows, discounted at the cost of capital of the project, and the IRR is the discount rate at which the NPV equals zero. Therefore, if the cost of capital equals the IRR, the project will break even operationally; if the cost of capital is higher than the IRR the project will have operational loses (i.e. the

NPV will be negative); and if the cost of capital is lower than the IRR, the project will have operational earnings (the NPV will be positive).

Since the cost of capital of this project is not available, the IRR can be used as guideline for what the cost of capital should be in order for the project to be profitable (or break even). However, calculating the NPV can contribute to the analysis, since it can be used to determine limits to what certain parameters (such as the gate fee) should be for the project to break even. It is important to keep in mind that once financing costs are included, both, the NPV and the IRR, will decrease; and also, that the model can be considerably sensible to variations in the different items due to factors such as inflation.

Under a public ownership model, the plant is not expected to be financially attractive; it is only expected break even. That is, the NPV of the project is expected to be zero, or equivalently, the cost of capital equal to the IRR. However, the government may decide to build the plant even if it has loses, for reasons such as lack of space for a new landfill, or desire to advance in sustainable waste management.

Contrary to the case of public ownership, under a private ownership model, the plant needs to be financially attractive, that is, the NPV has to be positive (or equivalently, the cost of capital lower than the IRR).

It is estimated that it would take approximately 38 months to build the plant, and that it would be operational for at least 20 years without having to do any mayor refurbishing. Therefore, the payback period used in the financial analysis will be of 23 years.

Since the cost of capital for the calculation of NPV is not available, current levels of Uruguay government bonds in US$ with maturity in approximately 23 years will be used as guideline.

There are two USD bonds issued by the Government of Uruguay currently trading in the international markets that mature in approximately 23 years. That is, January 2033, and March 2036. The yields of these bonds, as of October 5, 2011, were 6.10% for the 2033 bond, and 6.12% for the 2036 bond[20]. Therefore, the cost of capital of the government of Uruguay will be assumed at 6% in USD, and the cost of capital of private investors to be higher than 6%. For illustration purposes, examples of NPV calculation with 6%, 10% and 13% discount rate will be provided.

Carbon credits are difficult to originate due to all the stringent requirements and long scrutiny processes that the project has to go through. Therefore, it would not be realistic to assume that the plant is certain to receive an income from carbon credits. For this reason, this analysis will present scenarios including revenues from carbon credits, and scenarios without these revenues.

Moreover, many times, for these plants to be feasible without increasing the gate fee too much, subsidies or grants are needed. Therefore, this analysis will also include cases where the plant is partially subsidized.

Since the current MSW, and industrial waste gate fees are US$15/ton, and US$29/ton, respectively, the weighted average of these fees (US$16/ton) will be used as the reference gate fee in this analysis.

Table 10 below shows a summary of proposed plant characteristics, and materials generation and recovery; Table 11 a summary of its costs; and Table 12 a summary of its revenues.

**Table 10, Proposed plant characteristics, and materials generation and recovery**

| Item | Amount |
|---|---|
| Capacity per line | 960 tons/day |
| Number of lines | 2 |
| Total capacity | 640,000 tons/yr. |
| Net electricity generation | 0.6 MWh/ton |
| Ash generation | 0.24 tons ash/ton waste |
| Ferrous metals recovered | 0.0065 tons metal/ton waste |
| Non-ferrous metals recovered | 0.0002 tons metal/ton waste |

**Table 11, Proposed plant costs**

| Item | Total cost (million US$) | Cost per ton (US$/ton) |
|---|---|---|
| Capital | 420 | 656 |
| Operating | 22 (annual) | 34.4 |

**Table 12, Proposed plant revenues**

| Item | Price | Revenue per ton (US$/ton of waste) | Annual income (million US$) | % of total (with carbon credits) |
|---|---|---|---|---|
| Electricity sale | US$92/MWh | 54.63 | 34.96 | 63.0% |
| Ferrous metals sale | US$600/ton of metals | 3.90 | 2.50 | 4.5% |
| Non-ferrous metals sale | US$1,000/ton of metals | 0.16 | 0.10 | 0.2% |
| Carbon credits | US$12 | 12.00 | 7.68 | 13.8% |
| Gate fee (reference fee) | US$16/ton of waste | 16.00 | 10.24 | 18.5% |
| **Total without carbon credits** | | **74.69** | **47.08** | **-** |
| **Total including carbon credits** | | **80.69** | **55.50** | **100%** |

Scenario 1

This scenario assumes that there are no subsidies or grants in place.

The IRR for gate fees from US$0 to US$80 with and without income from carbon credits (CC) are shown in Table 13 and Figure 17 below.

**Table 13, IRR for different gate fees (no subsidies or grants)**

| Gate fee | IRR without carbon credits | IRR including carbon credits |
|---|---|---|
| 0 | -2.55% | 0.83% |
| 10 | 0.33% | 3.12% |
| 20 | 2.69% | 5.11% |
| 30 | 4.73% | 6.90% |
| 40 | 6.56% | 8.55% |
| 50 | 8.23% | 10.08% |
| 60 | 9.78% | 11.53% |
| 70 | 11.25% | 12.90% |
| 80 | 12.63% | 14.21% |

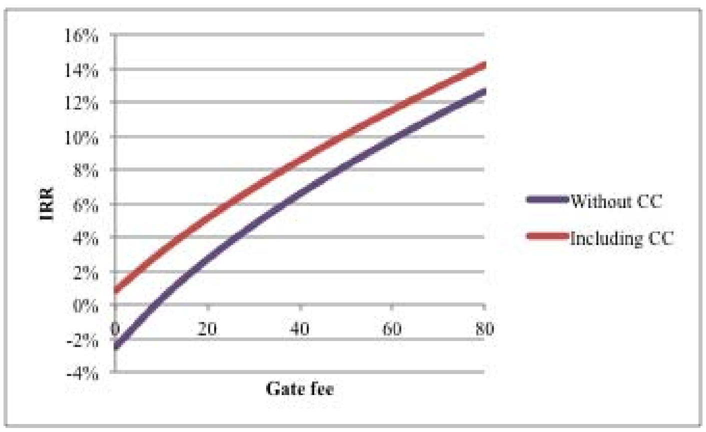


**Figure 17, IRR for different gate fees (no subsidies or grants)**

These calculations show that, at the current gate fee of US$16/ton, the IRR is lower than 6% (the cost of capital of the government) and therefore the NPV, at any discount rate equal to or higher than 6%, is negative. This means that the project would not be feasible if privately owned, and if publicly owned, the government would have to consider that the investment cost would not be recovered in the 23-year period that was assumed in this analysis.

In particular, the NPV at 6%, 10%, and 13% discount rates, and IRR at a gate fee of US$16/ton are:

**Table 14, NPV and IRR at US$16/ton gate fee (no subsidies or grants)**

| | Without carbon credits | Including carbon credits |
|---|---|---|
| IRR | 1.8% annual | 4.3% annual |
| NPV (6%) | - US$127 million | - US$54 million |
| NPV (10%) | - US$183 million | - US$134 million |
| NPV (13%) | - US$204 million | - US$167 million |

The gate fees required for the NPV to be zero at 6%, 10% and 13% discount rates are shown in Table 15 below.

**Table 15, Gate fee required for NPV = 0 (no subsidies or grants)**

| Discount rate | Gate fee (US$/ton) | |
|---|---|---|
| | Without carbon credits | Including carbon credits |
| 6% | 37 | 25 |
| 10% | 61 | 49 |
| 13% | 83 | 71 |

In conclusion, if the WTE plant is publicly owned, then the government should decide whether to:

- Maintain a gate fee of US$16/ton and assume that part of the capital investment will not be recovered in the payback period.
- Increase the gate fee to at least US$37/ton in the case that there is no income from carbon credits, or at least US$25 if the plant revenues include carbon credits.

If the second alternative is selected, the increase in gate fee could be subsidized by the government or charged to the population.

If the government decides that charging part of the gate fee to the citizens is not an option, then the decision between increasing the gate fee or assuming that part of the capital investment will not be recovered, is just a matter of deciding where (in which government entity) to register the loss.

On the other hand, if there are private investors involved in the WTE plant project, then the gate fee will need to increase to at least US$49/ton if carbon credits are issued, or to at least US$61/ton if carbon credits are not issued, if the cost of capital is 10% or higher.

Another alternative would be for the plant to be partially subsidized by means of a grant. If the plant is fully or partially publicly owned, it could receive a grant from a multilateral organism such as the InterAmerican Development Bank (IADB) or the International

Financing Corporation (IFC). If the plant is privately owned, it could also receive a subsidy from the government.

The following scenario shows IRR and NPV calculations for the case in which part of the capital is subsidized.

Scenario 2

This scenario assumes that 30% of the capital cost is subsidized.

The IRRs for gate fees from US$0 to US$80 with and without carbon credits are shown in Table 16 and Figure 18 below.

**Table 16, IRR for different gate fees (30% subsidy or grant)**

| Gate fee | IRR without carbon credits | IRR including carbon credits |
|---|---|---|
| 0 | 0.44% | 4.26% |
| 10 | 3.68% | 6.88% |
| 20 | 6.38% | 9.20% |
| 30 | 8.75% | 11.31% |
| 40 | 10.90% | 13.26% |
| 50 | 12.88% | 15.09% |
| 60 | 14.74% | 16.83% |
| 70 | 16.49% | 18.49% |
| 80 | 18.16% | 20.07% |

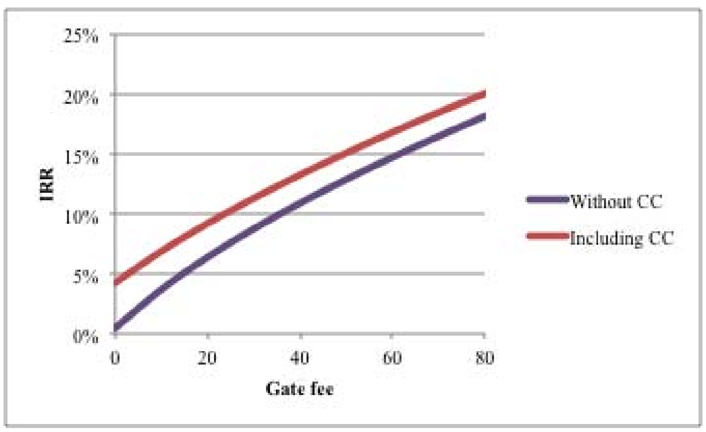


**Figure 18, IRR for different gate fees (30% subsidy or grant)**

The NPV at 6%, 10%, and 13% discount rates, and IRR at a gate fee of US$16/ton for this scenario are shown in Table 17.

**Table 17, NPV and IRR at US$16/ton gate fee (30% subsidy or grant)**

| | Without carbon credits | Including carbon credits |
|---|---|---|
| IRR | 5.4% annual | 8.3% annual |
| NPV (6%) | -US$15 million | US$58 million |
| NPV (10%) | -US$79 million | -US$31 million |
| NPV (13%) | -US$106 million | -US$69 million |

This results show that with a subsidy or grant equivalent to 30% of the capital cost, the IRR of the project is 5.4% without carbon credits, and 8.3% including income from carbon credits. Therefore, if the cost of capital of the project is lower than those rates, the NPV will be positive, and the project will be feasible. This implies that if the plant is publicly owned, and carbon credits are issued, then even with a smaller grant, the project could break even (NPV = 0) with a gate fee of US$16. Table 18 below, shows the percentage of grant needed for the NPV to be zero at a gate fee of US$16/ton, and a discount rate of 6%.

**Table 18, Grant percentage required for NPV = 0 (US$16/ton gate fee, 6% discount rate)**

| Grant (percentage of capital) | |
|---|---|
| Without carbon credits | Including carbon credits |
| 34% | 14% |

If there are private investments in the project, then the cost of capital is likely to be higher than 6%. Therefore, if the plant does not have income from carbon credits, the project is unlikely to be feasible with a gate fee of US$16/ton, because the IRR is 5.4%. On the other hand, if carbon credits are issued, then a project with private investments can be feasible if the cost of capital is lower than 8.3%, which is an aggressive scenario, in particular because financing costs were not included in these calculations.

However, if the cost of capital is higher than 8.3% or the plant does not receive income from carbon credits, then the gate fees will have to increase in order for the project to be feasible. The gate fees required for the NPV to be zero at 10% and 13% discount rates are shown in Table 19 below.

**Table 19, Gate fee required for NPV = 0 (30% subsidy or grant)**

| Discount rate | Gate fee (US$/ton) | |
|---|---|---|
| | Without carbon credits | Including carbon credits |
| 10% | 36 | 24 |
| 13% | 51 | 39 |

Moreover, the subsidy or grant percentage required for the project to break even at a gate fee of US$16/ton and discount rates of 10% or 13% are shown in Table 20.

**Table 20, Grant percentage required for NPV = 0 (US$16/ton gate fee)**

| Discount rate | Grant (percentage of capital) | |
|---|---|---|
| | Without carbon credits | Including carbon credits |
| 10% | 53% | 39% |
| 13% | 62% | 51% |

Table 20 shows that if the cost of capital is 10% or higher, the subsidy required in order to maintain the gate fee at US$16/ton is at least 40% of the capital cost of the plant, which seems highly unlikely.

To conclude this scenario, Table 21 and Figure 19 show the IRR corresponding to the current landfilling fee of US$16/ton and subsidies or grants from ranging from 0% to 90% of the capital cost.

**Table 21, IRR for different percentages of subsidy or grant (US$16/ton gate fee)**

| Subsidy | IRR without carbon credits | IRR including carbon credits |
|---|---|---|
| **0%** | 1.79% | 4.34% |
| **10%** | 2.79% | 5.45% |
| **20%** | 3.96% | 6.75% |
| **30%** | 5.35% | 8.30% |
| **40%** | 7.06% | 10.22% |
| **50%** | 9.23% | 12.68% |
| **60%** | 12.16% | 16.02% |
| **70%** | 16.46% | 20.97% |
| **80%** | 23.78% | 29.47% |
| **90%** | 40.98% | 49.35% |

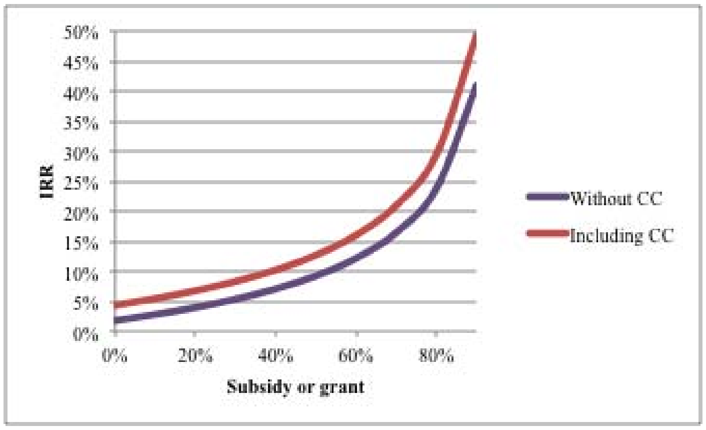


**Figure 19, IRR for different percentages of subsidy or grant (US$16/ton gate fee)**

## 10. CONCLUSIONS TO PART 1

Building a WTE plant in Montevideo would help the city, and the country, advance in sustainable waste management. Montevideo has a fairly good waste management system that could guarantee the daily delivery of certain amount of wastes to the WTE plant.

The best-suited thermal treatment technology for Montevideo is grate combustion of as received waste. The reasons are that it is the most proven thermal treatment technology in the world, it has high plant availability (90%), it is easy to operate, and it has low, and easy to train, personnel requirements.

The plant analyzed has a capacity of 640,000 tons per year, that is, it is a WTE plant with two furnaces each capable of handling 40 tons of waste per hour, with 90% availability (8,000 hours per year).

In 2010, Montevideo landfilled nearly 850,000 tons of waste, of which 91% was MSW, and 9% industrial (including sterilized hospital waste). Therefore, the two-line WTE plant will be able to handle 75% of the waste landfilled in 2010. The capital investment required to build the facility was estimated at US$420 million, and the operational costs are estimated at US$22 million per year.

The WTE plant will export to the grid 0.6 MWh of electricity per ton of waste incinerated, that is, 380 GWh of electricity per year. This electricity generation will translate into approximately US$35million revenues per year for the plant. Moreover, this amount of electricity is equivalent to 2% of Uruguay's installed capacity.

The next most important revenue source for the plant will be the gate fee, which currently is US$16/ton for waste disposal in Montevideo's landfill. Other revenue sources for the WTE plant could be sale of metals recovered and carbon credits.

The plant financing is the biggest challenge of building the projected WTE plant in Montevideo. According to the financial analysis presented in this thesis, if the plant is owned by the government, in order to maintain the current gate fee of US$16/ton, and recover the capital investment over the payback period of 23 years, the cost of capital would have to be lower than 1.8% if no carbon credits are issued, or lower than 4.3% including revenues from carbon credits. These rates are lower than the 6% current yields of Uruguay government 23-year bonds denominated in USD, trading in the international markets.

If the cost of capital for the government is close to 6%, then, in order to be able to recover the capital investment over the 23 years, the gate fee for the WTE plant must be increased to at least US$25/ton or US$37/ton depending on whether carbon credits are issued or not. The problem with increasing the gate fee, is that the portion corresponding to MSW (91%) is subsidized by the government, and therefore, to increase the gate fee so as to avoid losses in the WTE plant would require shifting the burden to other priorities of the city and the nation. That is, the government would have to absorb those costs one way or the other, unless it decides to start charging at least part of the gate fee to the citizens; which could bring about a lot of public discontent, and potentially increase illegal waste dumping. Another option for improving the economics of the plant would be for the government to obtain a grant or a low rate loan from a multilateral organism such as the IDB or IFC.

If the plant is privately owned, the cost of capital will most likely be higher than the government's cost of capital. This implies that in order for the plant to have revenues and become an attractive investment for private entities, the gate fee will have to increase even further, and /or subsidies or grants will be needed. The financial analysis showed that, considering a cost of capital of at least 10% and without subsidies or grants, the gate fee would have to be increased to at least US$50/ton; if the gate fee were to remain at the current cost of landfilling (US$16/ton), the subsidy or grant needed would be at least 40% of the capital cost. The author believes that these scenarios are difficult to achieve, and therefore, this project is unlikely to be feasible under private ownership.

Two alternatives for improving the economics of the plant are to improve MSW collection and transportation in such a way that the current costs are reduced and such reduction is transferred to the WTE plant; and to increase the amount of industrial waste that enters the formal system, since the gate fee for these wastes is higher than the gate fee for MSW.

It is also important to mention that in addition to financing, two other challenges must be taken into account with regard to a WTE plant: Potential public opposition, and the existing large population of "clasificadores" (scavengers). Public opposition is a challenge that most countries face when introducing WTE for the first time, and also, Montevideo has history of public opposition to incinerators. Therefore, introducing a public education campaign during the earliest stages of the project is of outmost importance.

The scavengers' population is a problem because some of their discards do not reach the formal waste management system (they are dumped in open fields or burned). Therefore, Montevideo cannot fully advance in waste management without addressing this problem. A first approach, which is actually already being considered, is to try to employ clasificadores in materials recovery facilities.

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# PART 2: WASTE-TO-ENERGY IN SMALL ISLANDS

## 1. INTRODUCTION

Rapid economic development and also population growth of urban centers in developing island nations have resulted in the generation of large amounts of MSW that in the past were dumped in uninhabited areas indiscriminately. Also, islands have very limited space for new sanitary landfills.

This study examines islands where WTE has been implemented successfully (Bermuda, Martinique, St. Barth) and others (Jamaica, Mauritius, Rhodes) where WTE has been considered and is in various stages of implementation.

The study shows that the per capita generation of MSW increases as GDP per capita increases. Also, it is usually recommended to improve the waste management system one step at a time, that is, to go from dumps to sanitary landfills, to waste to energy; it is interesting to note that the three islands examined in this study went directly from dumps to WTE. This phenomenon can be partly attributed to the scarcity of land for new landfills, but may also be due to the desire to develop a local and renewable energy source.

This part of the document starts by examining cases where WTE has been implemented successfully, and then moves to cases where WTE has been considered and is now in process of being implemented.

The analysis of each site gives a general overview of the island, explores its waste and waste management system, and describes the existing or proposed WTE facility. The information presented is not homogeneous for all cases, as it was not always possible to obtain the same information for the different sites.

The study concludes by comparing the analyzed islands to try to identify needs and characteristics that may lead to a successful implementation of WTE, and also obstacles that may be needed to overcome.

## 2. BERMUDA


**Figure 20, The archipelago of Bermuda**[21]

Bermuda is a self-governing overseas territory of the United Kingdom. It is an archipelago formed by approximately 138 small islands (the largest seven connected by bridges), comprising an overall land area of 53 $km^2$ (20.5 $mi^2$ – similar to the size of Manhattan). It is located in the North Atlantic Ocean, 1,000 km southeast of North Carolina, USA. It has a population of 68,000 (2010 est.[21]), and a population density of approximately 1,300 people/$km^2$; Bermuda is actually the seventh most densely populated country in the world (2008[22]). The GDP per capita of Bermuda, in 2009, was US$86,758[23], one of the world's highest. The main contributors to the GDP are international business (such as insurance and reinsurance) and financial intermediation (accounting for over 70% of the GDP). Tourism is also important to the economy, even though it has declined somewhat in recent years. Agriculture and manufacturing make only small contributions to the economy, which is highly dependent on imported goods and provision of services.

The amount of waste generated in Bermuda is reported to range between 80,000[24] and 100,000 tons/year[25], i.e. between 1.17 and 1.46 ton/capita/yr., and has a calorific value ranging seasonally from 9 to 11 MJ/kg[26]. The amount of waste per capita and calorific value are high, due to tourism and the fact that Bermuda imports 85% of the items the locals consume, which need to be well packed (mainly using plastics) in order to arrive in good conditions to the archipelago. The following figure shows the composition of residential waste in 2000.

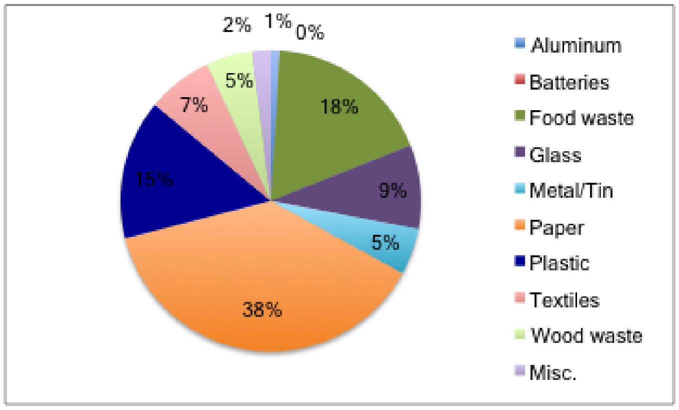


**Figure 21, Residential waste composition in Bermuda (Feb. 2000, sample size 345kg.)**[25]

In the past, MSW was disposed in the Pembroke Dump, which received around 80% of the island's waste. In 1975, this landfill was reaching its maximum capacity and a shredding plant was installed to extend its life. Nevertheless, it was apparent that the landfill had a very short lifetime. Therefore, in 1977, the Government decided to replace it with a waste-to-energy facility. In 1987, Von Roll Ltd. of Switzerland was commissioned to build the new waste-to-energy facility. The construction of the facility began in 1991, and operations started in late 1994. The cost of the facility (nominal capacity: 96,000 tons) was US$70 million[27] and was financed by the Government of Bermuda. Pembroke Dump closed after the opening of the WTE facility ("Tynes Bay Waste Treatment Facility"). Part of the land that Pembroke Dump occupied is now a recreational park, but most of it is used for windrow composting (now called Marsh Folly Composting Facility).

*Photo courtesy of the Ministry of Works and Engineering and Housing*

**Figure 22, Pembroke Dump**[25]

*Photo courtesy of the Department of Planning*

**Figure 23, Tynes Bay Waste Treatment Facility[25]**

The Tynes Bay waste-to-energy facility consists of two lines, each capable of incinerating 6 tons/hr., and producing 3.6MW of electricity[27]. The facility burns, on the average (2000-2009), 68,000 tons of waste per year[28]. The waste incinerated is composed of domestic waste (≈35%), commercial waste (≈45%), and wood waste (≈20%). The facility produced, in average, around 18,000 MWh[28] of electricity per year (equivalent to 2.7% of the country's electricity consumption), from 2005 to 2009. In the same period, approximately 40% of the electricity produced was consumed by the facility (for the incinerator and to run a Reverse Osmosis desalination plant), and the remaining 60% was sold to Bermuda Electric Light Company Limited (BELCO). On the average, 160 kWh were exported to the grid per ton of waste burned. The on-line time for the WTE plant was 6,660 hours/year.[28] Currently, higher volumes of waste have resulted in lower electricity production, due to the fact that the facility does not have the capacity to use the extra heat, but it requires more energy to process the additional waste. Tynes Bay facility is planning to refurbish the two existing lines and expand its capacity by adding a third, more efficient, stream.

Regarding emissions control, the facility has to be permitted annually by the Environmental Authority. Particulate matter (99%) is removed from combustion gases using electrostatic precipitators. Carbon monoxide, sulphur dioxide, and hydrogen chloride emissions are monitored to comply with the established limits. In 2009, the following levels were reported:

**Table 22, Bermuda WTE stack emissions (2009)[28]**

| Pollutant | Units (11% $O_2$) | Reading | Limit |
|---|---|---|---|
| Particulate | $mg/Nm^3$ | 33.1 | 35.0 |
| Carbon Monoxide | $mg/Nm^3$ | 7.9 | 80.0 |
| Hydrogen Chloride | $mg/Nm^3$ | 351.0 | 1,200.0 |
| Sulfur Dioxide | $mg/Nm^3$ | 20.1 | 200.0 |
| Equivalent Dioxins and Furans (TEF) | $ng/Nm^3$ | 3.9 | 1.0 |

Ferrous metals are removed from the bottom ash with a magnetic separator, and the remaining ash is mixed with concrete to form two-ton, $1m^3$ concrete blocks that are used for shore protection and land reclamation at the Bermuda airport (see Appendix 1 for a description of Bermuda's waste facilities). The amount of metal recovered from ash, in average (2007-2009), was 1,000 tons/year and 11,700 $m^3$ of concrete ash cubes were produced[28]. According to the Ministry of the Environment, "Studies by the Benthic Lab at the Bermuda Biological Station for Research (BBSR) have shown that the ash blocks remain relatively stable when placed in the marine environment with little or no adverse effects on marine organisms"[25].

Bermuda incinerates approximately 80% of the waste generated, composts around 15%, and only landfills bulky items (e.g. cars, tires, A/C units) and special waste (e.g. batteries). The recycling rate is still low, but the government is trying to increase the rate though educational programs.

WTE in Bermuda has been operating successfully for 17 years. It was a solution for the management of their high waste volumes in such limited space, made possible by Government financing. It is relevant to mention that Bermuda went from disposing the waste in dumpsters to WTE, without the intermediate step of sanitary landfilling.

## 3. MARTINIQUE


**Figure 24, Map of Martinique[29]**

Martinique is part of the Windward Islands, overseas region of France and located in the Caribbean, southeast of the island of Dominica. It occupies an area of 1,100 $km^2$ (425 $mi^2$)[30], has a population of 403,000[31], and a population density of 366 people/$km^2$. Martinique's GDP in 2009 was US$24,908[32] per capita. The economy is primarily based on tourism and services.

The waste generated in Martinique is estimated at 370,000 tons/year, i.e. about 0.92 tons/capita[33]. The following figure shows the composition of the waste:

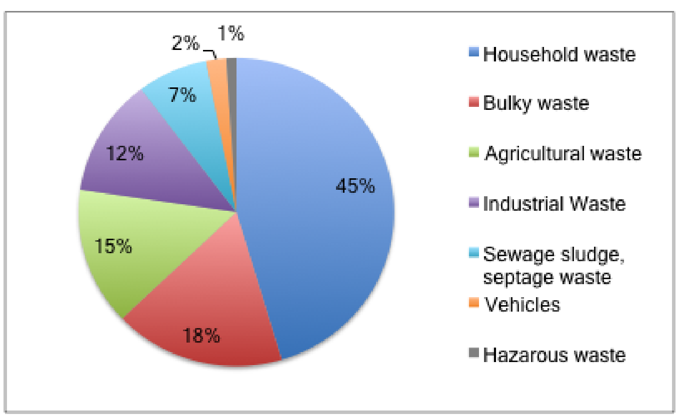


**Figure 25, Martinique's waste sources[33]**

Waste management in Martinique is the responsibility of four public entities: CACEM (Communauté d'Agglomération du Centre de la Martinique), CCNM (Communauté de Communes du Nord Martinique), CAESM (Communauté d'Agglomération de l'Espace

Sud de la Martinique), and SMITOM (Syndicat Mixte pour le Traitement des Ordures Ménagères de la Martinique).

The island has the following facilities for the disposal of its waste: Three operating dumps (9 more in project), three open landfills, two transfer stations (5 additional planned), one anaerobic digestion composting facility capable of receiving 20,000 t/yr. of organic waste, and one waste to energy facility.

The WTE facility started operations in 2002, and it was developed by CACEM to treat the waste of its four municipalities. It has a capacity of 112,000 tons/yr.[34] (30% of the island's waste), including 600 tons of medical waste. The calorific value of the waste received in the facility is between 4.2 and 8.4 MJ/kg[34], and generates between 40,000 and 45,000 MWh/yr.[34] of electricity (4% of Martinique's electricity consumption), which is sold to the grid. The facility consists of two parallel lines, capable of handling 7 tons/hour each, and operates 8,000 hours/year.[34]


**Figure 26, Martinique WTE plant[35]**

After combustion, bottom ash is conveyed to a unit for ferrous and non-ferrous metal separation. Ash is first separated by size: fine fraction (0-40 mm.), and coarse fraction (40-200 mm). Both streams are passed though a magnetic band to separate ferrous metals for recycling. Then, the coarse fraction is separated with a centrifugal fan, the light (unburned) elements are transferred back to the incinerator, and the rest is disposed in a landfill. The fine fraction is separated once again, with particles smaller than 10mm transferred to a buffer bin; the remaining fraction is passed though an eddy current separator to extract non-ferrous metals for recycling (200 tons recovered/year[36]). The remaining ash "clinker" is stored for three months for curing and then it is used for road construction (22,000 tons/yr.[34]).

The measures for emissions control include: urea injection to reduce NOx levels, lime and activated carbon injection to remove volatile metals and dioxins (to less than 0.1 ng TEQ/$Nm^3$), flue gas scrubber, and baghouse to remove particulate matter. The fly ash containing the pollutants trapped by the smoke treatments are sent to France, where they are stabilized and neutralized (3,000 tons/yr.[34]). The facility was designed to have lower emissions than the limits established by the French Government, which were the limits the facility had to comply with. In fact, it was built to comply with Dutch Government emission limits, which at that time were stricter than the French standards.

**Table 23, Martinique WTE guaranteed emissions[36]**

| Pollutant | Guaranteed maximum | French standards (2002) | Dutch standards (2002) |
|---|---|---|---|
| Dioxines (ng TEQ/$Nm^3$) | 0.1 | 0.1 | 0.1 |
| HF (mg/$Nm^3$) | 0.8 | 1 | 1 |
| Hg (mg/$Nm^3$) | 0.5 | 0.5 | 0.5 |
| $SO_2$ (mg/$Nm^3$) | 20 | 50 | 40 |
| HCl (mg/$Nm^3$) | 10 | 10 | 10 |
| Dust (mg/$Nm^3$) | 5 | 10 | 5 |

The cost of the WTE plant was €53 million[34]. The four municipalities of the CACEM funded 10% of the project, and other parties funded the remaining 90%. These included the European Regional Development Fund, the French government Agency for Environment and Energy Management (ADEME), the French Government, and the Regional Council and General Council of Martinique. A consortium of CGEA-ONYX, Vinci Environnement, CT Environnement, and SOGEA Martinique carried out the construction of the facility. The association (SEEN and ONYX) is in charge of operating the facility.

The Martinique WTE plant has been operating successfully for nearly nine years. It was made possible by funding provided by various entities of the local and French Government, and also by E.U. Regarding waste management, it is worth noting that even though Martinique has modern, sanitary landfills, they still maintain dumps.

## 4. ST. BARTH


**Figure 27, Map of St. Barth[21]**

Saint Barthelemy (St. Barth) is part of the French West Indies. It has an area of 21 $km^2$ (8$mi^2$), a population of 7,406 (2010 est.[21]), and a population density of 353 people/$km^2$. The GDP of St. Barth is estimated at US$35,100 per capita[12]; the economy of the island is based in tourism and duty-free luxury commerce. The island has limited freshwater resources, forcing them to import all the food, energy, and most manufactured goods.

St. Barth has a WTE facility in which almost all of the island's waste is disposed. This plant is coupled with a thermal (Multiple Effect Distillation) seawater desalination plant. There is not much recycling prior to bringing the MSW to the WTE, but there is a campaign in place to promote some source separation of recyclables. The idea is to separate: trash, paper/cardboard, and plastic bottles/containers to be sent to the WTE facility; glass to be pulverized and then used to create sub-strata for road paving, laying water pipes, or filtering water in swimming pools; aluminum and other metals to be exported for recycling; and batteries to be sent to Guadeloupe for disposal or recycling.

**Figure 28, St. Barth WTE plant[35]**

The motivation for the WTE-desalination facility was to improve the waste management system of the island, and to meet the freshwater needs at the peak tourist season. The French waste management company, Groupe TIRU, built and has 100% ownership of the WTE plant that started up in 2001. The process used by the WTE facility is combustion with energy recovery in a Cyclerige oscillating kiln processing 1.5 tons/hour. Its annual capacity is 9,000 tons[37], and the amount of steam delivered allows the production of 1,200 - 1,720 $m^3$ of drinking water per day[38]. Tiru reported[39] that in 2008 and 2009, 9,762 and 9,038 tons of waste were incinerated, respectively; and that the amount of energy (in form of heat) sold in those two years was 20,666 MWh, and 19,876 MWh, respectively.

The sources of waste combusted in 2009 are shown in Figure 29.

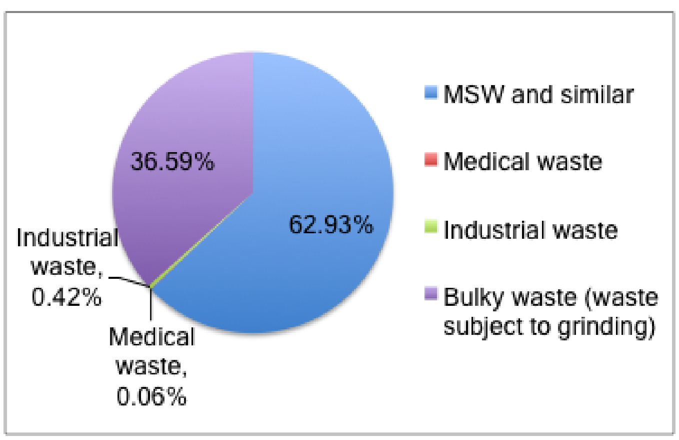


**Figure 29, Sources of waste combusted in St. Barth WTE (2009)[39]**

The reported emissions of the WTE facility in 2009 are shown in Table 24.

**Table 24, St. Barth WTE emissions (2009)[39]**

| Pollutant | Average concentration | Regulatory limit |
|---|---|---|
| Dioxines (ng TEQ/$Nm^3$) | 0.003 | 0.1 |
| NOx (mg/$Nm^3$) | 225.57 | 400 |
| $SO_2$ (mg/$Nm^3$) | 2.65 | 50 |
| HCl (mg/$Nm^3$) | 3.93 | 10 |
| Dust (mg/$Nm^3$) | 2.57 | 10 |

The residues from the WTE facility are transported to Guadeloupe for landfilling.

The amount of water desalinated by the coupled plant provides approximately 40%[38] of the island's water demand; a Reverse Osmosis desalination plant supplies the rest.

Similarly to the case of Martinique, St. Barth's WTE has been operating for nearly ten years, and was made possible by the funding and "know-how" of France. It is important to note that, apart from the WTE facility, St. Barth does not have other legal way of disposing waste. Whatever is not sent to the WTE facility, is either illegally dumped or burned, or sent to Guadeloupe for landfilling. It is also worth noting that the WTE was realized because of the dual need of managing waste and desalinating seawater.

## 5. JAMAICA


**Figure 30, Map of Jamaica[21]**

Jamaica is a Caribbean island located south of Cuba and west of Haiti. It has a population of 2.7 million[40], an area of about 10,991 $km^2$ (4,243 $mi^2$), and a population density of 246 people/$km^2$. The GDP per capita in 2009 was US$4,700 at the official exchange rate, and US$8,500 taking into account purchasing power parity[21]. The main contributors to the GDP (over 50%) are the service industries (e.g. finance, real estate, tourism). The principal foreign exchange earners for the country are tourism and bauxite (alumina) mining.

Jamaica imports 91% of its energy (petroleum based fuels), and generates the remaining 9% from renewable sources (solar, mini-hydro, wind, and biomass). The Government of Jamaica has set as target, to generate 20% of the energy consumed from renewable sources by 2030, as part of its "Vision 2030 Jamaica" development plan. As part of this initiative, Petroleum Corporation of Jamaica (PCJ) is responsible for planning and implementing two waste-to-energy facilities.

The amount of municipal solid waste (MSW) generated in Jamaica is estimated between 1,200,000 and 1,400,000 tons/yr. (0.44 and 0.52 tons/capita/year[41,42]). It is estimated that 70% of the waste generated is residential, 20% commercial, and 10% industrial. The National Solid Waste Management Authority (NSWMA) is the agency responsible for the management (collection, transportation, storage, recycling, reuse and disposal) of solid waste in Jamaica). In 2006, it conducted a characterization of waste study that resulted in the composition shown in Figure 31.

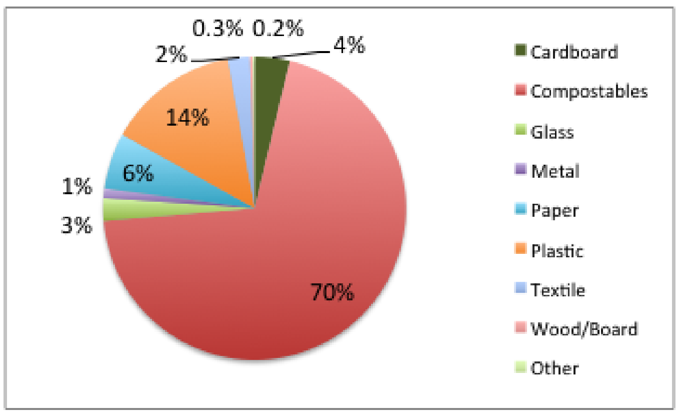


**Figure 31, Jamaica waste characterization[43]**

NSWMA estimates that 70%-75% of the waste is collected[43], and the rest is burned, buried or dumped in open lots or gullies. Furthermore, it estimated that in 2006, 38% of the residential waste was burned[44]. 25% to 30% of waste was not collected due to lack of accessibility and/or capacity (e.g. in 2007, NSWMA had a fleet of 145 trucks, and it was estimated that 175 trucks were needed to collect all the domestic waste[44]). Moreover, the NSWMA estimates that average cost of collection and disposal of waste on the island is US$100/ton[43].

With regard to sorting out recyclables from the MSW, little is done in Jamaica. There is some glass recycling, and there are a few private companies that collect paper, PET bottles and scrap metal for export, mainly from scavengers. The only bright spot is scrap metal collection by scavengers because it is well paid and exports were valued at US$100 million in 2009[43]. This has the benefit of incentivizing metal recycling, but the problem is that people have started stealing metal from the island's infrastructure, such as road signs and drain covers. Due to these incidents, in April 28, 2010, the Government issued a ban on scrap metal trading (with the exception of manufacturers who generate their own material, and do not buy from other sources)[45].

NSWMA has divided the Island into four "wastesheds" for purposes of waste management.

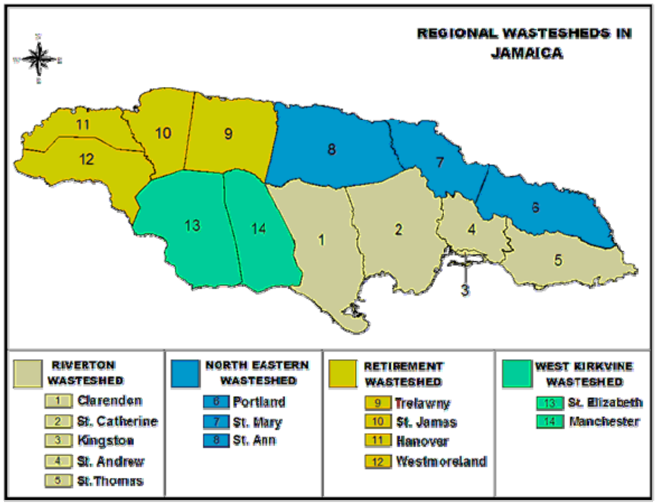


**Figure 32, Jamaica wastesheds[46]**

Jamaica has a total of eight disposal sites, none of which is a sanitary landfill. The sites selected for the proposed WTE plants are close to the main two disposal sites. These are Riverton, located in the Parish of St. Catherine (in No.2 of Figure 32); and Retirement, in the Parish of St. James (No.10). Riverton receives 60% of the Island's waste, and it is estimated to reach its maximum capacity in 2014[43], even though some improvements have been made to this landfill (construction of access road, landfill equipment, installation of lighting, and construction of administrative offices). Moreover, there were plans to build a sanitary landfill adjacent to it, but the project was abandoned due to lack of funds. The Retirement landfill is close to two sand mines, and receives waste mainly from residences and hotels, representing about 20% of the island's MSW.

The projected WTE facility near Riverton will receive 545,000 tons of waste and will have the potential to generate 45MW of electricity[47]. The WTE plant near Retirement will receive 219,000 tons of waste, and will generate 20MW[41]. Therefore, the two facilities will process 764,000 tons of waste (55%-60% of the island's total MSW), and will produce a total of 65MW of electricity. The plants are expected to run approximately 7,150 hr./yr.[41,47]. Therefore, they will provide 465,000 MWh to the grid, which is equivalent to about 7% of Jamaica's electricity consumption.

PCJ has already invited bids and selected the Miami-based company, Cambridge Project Development Company Inc., to form a joint venture with PCJ. The joint venture will finance, build, own and operate the two WTE facilities. Currently, the project-involved parties are under negotiations but the proposed financing scheme is to use debt for 80% of the capital cost. The proposed revenues for the facilities will be sale of electricity through a Power Purchase Agreement with the Jamaica Public Service, and a gate fee to be negotiated with NSWMA.

This project is yet to be implemented, but it is interesting to note, that as in the case of the previously mentioned islands, Jamaica will be advancing from non-sanitary landfills to WTE without the intermediate step of sanitary landfilling, and also with the advantage of having a relatively organized collection system.

It is also important to note that even though improving Jamaica's waste management system is an important objective of the project, the main motivation for building the two WTE facilities is to increase the indigenous sources of energy.

## 6. MAURITIUS


**Figure 33, Map of Mauritius[21]**

The Republic of Mauritius is a group of islands located in southern Africa, in the Indian Ocean, east of Madagascar. The group consists of the main island of Mauritius, Rodrigues, and several other islands located over 350 km away from the main island.

Mauritius has a population of 1.3 million (2010 est.[21]), a surface area of 2,040 $km^2$ (788 $mi^2$)[21], and a population density of 637 people/$km^2$. The GDP per capita in 2009 was US$7,300 at the official exchange rate[21] and US$13,500 taking into account purchasing power parity. The services sector represents approximately 70% of the GDP (financial services, tourism, communications technology); industry (textiles, jewelry, toys, clocks and watches) approximately 25% of the GDP; and agriculture (mainly sugar) 5%.

Solid waste in Mauritius used to be disposed in dumpsites. In the 1990s, the government built a sanitary landfill ("Mare Chicose") on the main island of Mauritius that now receives all of its waste. Rodrigues and the other islands dispose their waste in controlled landfills. The dumpsites in the main island were all closed due to their environmental impacts.

Mare Chicose is located in the south west of the island, 35km from the capital of Port Louis. The original plan of the government was to build two landfills, Mare Chicose and Mare D'Australia. Mare Chicose was designed to receive 300-400 tons/day[48], but since Mare D'Australia has not been built, all the waste is disposed in Mare Chicose. Therefore, it receives 1,164 tons/day, or 425,000 tons/year (0.33 tons/capita/year.)[49], which has had the result of reducing the life of the landfill from 19 to 8 years.

Additionally to the landfill, there are five transfer stations, where waste is compacted prior to being transported to the landfill. The waste delivered to Mare Chicose is 93% domestic (2008), and its composition (2004) is:

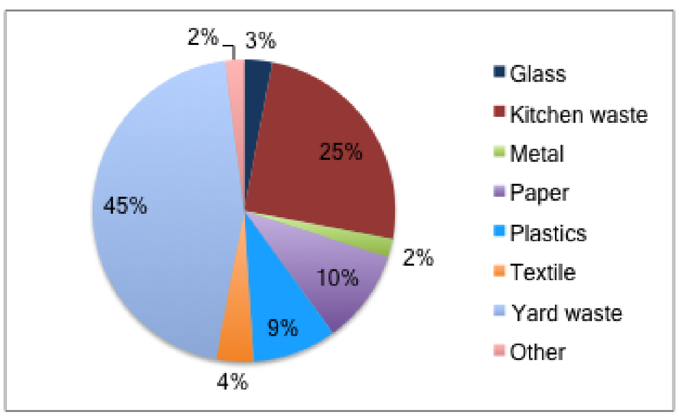


**Figure 34, Composition of waste received in Mare Chicose[49]**

Mauritius is trying to improve its waste management system through its "National Programme for Sustainable Consumption and Production", specifically through the "Integrated Solid Waste Management and Recycling" program that includes the improvement of Mare Chicose, recycling, composting, and waste to energy.

Mare Chicose is being expanded with new cells that have an improved double lining system to prevent ground waster contamination. Also, there are plans to capture the methane released (now flared) and generate electricity. It is estimated that the methane captured has the potential to generate 2 to 3 MW[49].

Regarding recycling, it is not economically feasible to recycle all waste streams in Mauritius. There is a scrap metal recycling plant that produces metal rods from the collected scrap. The bottle industry is regulated and they have to recycle PET bottles. The Bottlers Association collects, pelletizes, and then sends PET bottles to South Africa for recycling. Part of the paper is also collected, and is sent to China and India for recycling. Waste oil recycling (such as motor oil) is regulated by the Environment Protection Regulations 2006; this includes collection, storage, treatment, use and disposal of waste oil. The government has also introduced a tax on disposable plastic bags, which has been a successful measure in changing consumers' behavior.

Composting facilities in Mauritius could help reduce the amount of waste that is disposed in the landfill, given the fact that 60% of the waste is biodegradable (see Figure 34). The government has issued a letter of intent to a private company for the development of a composting facility in western Mauritius. The plant will have a capacity of 100,000 tons/yr.[49], equivalent to 24% of the total waste generated.

Waste to Energy is another alternative that the government is considering for the improvement of its waste management system. The government of Mauritius issued an Environmental Impact Assessment License to Gamma Energy Limited (a joint venture between Covanta Energy Corporation and Gamma Civic Ltd.) to build and operate a Waste to Energy plant at La Chaumiere, located at 6 km from Port Louis. The plant will have the capacity to process 300,000 tons of waste per year, and to generate up to 20 MW of electricity[50], equivalent to 7% of Mauritius electricity consumption. The capital cost of the plant is estimated at US$200 million[50].

According to Gamma Energy's website[50], the design of the WTE plant will meet the emission standards of the European Union (Directive 2000/76/EC) for waste incineration facilities, which are among the strictest international standards. The facility will have the latest pollution control equipment including measures to control odors, a NOx reduction system, a semi-dry scrubber to remove acid gases; an activated carbon injection system to control dioxins, furans and heavy metals; and a fabric filter baghouse to capture and remove dust, ash and particulates. It will also have a Continuous Emissions Monitoring System (CEMS) to monitor pollutant emission levels. The bottom ash will be used for construction purposes (Gamma is already a provider of cement, sand, and aggregate on the island). Fly ash will be mixed with cement to stabilize and immobilize pollutants and disposed in a monofill adjacent to the WTE plant. Also, wastewater will be used for operational processes such as cooling, to avoid using Mauritius' limited freshwater supplies.

In addition to drastically reducing the amount of waste landfilled, the WTE facility will have the advantage of reducing Mauritius' greenhouse gas emissions; in fact, the Government has approved and endorsed the project as a national project under the Kyoto Protocol's Clean Development Mechanism (CDM). Finally, the site selected for the WTE facility is located in a more densely populated area than the present landfill, which will translates into truck fuel savings and traffic reduction.

WTE would be a solution to Mauritius' waste management problems, but its implementation is yet to happen. It is worth pointing out that, unlike all the previously studied islands, Mauritius has a sanitary landfill in place.

## 7. RHODES


**Figure 35, Map of Greece**[21]

Rhodes (Rothos) is a Greek island, approximately 20 km southwest of Turkey. The total area of the island is of 1,400 $km^2$ (541$mi^2$); it has a population of approximately 120,000, and a population density of 86 people/$km^2$. The GDP per capita of Greece is US$30,200 (est. 2010, taking into account purchasing power parity)[21].

Rhodes generates 102,000 tons of MSW per year (0.85 tons/capita/yr.) and generation varies considerably between winter and summer months due to tourism. Waste is currently being disposed in a landfill that has a projected life of 3 years. The municipal waste management of Rothos (DEKR) plans to build an integrated waste management Environmental Park that will include composting of source-separated organics, recycling of source-separated recyclables (mostly paper, metals and some marketable grades of plastics), combustion of post-recycling MSW, and sanitary landfilling of the WTE ash that is not used beneficially.

The Earth Engineering Center of Columbia University, the engineering company EPTA, and the municipal waste management company of Rhodes (DEKR) collaborated on the pre-feasibility study of designing a thermal treatment plant that will recover energy and metals from the post-recycling municipal solid wastes (MSW) of the ten municipalities of Rhodes.

The site selected for the proposed environmental park is adjacent to the existing landfill in northern Rhodes. This site is convenient for the WTE facility because it is accessible by a major highway.

DEKR set as a requirement that the thermal treatment technology should be widely used and fully proven. The only WTE method that meets these specifications is controlled combustion of as-received MSW on a moving grate, also known as "mass burning". The preliminary configuration of the WTE facility consists of two parallel lines of 10 tons/hr. each, that is, the facility will have a total capacity of 160,000 tons of MSW per year, although it may be built with only one line (80,000 tons/yr.), and be expanded later.

The Air Pollution Control (APC) system will be state of the art and will include a dry scrubber for removing acid gases, activated carbon injection to remove volatile metals and dioxins, selective non-catalytic reduction (SNCR) of NOx, and removal of particulate matter in a fabric filter baghouse. The stack emissions will be monitored continuously and will be well below the EU standards. The emissions of the proposed WTE will be a fraction of the corresponding EU standards and considerably lower than the emissions from lignite-fired power plants in Greece. For example, the total annual dioxin emissions of the two-line 160,000-ton plant will amount to less than 0.04 grams of toxic-equivalent dioxins and furans. Also, in comparison to the present form of landfilling, the Greenhouse Gas emissions of the WTE plant will be lower by an estimated one ton of carbon dioxide per ton of MSW combusted rather than landfilled.

The two-line WTE facility (160,000 tons/yr.) will generate up to 96,000 MWh of net electricity for the grid. There will also be available another 80,000 MWh of thermal energy that may be used by an adjacent industrial operation that can make use of low-pressure steam, such as a paper recycling plant.

The capital cost of the two-line operation was estimated at €98 million and of the single-line plant €61 million. As the first WTE unit in Greece, this plant may benefit from a EU grant, similar to those that were provided for other infrastructure projects that reduced environmental impacts.

An economic comparison of the proposed WTE with a new landfill showed that that the landfill would require a lower investment and, during the first ten years of operation, may require a lower gate fee to be paid by the citizens (40 euro vs. 50-60 euro for the WTE). However, the new landfill would fill up in about twenty years and more land would be then required for another landfill. In contrast, the WTE can be maintained in such a way that, after the initial capital investment is paid off in 20 years, the plant can continue serving the population of the island and generating electricity for a very long time. In fact, there are several such WTE facilities is the US, e.g. the Saugus plant in northern Massachusetts, which in 2006 completed its first thirty years and is now on its second thirty-year period. Therefore, the Rhodes investment in a WTE facility will enrich the island's infrastructure for generations to come.

The preliminary technical and environmental studies have been completed and the projected environmental impacts of this installation have been submitted to the Ministry of the Environment and Public Works (YPEHODE). The project is on hold given the financial situation in Greece, as it is waiting for a Government grant to start its construction.

## 8. CONCLUSIONS TO PART 2

Islands have increasing amounts of waste, limited space, limited or inexistent sources of energy, and in some cases, limited freshwater resources. This situation may bring opportunities for the implementation of WTE.

In all cases analyzed in this study, the use of dumps for waste disposal is, or used to be, the common practice. Governments are now aware of the environmental consequences of such practices and are trying to improve their waste management systems.

It is usually recommended to improve a waste management system one step at a time, that is, to go from dumps to sanitary landfills, to waste to energy; but it is interesting to note that in some islands, they skipped the regulated landfill step, and went directly from dumps to WTE. This phenomenon can be partly attributed to their limited land available, but may also be due to the desire to develop local and renewable energy sources.

Therefore, WTE represented a solution for the island's waste problem, and also eased the burden in the energy front.

Table 25 and Table 26 present a summary of the main characteristics of the analyzed islands and facilitate comparisons.

**Table 25, Islands' population, land area, population density, and GDP**

| Island | Population | Land area ($km^2$) | Population density pp/$km^2$ | GDP per capita |
|---|---|---|---|---|
| Bermuda | 68,265 | 53 | 1,286 | 86,758 |
| Martinique | 403,000 | 1,101 | 366 | 24,908 |
| St. Barth | 7,406 | 21 | 353 | 35,100 |
| Jamaica | 2,700,000 | 10,991 | 246 | 8,500 |
| Mauritius | 1,300,000 | 2,040 | 637 | 7,300 |
| Rhodes | 120,000 | 1,400 | 86 | 30,100* |

* Greece GDP

**Table 26, Islands waste generated, WTE capacity, and percentage of waste incinerated**

| Island | Waste generated (total) | Waste generated (per capita) | WTE capacity | Percentage of waste incinerated |
|---|---|---|---|---|
| Bermuda | 100,000 | 1.46 | 68,000 | 68% |
| Martinique | 370,000 | 0.92 | 112,000 | 30% |
| St. Barth | 9,000 | 1.22 | 9,000 | 100% |
| Jamaica | 1,400,000 | 0.52 | 764,200 | 55% |
| Mauritius | 425,000 | 0.33 | 300,000 | 71% |
| Rhodes | 102,000 | 0.85 | 80,000 / 160,000 | 78% / 100% |

The comparison waste generation per capita and GDP per capita indicates, as one would expect, that as GDP increases, waste generation increases, with the exception of Rhodes, where Greece's GDP (instead of Rhodes) is used.

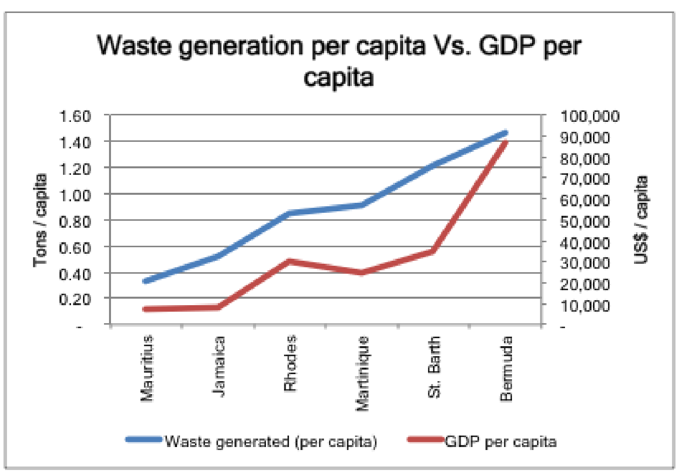


**Figure 36, Waste generation and GDP per capita comparison**

This observation leads to the conclusion that, given the limited space of islands, as their GDP increases so does the need for a better waste management, as well as the demand for energy, problems that WTE can ease.

The plot of waste generation per capita with population density (Figure 37) did not show a trend, in the case of the six islands examined in this study. Therefore, population density is overshadowed by other factors, such as GDP per capita and government interest in financing sustainable waste management.

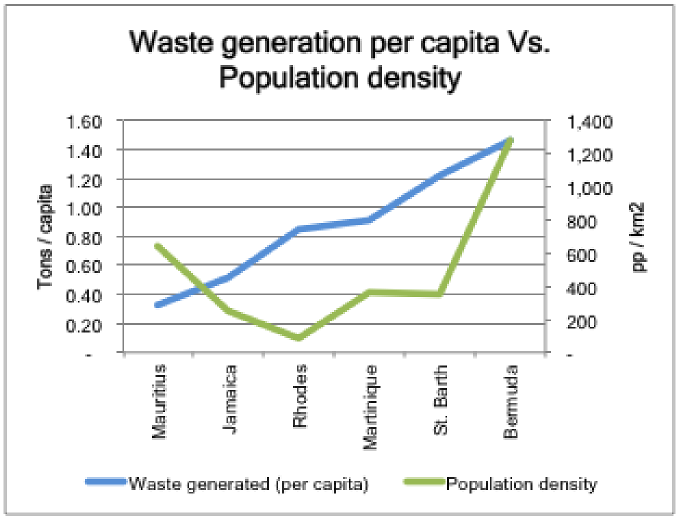


**Figure 37, Waste generation and population density comparison**

The three islands where WTE was implemented successfully (Bermuda, Martinique and St. Barth) exhibited a higher rate of waste generation and also the highest GDP per capita, with the exception of Martinique, that has a GDP lower than Greece, and considering that Bermuda has one of the highest GDP in the world; however, these three islands are territories of highly developed nations with long experience in the benefits of WTE. Therefore, the local government had at its disposal the "know-how" of the mother country and also the economic resources.

The three analyzed islands where WTE is in process of being implemented have to import the technology and "know-how", and learn as they go through the process. Moreover, the government may not be able to provide a large part of the large capital investment required for building a WTE facility.

Funding a WTE facility in a developing country may be complicated as the country may have other priorities before waste management. Also, in the case of the islands where the use of dumps is still the primary waste disposal method, the tipping fees are low or non-existent; hence the WTE alternative would appear to be very costly. It is therefore very important to ensure that the proposed WTE will be very energy efficient and that both electricity and "waste" steam are used to provide an indigenous and renewable source of energy, in addition to reducing the need for and environmental impacts of landfilling.

## APPENDIX 1, PART 2

Bermuda's waste disposal facilities:

- **Airport Facility:** air conditioning ducts, white goods (e.g. washers, dryers, refrigerators), motor vehicles, ceramic tile, construction and demolition debris, rubble and fill, dry wall, electronic goods, empty gas cylinders (e.g. freon, propane) and empty fuel storage tanks, empty metal paint cans, fiberglass, large pieces of glass and mirrors, motor vehicle tires, and PVC pipes.
- **Devon Springs Recycling Center:** residential drop off of glass bottles, tin cans, and aluminum cans.
- **Marsh Folly Composting Facility:** horticultural waste, animal carcasses, slaughterhouse waste, swill (commercial kitchen wastes), tree stumps and roots, and used animal bedding.
- **The Recycling Center:** commercial deliveries of glass bottles, tin cans, and aluminum cans.
- **Septage Disposal Facility:** swage.
- **Special Waste Facility (Sally Port Dockyard):** batteries, refrigerants, fire extinguishers, contaminated soils, corrosives (acids and alkalines), flammable liquids, medicines, mercury containing items, motor oil, paints, pesticides, fertilizers, weed killers, photo developing chemicals, swimming pool chemicals, unknown or unmarked waste, compressed gases.
- **Tynes Bay Drop-Off Facility:** residential disposal of the majority of the waste listed at the other facilities.
- **Tynes Bay Waste Treatment Facility:** cardboard, carpets, caulking, cooking Oil, dry Paint peelings, empty plastic paint cans, fiberglass insulation, household waste, lumber, paper, plastic, pullout couches and mattresses, Styrofoam, wooden furniture, wooden pallets, empty aerosol cans.

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