Proceedings of NAWTEC16
16th Annual North American Waste-to-Energy Conference
May 19-21, 2008, Philadelphia, Pennsylvania, USA

NAWTEC16-1928

LIFE CYCLE COMPARISON OF TWO OPTIONS FOR MSW MANAGEMENT IN PUERTO RICO: THERMAL TREATMENT VS. MODERN LANDFILLING

Giselle Balaguer-Dátiz
Earth Engineering Center
Columbia University in the City of New York

Nikhil Krishnan
Earth Engineering Center
Columbia University in the City of New York

ABSTRACT

The management of municipal solid wastes (MSW) in Puerto Rico is becoming increasingly challenging. In recent years, several of the older landfills have closed due to lack of compliance with federal landfill requirements. Puerto Rico is an island community and there is limited space for construction of new landfills. Furthermore, Puerto Rico residents generate more waste per capita than people living on the continental US. Thermal treatment, or waste to energy (WTE) technologies are therefore a promising option for MSW management.

It is critical to consider environmental impacts when making decisions related to MSW management. In this paper we quantify and compare the environmental implications of thermal treatment of MSW with modern landfilling for Puerto Rico from a life cycle perspective. The Caguas municipality is currently considering developing a thermal treatment plant. We compare this to an expansion of a landfill site in the Humacao municipality, which currently receives waste from Caguas.

The scope of our analysis includes a broad suite of activities associated with management of MSW. We include: (i) the transportation of MSW; (ii) the impacts of managing waste (e.g., landfill gas emissions and potential aqueous run-off with landfills; air emissions of metals, dioxins and greenhouse gases) and (iii) the implications of energy and materials offsets from the waste management process (e.g., conversion of landfill gas to electricity, electricity produced in thermal treatment, and materials recovered from thermal treatment ash).

We developed life cycle inventory models for different waste management processes, incorporating information from a wide range of sources - including peer reviewed life cycle inventory databases, the body of literature on environmental impact of waste management, and site-specific factors for Puerto Rico (e.g. waste composition, rainfall patterns, electricity mix). We managed uncertainty in data and models by constructing different scenarios for both technologies based on realistic ranges of emission factors.

The results show that thermal treatment of the unrecyclable part of the waste stream is the preferred option for waste management when compared to modern landfilling. Furthermore, Eco-indicator 99 method is used to investigate the human health, ecosystem quality and resource use impact categories.

INTRODUCTION

The management of municipal solid waste (MSW) has become more challenging in the past decade. Increasingly stringent regulations and higher environmental awareness of communities are driving the applications of MSW management systems that have lower environmental footprints. There is no universal favored system for waste management. In order to minimize environmental and economic impacts, the optimal system for a given area should be determined taking local aspects into account, regional particularities in waste composition, sitting concerns for disposal options, markets for recovered resources, local energy mix and economic situations. [1].

This study focuses on the environmental assessment of two MSW management alternatives for Puerto Rico, where a high per capita waste generation and poor management practices have led to a solid waste crisis in the island. Puerto Rico has an extension of about 14,000 km^2 (roughly the size of Connecticut), 3.9 million inhabitants and a municipal solid waste generation of approximately 9,900 tons per day. Around 90 % of the MSW generated in the island is disposed in 32 operating landfills and the remaining 10% is recycled [2]. Many of the 32 operating landfills do not fully comply with federal landfill regulations, therefore the United States Environmental Protection Agency (US EPA) issued in the past three years consent orders to close four landfills (Vega Baja, Aguadilla, Santa Isabel and Florida) and is currently pursuing a fifth consent order to close one of the island's biggest landfills that receives more than 14% of the island's waste (Toa Baja). In response to the need to comply with the EPA regulations, the Puerto Rico Solid Waste Management Authority (SWMA) undertook a systematic analysis of the MSW situation in Puerto Rico as well as potential future strategies for the island to pursue. Part of their efforts included the development of the Dynamic Itinerary of Infrastructure Projects in 2007 to provide a planning framework and define infrastructure strategies to manage Puerto Rico's MSW for the next 25 years in compliance with federal regulations. The Itinerary includes a goal to diverse 35% from landfills by 2016 with the operation of seven landfills (six current landfill expansions and construction of one new landfill facility). In order to successfully implement the strategy of diverting waste from disposal in landfills, the Itinerary includes the development of two thermal treatment processing facilities with a total capacity of 2,900 tons per day. The SWMA considered emerging thermal treatment technologies such as gasification as a potential alternative [2]. Currently there are no thermal treatment plants in Puerto Rico however Caribe Waste Technologies, Inc., operated by Interstate Waste Technologies, is in final negations to develop a Thermoselect facility in the municipality of Caguas.

Even though SWMA is considering thermal treatment processing technologies as an alternative to their current waste management practices and in spite of the advantages of these technologies, there exists considerable opposition from the PR community to this option, especially to emerging technologies like gasification. Also, the Itinerary fails to include an environmental assessment of the principal alternatives for waste disposal, modern landfill and thermal treatment. Life cycle assessment (LCA) is an excellent tool to understand the environmental burdens of the proposed options. Past LCA research activities examined impacts of landfilling and incineration in different regions, however, no studies have focused on assessing the impacts in Puerto Rico specifically. In addition, research efforts have not examined emerging thermal treatment technologies like gasification due to lack of data. This study seeks to fill these gaps by performing a LCA comparing a modern landfill versus a thermal treatment facility using Thermoselect Process technology, both located in the island of Puerto Rico.

NOMENCLATURE

Municipal Solid Waste (MSW); Life Cycle Assessment (LCA); United States Environmental Protection Agency (US EPA); Solid Waste Management Authority (SWMA). All tonnages shown refer to metric tons (1 metric ton = 1.1 short tons).

LIFE CYCLE ASSESSMENT SCOPE

We consider different landfilling and thermal treatment scenarios for Puerto Rico. The environmental impact of each scenario was normalized and compared per ton of MSW processed. The system boundary includes transportation from curbside to processing facility, process specific burdens from gasification and landfilling, such as energy and resource recovery, leachate collection and treatment, and gas collection systems (Figure 2). Since the distance from the Caguas municipality to the landfill and thermal treatment plant location is small, it is assumed that the waste is transferred directly from curbside to the processing facility; therefore the impact of transfer stations is not included. Impacts related to capital infrastructure were estimated using available life cycle inventory databases. The emissions associated with the extraction, transportation, and refining of fossil fuels inputs required for transportation of waste are included in this study.

Medium (16 t) trucks are used to collect MSW from residences in Puerto Rico. In this study we will focus on the waste generated in the municipality of Caguas, where a thermal treatment plant is proposed to be developed in the near future, and in the expansion of the currently in operation landfill in the municipality of Humacao. A GIS study of the waste allocation patterns in Puerto Rico indicated that the waste collected in the municipality of Caguas is processed at the Humacao Landfill around 21 miles to the southeast [3] (Figure 1). The Humacao landfill receives an estimated 14,000 tons of waste per week and it is proposed to be expanded up to an approximate capacity of 20,000,000 tons [2].

★ Caguas Municipality, proposed location of Thermal Treatment Plant

▲ Humacao Municipality, proposed location of modern landfill expansion.

Figure 1. Location of proposed thermal treatment plant and modern landfill expansion.

We use the software SimaPro, developed by Dutch Pre Consultants, as the LCA analysis tool, and the Eco-Indicator 99 damage assessment model. Upstream life cycle impacts associated with inputs to both waste management options such as offsetting of emissions associated with the generation of grid electricity that may be generated by the two options are included.

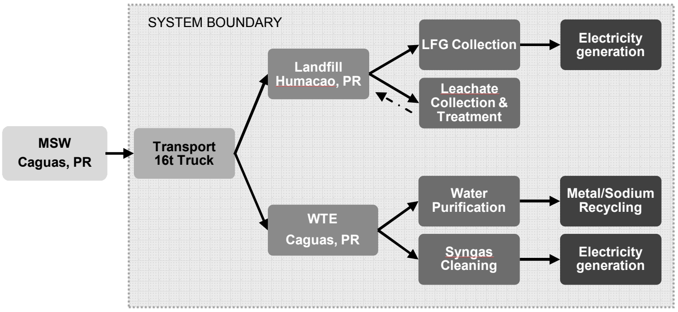

Figure. 2 Schematic of Life Cycle Operations

We seek to compare different options for the effective management of the disposed fraction of MSW that is currently and will continue to be exported to landfills. Impacts associated with the management of the rest of the MSW generated in Puerto Rico are excluded from this study. Descriptions of the scenarios and unit processes considered in this study appear in the following sections.

KEY SCENARIOS

We investigate potential alternatives by establishing four scenarios that incorporated thermal treatment and landfilling. Two thermal treatment scenarios with different emission factors and resource recovery conditions and two landfilling scenarios, one with and one without energy recovery and with different gas and leachate collection efficiencies, were assessed for their environmental impacts. The processes in each scenario were selected based on current technologies.

In scenario 1 and 2, waste is thermally treated by the Thermoselect-Process. The Thermoselect-Process uses a high temperature technology to degasify waste and recover synthesis gas, minerals, metals, sulfur and salts. The process consists of a press degassing channel, high temperature reactor and homogenizer, and gas purification and water treatment systems [4]. Water streams from the process of water vapor condensation in the synthesis gas, pass through a water purification unit [5]. The effluent from this water treatment process is used for cooling medium and therefore there are no water emissions from the Thermoselect facility.

The material and process data for the modeling of scenarios 1 and 2 was adapted from the Chiba JFE Thermoselect Facility in Japan. Specific modeling data for Puerto Rico include facility capacity, distances for waste transport from curbside to gate, location of the facility and local electricity mix. As pointed out before, the development of a Thermoselect facility in Puerto Rico is in the process of final negotiations. Facility capacity and distances were estimated based on information from the proposed facility in Caguas. In both scenarios the distance required to transport the waste generated in the municipality of Caguas to the thermal treatment facility proposed is 16 t-km. The facility would be expected to process 490,000 tons per year [2].

Table 1. Air emissions from the Thermoselect Process and US EPA emission standards for large MSW combustors.

Pollutant	Thermoselect Emissions[a,b] (Gas Engine) [mg/Nm^3]	US EPA Standards[c] [mg/Nm^3]
Particulate Matter (PM)	0.2	11
Sulfur Dioxide (SO2)	0.16	63
Nitrogen Oxides (NOx)	14	264
Hydrogen Chloride (HCl)	<5	29
Carbon Monoxide (CO)	3	45
Mercury (Hg)	0.002	0.06
Total Organic Carbon (TOC)	1.71	10[d]
Dioxins (TEQ), ng/m3	0.00039	0.14

[a] Emissions averaged from Thermoselect Plants in Karlsruhe, Germany and Chiba, Japan.
[b,c] Emission factors corresponding to scenario 1 and 2, respectively.
[d] EU emission standard

In scenario 1 (best case thermal treatment), the waste is thermally-treated with 649 KWh/ton electricity available for sale (energy recovery efficiency of 18%). In this scenario a 100% of the outputs of the Thermoselect Process (mineral, salts, sulfur and metals) are recycled in the metallurgy, concrete aggregate or chemical industries. Emissions data from the Thermoselect Chiba Plant in Japan were used to model air emission impacts. Emissions from this facility are lower than the US EPA air emission standards for large MSW combustors (Table 1).

Scenario 2 represents the worst case thermal treatment. The net electricity available for sale is 451 KWh/ton (energy recovery efficiency of 15%). We also assume that a 50% of the outputs of the Thermoselect Process (mineral, salts, sulfur and metals) are recycled in the metallurgy, concrete aggregate or chemical industries. The remaining 50% of the outputs are assumed to be landfilled. As a worst case setting, air emissions from this scenario will comply with US EPA emission standards for large MSW combustors (Table 1).

Table 2. Summary of process specific inputs and offsets for Thermal Treatment of Waste in Scenarios 1 and 2

Thermal Treatment				
Inputs		units	Values[a]	
	HCl	kg	3.6	
	Additives	kg	0.58	
	Oxygen	kg	470	
	Natural Gas	kWh	380	
	NaOH	kg	4.4	
Offsets			Scenario 1	Scenario 2
	Electricity	kWh	650	450
	NaCl	kg	20	10
	Chromite	kg	70	35
	Copper	kg	60	30
	Manganese	kg	40	20
	Zinc	kg	24	12

[a] Same values for both scenarios.

In scenario 3 and 4, waste is disposed of in a modern engineered landfill that follows federal regulations in 40 CFR Part 258 (Subtitle D of RCRA.). The landfill design specifications under Subtitle D include composite liners, leachate collection and removal systems and top coverage. Furthermore, additional design provisions under the Clean Air Act (56 FR 24468) require owners of landfill facilities to install gas collection and control systems when landfill design capacity exceeds 111,000 tons [6].

Air emissions from landfills are generated principally due to the anaerobic digestion of waste. Landfill gas (LFG) consists primarily of methane and carbon dioxide in fractions of approximately 0.5 each. The quantity of methane generated is determined by applying the methodology recommended by the IPCC guidelines [7]. Other air pollution emissions generated from the landfill are based on US EPA AP-42 emission factors for MSW landfills (Table 3).

Table 3. Calculated emission factors for uncontrolled emissions of air pollutants from landfill.

Pollutant	Calculated emission factor [kg/ton][a,b]
Carbon dioxide	620
Nitrogen Oxides	0.0702
Particulates	0.029
Carbon monoxide	1.3
Methane	51
Ethane	8.7
2-Propanol	0.99
Xylene	0.42
Ethanol	0.41
Hydrogen Sulfide	0.40

[a] Source: US EPA AP-42

[b] Emission factors per landfill scenario were calculated based on respective gas collection efficiencies.

Landfills also generate leachate from rainwater that trickles though the waste inside the landfill, collecting contaminants in the process. Depending on the efficiency of the leachate collection system, a fraction of the leachate may leak out without any treatment and a higher fraction will be treated. The collected fraction of the leachate is assumed to be treated in a treatment facility inside the landfill. We use the Ecoinvent database as a source of the modeling parameters for energy, land and resource requirements for the leachate treatment system. The amount of leachate generated in the landfill area per ton of MSW was roughly estimated using Humacao landfill site specific data for precipitation and catchment area (Table 4 and 5) [8]. The amount of trace elements present in the leachate was calculated from concentrations summarized by Christensen [9].

Table 4. Potential leachate quality

Substance	Concentration [µg/l][a]	Generation [mg/ton]
Benzene	820	10
Toluene	6200	78
Xylene	1800	22
Ethylbenzene	640	8.2
Trimethylbenzene	130	1.6
Naphtalene	130	1.7
Chlorobenzene	55	0.70
Trichloroethylene	380	4.8
Tetrachloroethylene	130	1.6
Methylene chloride	33	0.41
Chloroform	36	0.45
Phenol	600	7.6
Cresols	1100	13
Mecoprop	5.5	0.07
Acetone	2200	28
Diethylphthalate	340	4.3
Di-n-butylphthalate	10	0.13
Tetrahydrofuran	220	2.8
Tri-n-butylphophate	180	2.3

[a] Adapted from Christensen, T.H., 2001, "Biogeochemistry of landfill leachate plumes", Applied Geochemistry 16, 659-718

[b] Rough approximation using : Leachate = precipitation*Area*years in operation*(1-efficiency)/refuse MSW

Table 5. Potential leachate quantity

Parameter	Units	Value[a]
Precipitation	m/yr	82
Area of expansion	m^2	510,000
Refuse buried	Tons	10,010,000
Efficiency[b]	Fraction	0.99 or 0.50
Year of Operation	yrs	24
Potential leachate percolation	l/ton	13

[a] Humacao site-specific data

[b] Leachate collection efficiency for scenario 3 and 4, respectively.

In scenario 3 we consider a best case landfill with very effective leachate collection system efficiency (99% impermeable). This landfill also has a very efficient landfill gas collection system (85%) and energy recovery from landfill gas combustion in a gas engine (30% energy recovery efficiency). The electricity available for sale is calculated assuming a LFG heating value of 21 MJ/m^3 with a gas generation of approximately 250 m^3/ton. This provides an electricity offset of 87.5 kWh per ton of waste in the landfill.

In scenario 4 we consider a worst case landfill with poorer quality liner and collection system (50% efficient). This landfill also has poorer LFG collection system efficiency (60%) and no energy recovery from landfill gas combustion. LFG is flared.

RESULTS AND DISCUSSION

The modeling parameters and emissions presented in the previous section were arranged to generate overall life cycle inventories for the four scenarios. Impacts allocated to these inventories were separated into three environmental impact categories: human health (Disability Adjusted Life Years – DALY), ecosystem damage (Potentially Disappeared Fraction – $PDF*m^2yr$) and surplus of energy (MJ). The inventory characterization in terms of these environmental impacts is a feature of the Eco-Indicator 99 method. Negative values represent the offsetting of environmental effects as a result of resource recovery (energy or materials). A common trend among the environmental impact categories is that scenarios that include thermal treatment have generally lower impacts than landfilling options.

Analysis of the health damage per ton of MSW processed shows how implementation of thermal treatment in a large scale is preferred due to the avoidance of respiratory and carcinogenic compounds such as particulate matter (PM), nitrogen oxides (NOx) and sulfur oxides (SOx) (Figure 3). The offsetting of emissions of these compounds for the thermal treatment scenarios is due to the displacement of fossil fuel electricity. On the other hand, scenario 4 has the highest human health impacts. This is due to the fact that human health damages are sensitive to greenhouse gas emissions due to their climate change potential. In this scenario the main contributors to the impacts are methane and carbon dioxide.

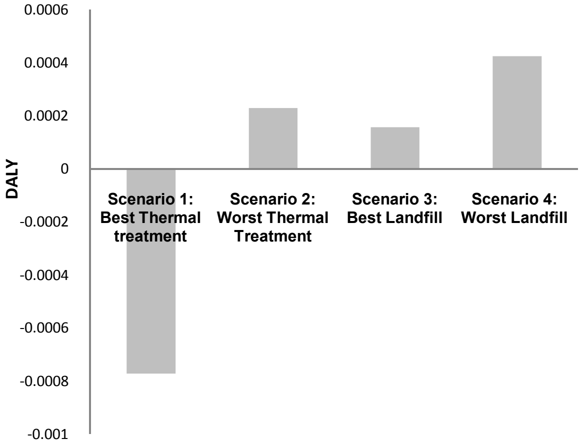

Figure 3. Summary of human health damage per ton of MSW.

Regarding ecosystem impacts, it can be seen that thermal treatment represents the preferred option due to lower damages to ecosystem quality (Figure 4). The ecosystem quality damage category consists of impacts from ecotoxicity, acidification and eutrophication, land use and land transformation. The thermal treatment scenarios show a negative impact primarily due to the avoidance of extensive land use and land transformations.

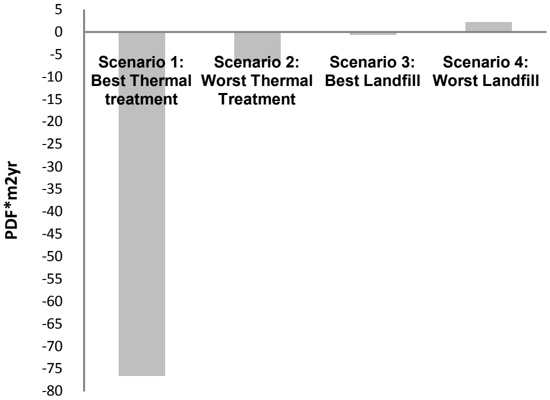

Figure 4. Summary of ecosystem damage per ton of MSW.

Resource use represents the additional energy it would take to mine and extract materials, given the resources consumed in the systems analyzed. Overall resource credits are given to scenarios 1 and 2 due to the ability of thermal treatment to significantly offset grid electricity and Thermoselect's capability to recycle most if not all of its outputs (Figure 5). It is important to note that we have not included temporal aspects of land use and transformations in this study. Landfill areas are restricted to that use for long periods of time, while land occupied by thermal treatment facilities could be more readily transformed into other uses.

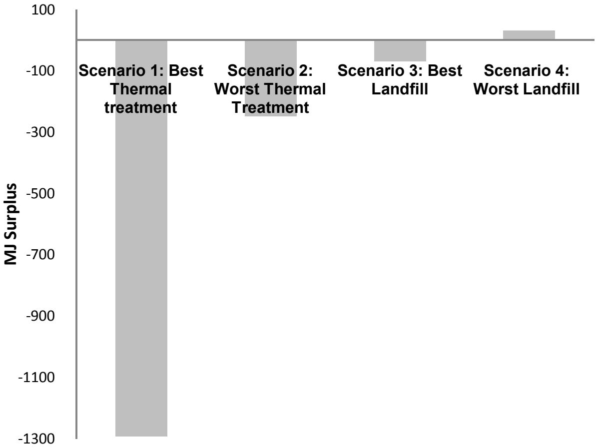

Figure 5. Summary of resource use per ton of MSW.

The results of the environmental life cycle assessment of thermal treatment and landfilling of the MSW of Puerto Rico are presented in this paper. Thermal treatment facilities are shown to be far superior to the best landfill scenarios in most of the impact categories. The current impacts of landfills in Puerto Rico are higher than the worst case scenario presented in this study due to the lack of compliance of the island's landfills with federal regulations. Thermal treatment with high material recovery efficiency is the preferred alternative.

REFERENCES

1. McDougall F., White P., Franke M., Hindle P., “Integrated Solid Waste Management: A Life Cycle Inventory”. Blackwell Publishing, 2001.

2. MP Engineers of Puerto Rico, P.S.C., “Dynamic Itinerary for Infrastructure Projects Technical Report”. San Juan, 2007.

3. Soto, S., “Solving a locational distribution problem of non-toxic solid waste on the island of Puerto Rico”, 2004.

4. Miyoshi F., Shimizu M., Marushima H., Kawasaki Steel “Thermoselect Waste Gasification and Melting Process. Kawasaki Steel Technical Report”, 46, 2002.

5. Calaminus B., Stahlberg R., “Continuous in-line gasification/vitrification process for thermal waste treatment: process technology and current status of projects”. Waste Management, 18, pp. 547-556, 1998.

6. “MSW Landfill Criteria Technical Manual” Environmental Protection Agency, Solid Waste and Emergency Response, 1993.

7. Houghton, J.T.,Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C.A. Johnson (eds.). “IPCC: Climate Change 2001: The Scientific Basis Contribution of Workign Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change”. Cambridge, United Kingdom and New York: ambridge University Press, 881, 2001.

8. Krishnan N., Themelis N.J., “Life cycle environmental impacts of two options for MSW management in New York City: modern lanfilling vs waste to energy”. Orlando: Proceedings of NAWTEC 13, 2005.

9. Christensen T.,. “Biogeochemistry of landfill leachate plumes”: Applied Geochemistry , 2001, Vol. 16. 659-718.

10. Tchobanoglous G., Theisen H., Vigil S. “Integrated Solid Waste Management: Engineering Principles and Management Issues”. Singapore: McGraw-Hill, 1993.

11. Hunter J., Arbona S., “Paradise lost-an introduction to the geography of water-pollution in Puerto Rico”. Social Science and Medicine, 40, pp.1331-1355, 1995.

12. Miranda M., Hale B., “Paradise recovered: energy production and waste management in island environments”. Energy Policy, 33, pp.1691-1702, 2005.

13. “Plan estrategico para el manejo de desperdicios solidos en Puerto Rico”. Solid Waste Management Authoity, San Juan, 2004.