Re-Covering All the Bases:
A Comparison of Landfills and Resource Recovery Facilities in Puerto Rico

by

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Executive Summary

Introduction

Every community in the United States, and indeed globally, must decide how to manage its municipal solid waste (MSW). Puerto Rico faces an extraordinary challenge today as it struggles to upgrade its solid waste infrastructure. Full management of MSW includes a mix of materials diversion, source reduction, and disposal activities, with the most appropriate mix depending on local economic, social, political, and environmental conditions.

Managing Municipal Solid Waste in Puerto Rico

Landfilling has long been the dominant form of waste disposal on the island. Until recently, landfills were often sited in sinkholes, providing leachate with a direct transport route to vital groundwater reserves. In 1989, the Environmental Quality Board (EQB) found that only two existing landfills were "well-operated," while 80-88% were termed "a disaster." These troubling findings led the Solid Waste Management Authority (SWMA) to undertake a comprehensive review of solid waste management in Puerto Rico as well as potential future strategies for the island to pursue. A 1995 plan developed by SWMA divides the island into eleven regions and incorporates new methods of MSW management. This forward-looking plan represents a strong commitment to changing substantially the way Puerto Rico manages its municipal solid waste.

Methodology

This study employs full social cost analysis to explore the relative attractiveness of different solid waste management strategies in Puerto Rico. Full social costs include production costs (e.g. capital and operation and maintenance costs), which are borne by the producers, as well as environmental costs, which society must bear (e.g., air and water pollution). We estimate the production and environmental costs for processing one ton of municipal solid waste in a modern resource recovery facility. We compare these costs to the production and environmental costs of landfilling one ton of MSW and generating some equivalent amount of electricity in a state-of-the-art oil-fired power plant. We then indicate how the recovery and sale of other materials would affect the comparative analysis. By comparing both production and environmental costs, we provide a common basis for comparing solid waste management options in Puerto Rico.

Scope of the Study

For this study, the authors were engaged by Recupera Partners, based in San Juan, Puerto Rico, to apply full social cost analysis methodology to solid waste management options using data specific to the local conditions in the northwest quadrant of Puerto Rico and assuming the use of the particular technology developed for Boiler #3 at the SEMASS resource recovery facility in Rochester, Massachusetts.

Data

We use data from the Cambalache Power Station to estimate production and environmental costs associated with oil-fired electricity production. We chose Cambalache for the comparative analysis because it is located in the study area and it is representative of the modern generation of Puerto Rican power production facilities. Given Puerto Rico's limited experience with Subtitle D landfills, we use data from the mainland United States to estimate these costs. The production and environmental costs associated with a RRF are based upon the design standards and operating data from Boiler #3 from the SEMASS resource recovery facility in Rochester, Massachusetts.

Comparing Options

The table below compares the management of one ton of MSW in a resource recovery facility and the resulting energy production using SEMASS technology with management of one ton of MSW in a Subtitle D landfill with corresponding energy production at the Cambalache power plant. The table provides two estimates of the landfilling option: one where the landfill gas escapes into the atmosphere (as is typical for landfills in Puerto Rico) and one where it is flared before being released, thereby converting the methane into carbon dioxide.

Total Social Costs of Managing One Ton of MSW in NW Puerto Rico (1997$/ton)

Costs	**Landfill + Oil-Fired** **no gas flaring**	**Landfill + Oil-Fired** **with gas flaring**	**RRF using SEMASS technology**
Production	61.7 - 89.6	64.6 - 92.5	51.5 – 61.4
Environmental	16.3 - 82.8	10.0 - 30.8	4.9 - 15.4
Materials Recovery	n.a.	n.a.	(1.4) – (2.9)
TOTAL	**78.1 - 172.4**	**74.6 - 123.2**	**55.0 – 73.9**

The low-end production costs of both landfill strategies are similar. The higher end of the landfill production costs reflects the likelihood that fully implementing Subtitle D requirements will result in higher capital outlays and that the potentially limited size of a new landfill in the region will increase tipping fees. The higher end of the resource recovery facility production costs reflects the possibility of significant increases in capital outlay on materials in Puerto Rico compared to the mainland United States. The range in environmental costs in both strategies reflects the uncertainty that underlies attempts to monetize environmental impacts. Overall, the resource recovery facility is estimated to produce significantly lower environmental costs compared to either landfill option. The cost range for the resource recovery facility generally falls below those for the landfill option. This result will hold especially so if solid waste managers are unable to identify a relatively large site for a regional landfill.

Conclusions

This study employs full social cost analysis to explore the relative competitiveness of landfilling waste versus waste treatment in a resource recovery facility. Several things stand out clearly from the analysis:

1. Resource recovery facilities are a good solid waste management option generally for Puerto Rico.
2. The northwest quadrant of Puerto Rico is especially well suited to a resource recovery facility approach.
3. A resource recovery facility based on SEMASS technology represents a very attractive sound solid waste management strategy for the northwest quadrant of Puerto Rico.

By incorporating both production and environmental costs, the methodology employed here provides a broad basis for making solid waste management decisions. Puerto Rico faces difficult challenges in solid waste management. At the same time, these challenges represent a tremendous opportunity for implementing a carefully tailored and state-of-the-art solid waste management strategy.

1. Introduction

Every community in the United States, and indeed globally, must decide how to manage its municipal solid waste (MSW). Puerto Rico faces a special challenge in the next several decades as it struggles to upgrade its solid waste infrastructure to be more environmentally benign and more responsive to a rapidly growing population. Full management of MSW includes a mix of materials diversion, source reduction, and disposal activities, with the most appropriate mix depending on local economic, social, political, and environmental conditions. This study focuses on several aspects of that mix--recovery, reuse, disposal--and uses full social cost analysis to assess the relative attractiveness in Puerto Rico of landfilling waste versus combusting it in a resource recovery facility.

2. Background

The dominant method for disposing of waste on the mainland United States, as well as in Puerto Rico, has traditionally been in landfills. Prior to the passage of the Resource Conservation and Recovery Act (RCRA) in 1976, solid waste was generally disposed of in dumps. Dumps were directly exposed to the air and ground and became the source of serious health and aesthetic concerns (Vesilind et al. 1988). RCRA banned dumps and required land disposal of waste to take place in sanitary landfills. Sanitary landfills are carefully engineered and maintained to minimize (although not eliminate) environmental and aesthetic impacts both during use and after closure.

As an alternative to landfilling solid waste, many communities began experimenting with waste incinerators during the 1960s and 1970s. These facilities, which for the most part did not co-generate any energy, were built before the United States enacted its current, more stringent air quality legislation. As a result, many of the facilities emitted high levels of both criteria and toxic air pollutants, and thus fell into great public disfavor (Miranda and Hale 1997). New regulatory restrictions and technological developments focusing on resource recovery and cleaner technologies have changed the waste combustion option dramatically.

Today's waste to energy (WTE) facilities retrieve significant amounts of energy from waste and minimize other potentially harmful emissions. A recent survey of WTE facilities in the United States revealed that all the plants were operating well below (20% or more) their permit levels for particulates, SO_2, HCl and NO_x (Hilts 1994). Another advance in WTE technology has been the development of the resource recovery facility (RRF) concept, which expands beyond simple energy recovery to extract material resources from the waste stream, pre and post-combustion.

In 1995, the United States landfilled 57% of its waste, while it recycled or composted 27% and combusted 16% of its waste (USEPA 1996). This differs substantially across regions. In 1996, North Carolina landfilled 76% and combusted 2% of its waste, while New Jersey landfilled only 34% and combusted 23% of its waste (USEPA 1996). Given the advances in both landfill and resource recovery technology, as well as the dramatic changes in regulatory requirements, communities today need clear and careful analysis to assess solid waste management alternatives.

3. Methodology

This study employs full social cost analysis to explore the relative attractiveness of two different solid waste management strategies in Puerto Rico. Full social costs include production costs (e.g. capital and operation and maintenance costs), which are borne by the producers, as well as environmental costs, which society must bear (e.g., air and water pollution). By calculating full social costs for a variety of solid waste management options, decisionmakers can assess alternatives based on both economic and environmental considerations.

Previous work has demonstrated the methodological strength of full social cost analysis (Miranda and Hale 1997, 1998). This paper focuses specifically on landfilling waste versus waste treatment in a resource recovery facility. Because RRFs dispose of waste, generate energy, and recover materials, comparisons to other solid waste management strategies are complicated. To put all relevant costs into a common cost metric, we estimate the production and environmental costs for processing one ton of municipal solid waste in a RRF. We compare these costs to the production and environmental costs of landfilling one ton of MSW and generating some equivalent amount of electricity in a state-of-the-art oil-fired power plant.[1] We then indicate how the recovery and sale of other materials would affect the comparative analysis. By comparing both production and environmental costs, we provide a broad basis for making solid waste management decisions in Puerto Rico.

Several previous studies have examined aspects of WTE systems. Chung and Poon (1997), Curlee et al. (1994), Ottinger (1990), Josselyn (1993), Åstrand (1990), Franklin Associates (1994), Pearce (1992), and Porteous (1993) all considered the issue of waste-to-energy production and associated environmental costs; each with varying results. These studies focused on WTE in Sweden, Taiwan, the United Kingdom, and the United States. The private production costs associated with WTE systems are typically more expensive than sanitary landfill systems; however, WTE systems may represent a reasonable option in areas where social and environmental conditions make it difficult to build and manage a low-risk landfill.

In 1997, Miranda and Hale published a comprehensive study comparing landfills with waste to energy technology. The study used full social cost analysis to put the costs and benefits of each option into a common metric. Using data and technologies from Germany, Sweden, the United Kingdom, and the United States, the study found that WTE plants may represent a reasonable alternative when:

[1] Miranda and Hale (1997) estimated an average yield (across plants in Germany, Sweden, the United Kingdom, and the United States) of 525 kWh per ton of MSW. As technologies for energy production improve, this number should increase.

- landfill production and externality costs are high;
- fossil fuel production and externality costs are high;
- WTE production and externality costs are low; and
- WTE production processes are able to maximize energy efficiency.

Miranda and Hale (1997) provide detail on the circumstances under which each of these conditions is likely to hold, many of which (e.g., high water tables, high population density, or difficulty in siting a large, low-cost landfill) may match up well with small island environments.

4. The Puerto Rican Context

4.1 General Information

Puerto Rico is a commonwealth of the United States bordered on the north by the Atlantic Ocean and on the south by the Caribbean Sea. About the size of Connecticut, it measures approximately 100 by 35 miles. In 1997, the island's population was estimated at 3.8 million, translating into a density of 1,083 persons per square mile (Britannica Online 1999). The Puerto Rican population is growing rapidly and will likely exceed 4 million by the year 2000. Puerto Rico has also experienced a demographic shift from rural to urban areas, with 79% of the population located in urban areas by 1990 (Hunter and Arbona 1995). Manufacturing and service industries, rather than agriculture, now dominate the Puerto Rican economy.

4.2 Environmental Law in Puerto Rico

Puerto Rico's obligations for compliance with federal environmental law are similar to states of the United States. Since the Puerto Rico Environmental Public Policy Act was passed in 1970, the Puerto Rico Environmental Quality Board (EQB) has enacted a multitude of regulations. Like state-level environmental and health agencies, the EQB's daily operations are fairly independent, although the U.S. EPA maintains oversight and may enforce compliance with federal regulations. Federal laws of particular interest for resource recovery facilities include the Clean Air Act (CAA), the Clean Water Act (CWA), and the Resource Conservation and Recovery Act (RCRA).

Puerto Rico has an approved State Implementation Plan (SIP) for air emissions. As required, Puerto Rico's SIP includes New Source Performance Standards, National Emissions Standards for Hazardous Air Pollutants, and requirements for Maximum Available Control Technology for Hazardous Air Pollutants. These regulations apply as strictly in Puerto Rico as they do on the mainland. The CAA requires major sources[2] to obtain a location approval and construction permit that is approved by both state and federal agencies. The Clean Water Act is administered in a similar fashion. Although the EQB is authorized to permit pollutant discharges to surface waters, the permitting process remains under the auspices of the EPA. For disposal of MSW, RCRA

[2] The CAA generally defines major sources as those that: a) emit more than 100 tons of any criteria pollutant annually; or b) emit more than 10 tons of any hazardous air pollutant annually.

requirements apply in Puerto Rico, with the permitting process under the authority of the EQB (Fiddler, Gonzalez & Rodriguez 1998).

4.3 Managing Municipal Solid Waste in Puerto Rico

Puerto Rico generates approximately 8000 tons of waste per day (Broder et al. 1995). In 1990, this translated into approximately 4.1 pounds per person per day -- well below the U.S. average of 4.4 pounds per person per day (Hunter and Arbona 1995, EPA 1996). Landfilling has long been the dominant form of waste disposal on the island. Until recently, landfills in Puerto Rico were ecological nightmares -- often nothing more than holes in the ground filled with waste. Landfills were often sited in sinkholes, which provided leachate with a direct transport route to vital groundwater reserves. In 1980, almost all of the island's waste was being disposed of in 62 landfills. In 1989, the Environmental Quality Board (EQB) found that only two existing landfills were "well-operated," while 80-88% of them were termed "a disaster." These troubling findings led the Solid Waste Management Authority (SWMA) to undertake a systematic and comprehensive review of solid waste management in Puerto Rico as well as potential future strategies for the island to pursue. Based on its own analysis, SWMA decided to close 32 landfills immediately. These were landfills that would not be able to meet Subtitle D standards,[3] where it would be too costly to implement Subtitle D standards, or that were reaching capacity (SWMA 1995).

A 1995 plan developed by SWMA incorporates new methods of MSW management. The plan divides the island into eleven regions each to be served by a regional landfill that would meet Subtitle D requirements. The SWMA plan calls for setting up a network of transfer stations to connect municipalities in each region with their respective landfills. The plan provides for the construction of two WTE plants in Guaynabo (in the San Juan metropolitan area) and Arecibo, the two regions with the highest levels of waste production. The plan also incorporates other means of resource recovery, including facilities to process recyclable materials, wood, and compost. This forward-looking plan represents a strong commitment to changing substantially the way Puerto Rico manages its municipal solid waste. However, it is unclear how closely the plan will be followed and when changes in the Puerto Rican waste management infrastructure will be realized.

[3] Subtitle D of the Resource Conservation and Recovery Act outlines the siting, design, management, monitoring, and closure requirements for sanitary landfills. Among the requirements, landfills cannot be sited in wetlands or areas within 100-year floodplains. Landfills must be lined and equipped with a system that collects and traps leachate. Further, the groundwater surrounding the landfill must be monitored periodically for signs of possible leaks. Upon closure, the landfill must be capped. Subtitle D requires that collection of the leachate and groundwater monitoring must continue for a minimum of 30 years after closure.

4.4 Scope of the Study

For the current study, the authors were engaged by Recupera Partners, based in San Juan, Puerto Rico, to apply full social cost analysis methodology[4] to solid waste management options using data specific to the local conditions in the northwest quadrant of Puerto Rico and assuming the use of the particular technology developed for Boiler #3 at the SEMASS facility in Rochester, Massachusetts.

4.5 The Study Area

Particular interest exists in the economic attractiveness of building and operating a RRF facility in northwest Puerto Rico. Consequently, we concentrate on two of the eleven regions defined in the 1995 SWMA plan -- Arecibo and Añasco. Arecibo was one of the two regions identified in the 1995 SWMA plan as a potential site for a WTE facility. The combined regions of Arecibo and Añasco contain 29 municipalities and will generate an estimated 1936 tons of MSW per day by 2010 (SWMA 1995). The two regions stretch from the north coast of Puerto Rico from Toa Baja west, south to Ciales, Utuado, Lares, and Maricao, then southwest to Cabo Rojo.

The United States Geological Survey (USGS) divides Puerto Rico into three distinct regions: alluvial coastal plains, karst, and mountainous interior (USGS 1996). The island's interior is mountainous, volcanic in origin, and dominated by volcanic and intrusive igneous rocks. Puerto Rico's coastal plain consists primarily of alluvial deposits of varying age. Moving from east to west on the island's northern shore, alluvial plains yield to extensive limestone deposits along the northwest coast. Weathering and dissolution of the limestone has resulted in the development of a mature karst throughout the area (USGS 1996). The karst band reaches a maximum north-south width of 14 miles, and extends for approximately 60 miles from the island's northwestern corner east towards San Juan (Monroe 1980). As is typical with karst formations, the area contains an extensive aquifer, which in combination with high annual rainfall patterns, makes siting a Subtitle D landfill especially challenging.

Orographic rainfall contributes significantly to the island's weather patterns. As the prevailing northeasterly trade winds are uplifted and cooled by Puerto Rico's extensive mountain ranges, large amounts of precipitation fall on the island, particularly in the northeast. Rainfall in Puerto Rico ranges from 190 inches in the El Yunque rainforest to less than 40 inches in the drier southwest (Johnson 1988). Within the study area, annual rainfall varies widely: from 100 inches in the mountains to approximately 30 inches in the southwest (NOAA 1990; USGS 1996).

Natural land cover includes subtropical wet forest in the north, subtropical dry forest in the southwest, and wetlands along the coasts (Johnson 1988; USGS 1996). Human land uses include urban areas (mainly on the coastal plains), agriculture (e.g., sugar cane, pineapples, vegetables), grazing, and industry (USGS 1996).

[4] The full social cost analysis methodology was developed in the 1997 study on waste-to-energy technologies and then refined in a 1998 study on forest residue combustion for energy production (Miranda and Hale 1997, 1998).

4.6 Data

We use data from the Cambalache Power Station near Arecibo to estimate production and environmental costs associated with oil-fired electricity production. We chose Cambalache for the comparative analysis for two reasons. First, it is located in the study area. Second, as a new facility, it is representative of the modern generation of Puerto Rican power production facilities. Given Puerto Rico's limited experience with Subtitle D landfills, we use data from the mainland United States to estimate these costs. The production and environmental costs associated with a RRF are based upon the design standards and operating data from Boiler #3 from the SEMASS plant in Rochester, Massachusetts.

Estimates of environmental costs rely on previous work by the authors (Miranda and Hale 1997, 1998), as well as other attempts to estimate environmental costs imposed by energy production and waste management facilities (SRI 1992, Chung and Poon 1997, Josselyn 1993, ORNL 1995). Estimating environmental costs generally involves: a) determining an appropriate marginal damage cost function for relevant emissions or other negative outputs; b) determining the level of emissions; and c) multiplying the damage cost function by the total level of emissions/output to determine the cost of environmental impacts. See Appendix B for a more detailed discussion of environmental cost valuation. We begin our analysis by estimating the production and environmental costs associated with the oil-fired plant/landfill option. We then develop a parallel estimate for resource recovery facilities and compare the two different sets of numbers. This analysis allows for a rigorous and common metric comparison of the major solid waste disposal alternatives available to Puerto Rico.

5. The Oil-Fired Plant/Landfill Combination Option

5.1 Production Costs for Oil-Fired Facilities

Production costs include the initial capital costs incurred during planning and construction of the facility, as well as the operation and maintenance costs incurred during active use of the facility. The current Puerto Rican system is in transition from an archaic system with outdated, polluting facilities to one supplied by new, modern plants, such as Cambalache, as well as retrofitted plants, such as the San Juan Power Station. As such, estimates that reflect costs associated with the more modern facilities (rather than an overall average for the island) provide a more longterm basis for analysis.

Ideally, we would estimate production costs directly from Cambalache data. Unable to obtain such data, we use two distinct approaches to estimate overall production costs for the facility.[5] In the first, we estimate production costs based on the rate residential consumers pay for electricity. From August 1995 through July 1998, the Puerto Rico Industrial Development Corporation (PRIDCO) reported an average price of 9.87¢/kWh, with considerable variation among residential, commercial, industrial, and government buyers. Alternatively, Standard and Poor (1996) estimated the year 2000 residential rate

[5] The Cambalache Bond Report states that the capital costs for the facility were $147.3 million. This translates into a per MWh cost of $6.6, but fails to incorporate operation and maintenance costs.

in Puerto Rico at 11.6¢/kWh and more recently predicted a year 2002 residential rate of 11.8¢/kWh (Standard and Poor 1998). Given the substantial capital infusion required for infrastructure development and plant retrofits, we use the Standard and Poor predictions as they likely are more reflective of long-term electricity prices as Puerto Rico moves to a substantially enhanced energy production system. Coffey (1995) estimates that approximately 50% of the residential rate represents the actual production costs involved. Using Coffey's 50% benchmark and deflating to 1997 dollars at 2.8% annually (DRI 1998) provides an estimate of 5.1-5.4¢/kWh or $51-54/MWh.

The second approach for estimating production costs uses an "avoided cost" estimate. This is the rate PREPA will pay a third party for producing electricity and is based on the cost PREPA "avoids" by allowing a third party to produce the electricity. In a recent agreement with AES Corporation, which is developing a coal-fired plant in Guayama, PREPA agreed to buy electricity at a rate of 6.4¢/kWh or $64/MWh (Coal Week International 1994). The cost estimates associated with both approaches are summarized in Table 1.

Table 1: Cost of Oil-Fired Electricity Production (1997$/MWh)

	Residential Rate Method	Avoided Cost Method
Production Cost	51 - 54	64

5.2 Environmental Costs for Oil-Fired Facilities

Oil-fired energy production can lead to a wide range of social costs resulting from the extraction, transport, and combustion of the fuel. The Cambalache power plant represents a new stage in the evolution of power production in Puerto Rico. The plant burns No. 2 fuel oil, which is relatively clean burning and has a low sulfur content (USEPA 1994). The plant possesses a selective catalytic reduction (SCR) system to control nitrogen oxide (NO_x) emissions. It controls other emissions through good combustion practices.

In order to calculate environmental costs from plant emissions, we multiply the per MWh emissions[6] of each pollutant by a marginal damage cost function for that pollutant. The marginal damage cost functions provide an estimate of the impact of one unit of pollutant on human and environmental health and are derived from a series of previous studies. See Appendices A and B for additional information on this method. We use actual emissions data from the Cambalache plant submitted for Title V purposes (Rodriguez 1999). We estimate the cost of several monitored air pollutants: nitrous oxides (NO_x), sulfur oxides (SO_x), carbon monoxide (CO), particulate matter (PM), lead (Pb) and volatile organic compounds (VOC).

[6] Lacking some information about plant operations, we make several assumptions about production within the plant. We assume that the plant operates at base load (as defined in the application) 6000 hours per year. We assume that the plant operates at spinning reserve 2000 hours per year. The remaining time is in start-up, shut-down, or maintenance.

We supplement the costs estimated from the emissions data with other studies concerning carbon dioxide externalities (Miranda and Hale 1998), ozone damage (ORNL 1995), and oil spill externalities (ExternE 1995). The CO_2 cost is based on carbon dioxide emissions from the entire oil fuel cycle. The ozone estimate includes damage to crops and humans. The oil spill externality focuses primarily on clean-up costs. As such, it does not account for potential impacts on Puerto Rico's fragile marine environment or on the Puerto Rican tourism industry.

The power station also uses groundwater in its production processes. Although the removals come from a deep aquifer, some concern exists about potential saltwater encroachment from excessive pumping. Although we are unable to monetize this potential adverse effect, the threat to the ground water supplies should not be discarded lightly. The loss of these aquifers would have a tremendous impact on the northern part of the region, as it obtains approximately 60% of its public water supplies from groundwater (Hunter and Arbona 1995).[7]

Table 2 presents the estimates of environmental costs from oil-fired facilities. The most significant effects are associated with CO_2, particulate matter, NO_x, and SO_2.

Table 2: Environmental Cost Estimates from Oil-Fired Power Plants (1997$/MWh)

Cost	**low**	**high**
CO_2	2.3	6.5
Other Air	1.6	4.2
Ozone damage	0.1	0.1
Oil spills	0.6	0.6
TOTAL	**4.6**	**11.4**

5.3 Transforming Energy Costs to Dollars per Ton of MSW Processed

The preceding sections calculate the production and environmental costs associated with producing electricity from an oil-fired facility, such as the one at Cambalache. In order to make an appropriate comparison with a resource recovery facility, we need to convert

[7] Recent studies have shown increasing levels of bacteria, heavy metals, and organic compounds in the aquifers. Already by 1987, 29% of the public supply wells along the central Northern coast had been closed due to contamination (Hunter and Arbona 1995). Other regions in Puerto Rico whose aquifers have been contaminated have been forced to rely upon surface water sources. However, most surface waters in Puerto Rico are polluted, carry heavy sediment loads, and require substantial treatment to be rendered potable. Moreover, the reservoirs from which this water is obtained are suffering from high rates of sedimentation. The Lago Dos Bocas reservoir on the Rio Grande de Arecibo lost 35% of its capacity between 1942 and 1985. Its remaining life has been estimated at 32 years, half of the original projections. This reservoir also suffers from excessive phosphorus loading. Finally, Puerto Rico has exploited most of its potential reservoir capacity. Future water needs will have to be filled by other means, such as desalination, should the aquifers become contaminated (USGS 1997).

the estimates to a common metric: cost per ton of MSW processed. To do this, we use the amount of electricity the SEMASS facility produces per ton of MSW, 644 kWh, as a conversion factor. However, electricity production per unit waste depends heavily on the caloric value of the MSW, which can vary daily and does vary regionally. The waste stream in Puerto Rico differs from that of Massachusetts, possessing a lower paper content and a higher moisture, metal, and plastic content -- the first three act to decrease and the fourth to increase the caloric content of the MSW. In addition, the SEMASS facility converts all of its heat energy to electricity and essentially sells it to the grid. A significant portion of the energy value is lost in this conversion process. Were a new Puerto Rican RRF able to sell steam or hot water to an industrial user, the energy recovery rate per ton of MSW would increase substantially. In order to account for these uncertainties, we convert our estimates using electricity production rates ± 15 % of those observed at SEMASS (547 kWh/ton MSW, and 740 kWh/ton MSW, respectively). We list the estimates in Table 3.

Table 3: Production and Environmental Cost Estimates for Oil-Fired Facility Converted to a Solid Waste Metric (1997$)

		1997$/ton MSW processed		
		low energy output	**middle energy output**	**high energy output**
Costs	**$/MWh**	**$/547 kWh[a]**	**$/644 kWh[b]**	**$/740 kWh[c]**
Production	51.0 - 64.0	27.9 - 35.0	32.8 - 41.2	37.7 - 47.4
Environmental	4.2 - 11.6	2.5 - 6.3	3.0 - 7.4	3.4 - 8.5
Total	**55.2 - 75.4**	**30.4 - 41.3**	**35.8 - 48.6**	**41.2 - 55.8**

[a] Assumes one ton of MSW generates 547 kWh – 15% below SEMASS average. [b] Assumes one ton of MSW generates 644 kWh – same as SEMASS average. [c] Assumes one ton of MSW generates 740 kWh – 15% above SEMASS average.

5.4 Production Costs for Landfills

The 1995 SWMA plan still relies heavily on landfills as a primary means of waste disposal. Nine of the eleven waste management regions are to rely on landfills as their primary means of waste disposal, with the remaining two using some type of WTE technology. Unlike existing landfills in Puerto Rico, the new landfills in the SWMA plan will have to meet Subtitle D requirements. This means they must be lined, they must collect and treat leachate, and they must provide a system for monitoring impacts both during operation and post-closure. Such requirements significantly increase landfill production costs, while simultaneously reducing environmental costs. Production costs typically include land acquisition, site construction, leachate and gas control systems, site closure, and long-term site monitoring. Further, costs are incurred in the day-to-day operation and maintenance of the site.

Landfill production costs are strongly driven by economies of scale (Crate 1992). Larger landfills amortize high fixed costs over a larger capacity and thus deliver lower costs per ton of waste as compared to smaller landfills. This has important implications for Puerto

Rico where available land suitable for landfills is scarce, and not often found in large contiguous areas. The SWMA plan calls for a 294-acre landfill in the Añasco region, which would only handle waste from that region. If suitable parcels of lands are not available to site a landfill, multiple, smaller landfills may have to replace the regional landfills laid out in the SWMA report. In this case, the estimates listed below would represent significant underestimates of landfill production costs.

In order to estimate production costs, we use data from Crate (1992) and SWMA (1995). Crate (1992) provides an estimate of development costs, which are similar to capital costs. SWMA (1995) provides data on land acquisition, scale system, permitting, gas collection system, closure, and post-closure costs. Much of the SWMA cost data is provided in terms of cost per acre. We convert these costs using the characteristics of the landfill proposed for Añasco (SWMA 1995). We calculate figures for two types of landfills, both meeting Subtitle D standards: one with no gas recovery system and one with a gas recovery system. We assume the gas recovery system allows the operators to flare the landfill gas (converting methane into carbon dioxide) but does not provide for energy recovery. We list our estimates in Table 4. Crate (1992) cautions that his data would be underrepresentative of costs in areas with high water tables, karst topography, or steep slopes – all features of the study area. Thus, the real cost is likely to lie at the high end of our calculated ranges.

Table 4: Production Costs for Landfills (1997$/ton MSW)

System	low	high
no gas recovery	$ 33.8	$ 42.2
gas recovery	$ 36.7	$ 45.1

Assuming that landfill owners have a good sense of the costs of building and running such facilities -- certainly a reasonable assumption -- the per ton tipping fee charged at the landfill should provide another estimate of the private production costs associated with processing a ton of MSW through landfill disposal (Miranda and Hale 1997). As such, we can compare known tipping fees to our estimated production costs. Actual Puerto Rican tipping fee data reveals a wide range of tipping fees from $2/ton MSW to $90/ton (SWMA 1995; CRF 1998). However, none of these figures correspond to Subtitle D landfills, and some may include fees paid by one community to another for inter-regional transfer of waste. Glenn (1998) reports an average tipping fee in the United States of $31.7/ton. He also provides an average tipping fee for Florida ($43/ton), which shares many important characteristics with Puerto Rico (high groundwater tables, high population density, and warm and humid climate). These estimates bracket the landfill production costs listed in Table 4 and thus confirm the suitability of the ranges used in this study.

5.5 Environmental Cost Estimates for Landfills

In addition to aesthetic costs that we do not estimate here, landfills typically generate environmental costs through air and water emissions. As the material in a landfill degrades, it produces gas. This gas consists primarily of methane (CH_4), a potent greenhouse gas. Landfills emit low levels of other gases as well, many of which are volatile organic compounds. The impact of these emissions on local environments may be significant. Using data from the Tellus Institute (1991), Josselyn (1993), Franklin Associates (1994), and SRI (1992), we estimate the environmental costs from landfill air emissions of CO, CO_2, CH_4, SO_2, trichloroethylene, carbon tetrachloride, vinyl chloride, 1,1,1-trichloroethane, benzene, chloroform, 1,2-dichloroethane, and methylene chloride.[8]

The resulting range is provided in Table 5. The wide range of estimates is driven by uncertainty in landfill gas composition. The greatest cost results from methane externalities and thus could be internalized through some type of gas flaring or recovery on site.[9] Other significant releases include carbon dioxide (CO_2), vinyl chloride, and benzene. In Table 5, we provide two sets of estimates: one for landfills that do not flare landfill gas and one for landfills that do flare landfill gas. The estimates for gas flaring stem from a NREL analysis that assumes 80% efficiency in methane collection (SRI 1992). The range also accounts for differential impacts due to variability in local population densities, geology, and climate, as captured by the marginal damage cost functions listed in Appendix B.

Table 5 also provides estimates of environmental costs due to leachate impacts. As landfilled material degrades and interacts with precipitation inputs, leachate is produced. The content of the leachate varies widely; however, it may contain toxic compounds. Liners are designed to capture leachate before it leaks into local soils and groundwater. As no liner is 100% effective in capturing leachate, there will always be some level of cost associated with leachate production in a landfill. Our estimates do not include the risk associated with a catastrophic liner rupture, which could have very serious impacts on the local ground water. Again, the geology of the local area will play an important role in determining how quickly leaking leachate will contaminate ground water.[10] We use estimates of leachate composition and amounts from a 1992 NREL report on sanitary landfills to estimate the associated environmental costs (SRI 1992). Since the NREL data comes from the mainland, where precipitation and resultant leachate production is lower, it may underestimate the actual environmental costs in Puerto Rico.

Table 5: Environmental Cost Estimates for a Subtitle D Landfill (1997$/ton)

Cost	**No CH_4 Flaring**	**CH_4 Flaring**
leachate	0.0 - 1.0	0.0 - 1.0
air emissions		

[8] To monetize these impacts, we use the same approach of multiplying marginal damage costs functions by emissions levels as explained in Section 5.2 above and detailed in Appendix B.
[9] The basic result of these flaring methods is the conversion of CH_4 to CO_2.
[10] For example, sediments and microorganisms can be rapidly transported through to karst aquifers (Arbona and Hunter 1995). Thus, they are at high risk for contamination.

CH_4	8.8 - 59.5	2.1 - 6.9
CO_2	0.4 - 1.4	0.7 - 2.0
vinyl chloride	4.3 - 4.8	4.3 - 4.8
benzene	0.1 - 2.8	0.1 - 2.8
others	0.3 - 4.8	0.3 - 4.8
Total	**13.8 - 73.4**	**7.5 - 22.3**

5.6 Total Costs for the Oil-Fired Plant/Landfill Combination

Table 6 summarizes the total costs for the option of producing electricity from the Cambalache power plant and managing MSW in a Subtitle D landfill. The range for oil costs spans the entire range of costs calculated based both on 547 kWh/ton MSW and 740 kWh/ton MSW. Two options are provided for the landfill: it either does or does not flare its landfill gas. Significantly lower environmental costs are encountered with the gas flaring option due to the conversion of CH_4, a very potent greenhouse gas, to CO_2, a less powerful though still important greenhouse gas.

Table 6: Total Costs for Oil-Fired/Landfill Option ($/ton)

Cost	**No CH_4 Flaring**	**CH_4 Flaring**
Production Costs		
Electricity	27.9 - 47.4	27.9 - 47.4
Landfill	33.8 – 42.2	36.7 – 45.1
TOTAL	61.7 – 89.6	64.6 – 92.5
Environmental Costs		
Electricity	2.5 - 8.5	2.5 - 8.5
Landfill	13.8 - 73.4	7.5 - 22.3
TOTAL	16.3 - 82.8	10.0 - 30.8
Total	**78.1 - 172.4**	**74.6 - 123.2**

6. The Resource Recovery Facility Option

6.1 Production Costs for a Resource Recovery Facility

The production costs for a resource recovery facility include the initial capital costs incurred during planning and construction of the facility, as well as the operation and maintenance costs incurred during active use of the facility. We use the original data from the construction of Boiler #3 at the SEMASS facility to estimate a production cost per ton of waste processed. We convert these figures into 1997 dollars.

We make several adjustments to adapt the SEMASS data appropriately to Puerto Rico's island economy. The R.S. Means Company calculates and publishes construction cost indexes for 689 U.S. and Canadian cities that may be used to compare costs between cities and across regions (R.S. Means, 1998). The 1998 publication includes indexes for 14 cities in Massachusetts, including three (Buzzards Bay, Hyannis, and New Bedford), that are relatively close to Rochester (the site of the SEMASS facility). Material costs hover around the national average throughout Massachusetts, and especially so in the nearby cities (97.2%, 99.7%, and 102.6% of the national average, respectively). Installation costs, driven primarily by wage rates, are substantially above the national average in most Massachusetts cities and 17-18% above the national average in the cities close to Rochester. Unfortunately, R.S. Means does not include a cost index for any city in Puerto Rico.

Because Puerto Rico will need to import significant amounts of construction material to build a resource recovery facility, materials costs will likely be higher than in Massachusetts. This is mitigated to some extent in the study area because of the proximity of the Port of Arecibo to the proposed construction site. Installation costs, on the other hand, will be substantially lower due to significantly lower labor costs on the island. A Bureau of Labor Statistics report (1998) estimates that Puerto Rican wages are, on average, 60-78% of average mainland United States wages, with the widest disparity in blue-collar sectors of the economy.

Cost data for constructing Boiler #3 at the SEMASS plant were not tracked in a way that makes it possible to split out materials and installation costs. This makes it very difficult to determine if overall costs for a RRF will likely be higher or lower in Puerto Rico. To account for the uncertainty that underlies building a RRF in Puerto Rico, we take the original SEMASS capital cost data, update it to 1997 dollars, and then adjust it by ±20%. Since the Puerto Rican facility will be smaller than the SEMASS facility (daily capacity of 2000 tons MSW, compared to SEMASS's 3000 tpd), we need to adjust the O&M costs to account for resulting losses in economies of scale. Thus, we adjust the SEMASS O&M costs up by 20%. Table 7 provides the capital and operating and maintenance costs (O&M) for building a RRF in Puerto Rico, based on the data from Boiler #3 at the SEMASS facility.

Table 7: Production Costs for RRF using SEMASS Technology (1997$/ton MSW)

cost	low	high
Capital[a]	17.0	25.5
Operation and Maintenance--SEMASS	*26.9*	*26.9*
Operation and Maintenance--adjusted for smaller capacity facility[b]	32.2	32.2
landfill (fly ash and bulky waste)	2.2	3.6
TOTAL	**51.5**	**61.4**

[a] Capital costs are ± 20% of the SEMASS data. [b]O&M are adjusted upward by 20% to account for the smaller facility size to be built in PR.

Resource recovery facilities produce ash that requires disposal. SEMASS disposes of its bottom ash (typically 9% by weight of waste combusted) by the production of boiler aggregate, which is sold for construction purposes, and the sale of recovered ferrous and non-ferrous metals. SEMASS landfills its fly ash (typically about 10% by weight of the waste combusted) in a monofill. In addition, resource recovery facilities dispose of bulky items that are not suitable for combustion in landfills. Bulky waste accounts for 0.9% by weight of the waste stream at the SEMASS facility. We assume that all of the fly ash, as well as bulky waste, are landfilled. These additional costs are included in Table 7. The Arecibo resource recovery facility plans to process and sell all of its bottom ash by producing boiler aggregate and through the recovery of ferrous and non-ferrous metals. As a result, we assume that none of the bottom ash is landfilled, which is consistent with materials flow management at SEMASS.

6.2 Materials Recovery

We already take into account the energy recovery that occurs in an RRF based on SEMASS technology. Resource recovery facilities also generate income from the sale of recovered metals (ferrous and non-ferrous) and boiler aggregate. A study by Broder et al. (1995) estimates that ferrous metals generate revenue of $20 – 90 per ton of metal. The SEMASS facility sells non-ferrous metals for $240 per ton, and boiler aggregate has a market value of approximately $6 per ton. For the purposes of a conservative analysis, we assume that the market prices in Puerto Rico may be lower, and thus we estimate potential revenue using a range of 75-100% of current SEMASS materials recovery prices. Combining these price ranges with the material recovery data from the SEMASS facility, we estimate the potential income received from the recovery of materials. Table 8 summarizes the revenue estimates for the proposed Arecibo facility.

Table 8: Revenue from Sale of Recovered Materials ($/ton MSW)

Recovery Type	Low	High
Non-Ferrous Metals	0.8	1.0
Ferrous Metals	0.2	1.4
Aggregate	0.4	0.5
Total	**1.4**	**2.9**

6.3 Environmental Costs for RRF Using SEMASS Technology

Resource recovery facilities produce impacts that are not covered under the costs incurred in normal production. Using the 1997 results from emissions tests from the SEMASS facility, we estimate potential impacts from similar emissions in the Puerto Rican environment. These emissions include PM, SO_2, HCl, NO_x, CO, Cd, Pb, Hg, and dioxins. Since CO_2 is of particular interest due to global climate concerns, we also estimate impacts from average carbon dioxide emissions using data from SRI (1992). Two emissions account for the majority of the associated social costs: CO_2 and NO_x. The CO_2 cost may represent an overestimate in part. Carbon emissions from plastics derive originally from carbon stored in petroleum deposits. As such, they represent net additions to the atmospheric carbon budget and contribute to global climate change. However, carbon emissions originating from wood and paper products would have eventually been released under normal decomposition and thus do not represent net additions to the atmospheric carbon budget.

In estimating environmental costs for the RRF, we assume that the facility will be a zero emissions facility with respect to water (similar to the SEMASS facility). Table 9 presents environmental costs for a RRF using SEMASS technology in Puerto Rico. Unlike the emissions for the landfill site, the variability in the range of costs does not represent variability in emissions from the facility. Emissions at the SEMASS facility are well established through monitoring and reporting required by the 1990 Clean Air Act Amendments. The variability stems from the range of marginal damage cost functions we use for each pollutant monetized (see Appendix B).

Table 9: Environmental Costs for RRF Using SEMASS Technology (1997$/ton MSW)

Costs	Low	High
Air emissions		
CO_2	2.3	6.4
NO_x	1.7	7.2
others	0.7	1.1
Ash monofill	0	0
Bulky waste disposal	0.1	0.6
TOTAL	**4.9**	**15.4**

Miranda and Hale (1997) concluded that disposal of ash in a monofill -- a landfill that only receives one material -- results in no significant environmental impacts. This conclusion was based on studies by SRI International (1992) and Goodwin (1993). Both studies present data from fly ash monofill leachate demonstrating extremely low or undetectable levels of heavy metals. Since the SEMASS facility disposes fly ash in monofills, we assume that the Puerto Rican facility will do the same with both fly and bottom ash. However, the facility does need to dispose of bulky items that are not suitable for combustion. At SEMASS, this accounts for approximately 0.9% of the incoming waste stream. Thus, we estimate additional environmental costs due to the bulky waste disposal in a landfill site by multiplying 0.9% times the total environmental costs imposed by landfills. All RRF environmental costs are reviewed in Table 9.

6.4 Total Costs for RRF Using SEMASS Technology

Table 10 summarizes the production and environmental cost estimates and materials recovery income for a RRF using SEMASS technology in northwest Puerto Rico.

Table 10: Total Costs for RRF using SEMASS Technology (1997$/ton MSW)

Cost	Estimate
Production	51.5 - 61.4
Environmental	4.9 - 15.4
Materials Recovery	(1.4) – (2.9)
Total	**55.0 – 73.9**

7. Analysis

7.1 Comparing Options

Table 11 and Figure 1 compare the management of one ton of MSW in a resource recovery facility and the resulting energy production using SEMASS technology with management of one ton of MSW in a Subtitle D landfill with corresponding energy production at the Cambalache power plant. The table provides two estimates of the landfilling option: one where the landfill gas is allowed to escape into the atmosphere and one where it is flared before being released, thereby converting the methane into carbon dioxide. It is immediately obvious that methane flaring represents a preferable strategy. The environmental costs decline significantly with the conversion of methane to carbon dioxide in the flaring process and more than compensate for the slightly higher production costs.

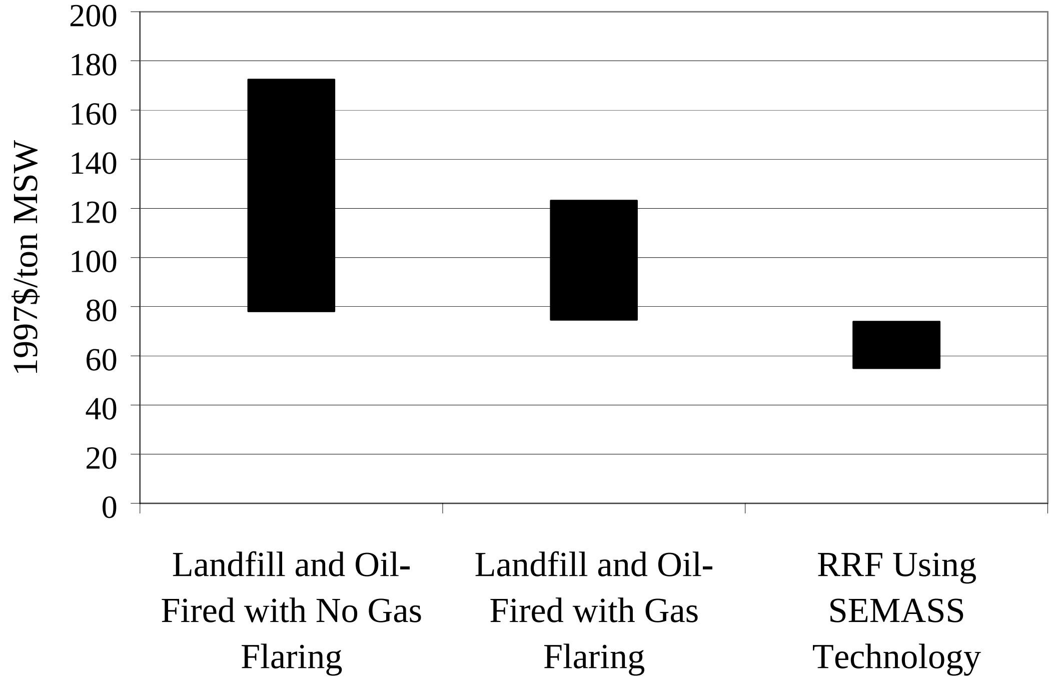
Table 11: Total Social Costs of Managing One Ton of MSW in NW Puerto Rico (1997$/ton)

Costs	**Landfill + Oil-Fired no gas flaring**	**Landfill + Oil-Fired with gas flaring**	**RRF using SEMASS technology**
Production	61.7 - 89.6	64.6 - 92.5	51.5 – 61.4
Environmental	16.3 - 82.8	10.0 - 30.8	4.9 - 15.4
Materials Recovery	n.a.	n.a.	(1.4) – (2.9)
TOTAL	**78.1 - 172.4**	**74.6 - 123.2**	**55.0 – 73.9**

The low-end production costs of both landfill strategies are similar. The higher end of the landfill production costs reflects the likelihood that fully implementing Subtitle D requirements will result in higher capital outlays and that the potentially limited size of a new landfill in the region will increase tipping fees. The higher end of the RRF production costs reflects the possibility of significant increases in capital outlay on materials in Puerto Rico compared to the mainland United States. The range in environmental costs in both strategies reflects the uncertainty that underlies attempts to monetize environmental impacts.[11] Overall, the RRF is estimated to produce significantly lower environmental costs compared to either landfill option.

[11] A good example of the underlying uncertainty is the controversy over global climate change. Both carbon dioxide and methane are potent greenhouse gases. A growing body of evidence indicates that the accumulation of these and other greenhouse gases is affecting the global climate. However, significant disagreement exists over the magnitude of these and future impacts. The range we use in this paper accounts for moderate to severe impacts from global climate change, but does not include potential

Figure 1: Comparing Options.



As is perhaps clearest from Figure 1, the RRF technology competes well with the landfill/oil-fired facility combination. The cost range for the RRF generally falls below those for the landfill option. This result will hold especially so if solid waste managers are unable to identify a relatively large site for a regional landfill.

7.2 Comparison to Miranda and Hale (1997)

Table 12 compares the results of the current study with a more general WTE study undertaken by the authors in 1997. Presenting both analyses allows an exploration of the relative economic and environmental attractiveness of RRF technology in general, as well as the specific performance of the proposed SEMASS technology facility. A few important differences should be noted between the 1997 study and the present one. First, the 1997 study looked at WTE technologies across the board. As such, it includes technologies with different costs and emissions and does not include full-scale resource recovery facilities. Second, it looked at coal, not oil, fired facilities. Coal production costs are typically lower due to cheaper fuel cost. However, coal combustion results in higher environmental costs than oil combustion. Overall, the total costs from the 1997 study for the landfill/energy option presented below may be slightly higher than what one would expect from the oil-fired energy production considered in this analysis. Third, the 1997 study used a weighted average of waste-to-energy conversion rates and estimated an average of 525 kWH per ton of MSW. The SEMASS technology lies at the more

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catastrophic effects. In addition to the uncertainty in actual impacts, the range of landfill estimates also includes uncertainty in the level of emissions that would be released from the facility.

efficient end of the energy conversion range and averages 644 kWh per ton of MSW processed. Thus, this specific technology should be more economically attractive than the weighted average technology used in the 1997 study. Finally, the 1997 study calculated a weighted average of methane flaring, based on the prevalence in the mainland U.S., and thus incorporates both sets of emissions into one estimate.

These methodological differences notwithstanding, comparing the two studies can provide important insights regarding the general appropriateness of using a resource recovery facility approach in Puerto Rico. It is perhaps most informative to compare the cost range calculated in this study for the oil-fired plant/landfill with flaring option to the WTE cost range calculated in the 1997 study (the two shaded cells in Table 12). There is tremendous overlap in the cost ranges, suggesting that WTE technology generally will compete well with landfills in Puerto Rico. The low end of the 1997 WTE cost range is more likely in plants with a more efficient waste-to-energy conversion rate, in settings where industrial users demand steam or hot water, and with technologies incorporating advanced pollution control approaches. The relative performance would improve further if a full-scale resource recovery facility was built rather than a more limited WTE plant analyzed in the 1997 study. Thus resource recovery facilities at the very least appear to be an equally good choice for Puerto Rico. Assuming the use of state of the art energy production and pollution control technology, resource recovery facilities may well represent a superior choice for Puerto Rico. This recommendation includes but is not limited to the technology in place at the SEMASS plant in Rochester, Massachusetts.

Table 12: Comparison with Miranda and Hale (1997)

<table>
<tr><th>MSW Management Strategy</th><th>Present Study</th><th>Miranda and Hale (1997)</th></tr>
<tr><td>Landfill + External Energy Production (no gas flaring)</td><td>78.1 - 172.4</td><td rowspan="2">69.4 - 144.4[b]</td></tr>
<tr><td>Landfill + External Energy Production (with gas flaring)</td><td>74.6 - 123.2</td></tr>
<tr><td>Resource Recovery Facility</td><td>55.0 - 73.9[a]</td><td></td></tr>
<tr><td>Generic Waste-to-Energy Facility</td><td></td><td>83.0 - 164.4[c]</td></tr>
</table>

[a] RRF using SEMASS technology. [b] Figure calculated using weighted average of methane flaring based on mainland U.S. data. [c] Figure covers general WTE technology.

7.3 Caveats

Monetizing the costs associated with solid waste management is a complicated task. Best efforts notwithstanding, the calculations are characterized by considerable uncertainty, especially so for environmental effects. However, this uncertainty more likely affects whether we have calculated the levels correctly; we can be reasonably certain that the relative costs are on target. Thus while we might attach some concern to whether the numbers in Table 11 will hold absolutely, we can be confident that a resource recovery facility will perform well relative to the landfill/oil-fired option and thus constitutes a sound choice for Puerto Rico. These results are consistent with the general conditions set out in Miranda and Hale (1997).

Landfills have the option of collecting and combusting the emitted gas to produce energy. We mentioned above that this may increase production costs. Revenues from energy sales may offset the increased costs. Further, the gas combustion would reduce the social costs incurred by landfills. However, gas collection for energy combustion is feasible only at relatively large landfills.

Uncertainties also exist with regard to available markets for and expected revenue from the sale of recovered metals and boiler aggregate. We assume that the situation in Puerto Rico will be similar to that at SEMASS. If the markets do not evolve, or if prices are drastically different, this would have a resulting effect on the total costs involved with waste management. However, the impact will likely be marginal, due to the small magnitude of the associated revenues.

Landfill size remains a critical issue in Puerto Rico's solid waste management strategy. Small landfills are very expensive to build on a per ton capacity basis and will drive costs toward the upper end of the estimated range. If planners are unable to locate a larger landfill site in the northwest quadrant, a resource recovery facility will represent an even better choice for the island.

8. Conclusions

Puerto Rico faces a special challenge in the next several decades as it struggles to implement a comprehensive and carefully considered solid waste management plan. This study employs full social cost analysis to explore the relative competitiveness of landfilling waste versus waste treatment in a resource recovery facility. Several things stand out clearly from the analysis:

1. *Resource recovery facilities are a good solid waste management option generally for Puerto Rico.* Resource recovery facilities compete well economically with landfills. In addition, environmental costs associated with RRFs compare favorably, as would be expected in small island environments generally.
2. *The northwest quadrant of Puerto Rico is especially well suited to a RRF approach.* Factors such as the karst topography along the northern coast, mountainous terrain inland, and extensive aquifers in the area make it difficult to site a cost-effective and low-risk landfill. In addition, the high waste generation rates allow for the operation of a relatively large-scale (and thus less expensive per ton) resource recovery facility.
3. *A resource recovery facility based on SEMASS technology represents a sound solid waste management strategy for the northwest quadrant of Puerto Rico.* This is due primarily to the advanced technology both in production and pollution control that characterizes the technology.

By incorporating both production and environmental costs, the methodology employed here provides a broad basis for making solid waste management decisions. Puerto Rico faces difficult challenges in solid waste management. At the same time, these challenges represent a tremendous opportunity for implementing a carefully tailored and state-of-the-art solid waste management strategy.

9. Appendix A

In Table A1, we list emissions data from the Cambalache oil-fired power plant. The data comes from the information submitted to the Environmental Quality Board for Title V purposes (Rodriguez 1998). Carbon dioxide emission estimates were not included. Instead, we use data for CO_2 emissions from the oil-fuel cycle in Sweden from a previous study by Miranda and Hale (1997), as CO_2 emissions are relatively unaffected by the technology used in combustion.

Table A1: Emission Data from Cambalache Power Plant

Pollutant	**tons/per year**
NO_x	**158**
SO_2	**617**
H_2SO_4	**0**
PM	**273**
VOC	**52**
CO	**342**
CO_2[a]	**n/a**

[a] Cambalache did not provide CO_2 emissions estimates. Instead, we estimate emissions from data used in Miranda and Hale (1998). These data were from the oil fuel cycle in Sweden, but should approximate carbon dioxide emissions from any oil-fired facility.

In Table A2, we list the emissions data from Boiler #3 at the SEMASS facility in Rochester, Massachusetts. The data for all of the emissions except for CO_2 comes from actual emissions monitoring for the year 1996. Carbon dioxide emissions were not available for the SEMASS facility. Instead, we use data from the 1992 NREL report that was based on several sources of data, including SEMASS data (SRI 1992).

Table A2: Emissions Data from SEMASS Facility, Boiler #3

Pollutant	Units	Quantity Emitted
PM	gr/dscf	0.0002
NO_x	ppmdv	120
SO_2	ppmdv	9.32
HCl	ppmdv	3.62
CO	ppmdv	63.6
CO_2[a]	lbs/ton MSW	1424
Pb	µg/dscm	6.37
Hg	µg/dscm	3.67
Cd	µg/dscm	0.11
dioxins	ng/dscm	0.417

[a] CO_2 data are from SRI 1992.

10. Appendix B: Environmental Cost Estimation

In order to estimate environmental costs in this paper, we multiply actual (or estimated) emissions of specific pollutants from each respective facility by a marginal damage cost (MDC) function for that pollutant. The MDC provides the estimated value of the impact due to one unit of a pollutant released into the environment.

$$EC_x = EM_x * MDC_x$$

where:

EC_x = environmental cost from pollutant x ($/MWh or ton)

EM_x = emission of pollutant x per MWh or ton (unit/MWh or ton)

MDC_x = marginal damage cost per unit of pollutant x ($/unit)

The development of the MDC functions and indeed the quantification of environmental impacts from pollutants is a challenging task. The authors rely on previous work by Josselyn (1993), Bernow et al. (1991), Chernick and Caverhill (1989), Burrington (1991), Fritsche (1991), and Pearce et al.(1996) for the MDCs used in this analysis.[12] These studies use a range of techniques to quantify impacts, including direct estimates of human and environmental health impacts, cost-benefit analysis, abatement costs for specific pollutants, and contingent valuation of changes in human and environmental health. While none of these techniques provides perfect measures, they do provide a mechanism for translating environmental impacts into a common metric.

Table B1 lists the actual marginal damage costs used in this study. Using a cost range rather than point values for each pollutants makes several points. First, it reflects the inherent uncertainty in estimating MDC's. In addition to the inherent difficulties associated with placing dollar values on human and ecological health, scientific debate about the level of impact from various pollutants further complicates the analysis. Second, it may allow some flexibility in translating MDC's to the Puerto Rican environment. None of the valuation studies was conducted in Puerto Rico. In general, the MDC's were estimated in areas with temperate climates and a wide range of population densities (spanning rural to urban areas). The tropical climate of Puerto Rico (particularly the high levels of precipitation) would mean higher levels of wet deposition of air pollutants (due to faster washout rates) in local areas. More precipitation also increases the rate of leachate production, particularly in the northern part of the study area. The higher ambient temperature would also mean that chemical reactions would proceed more quickly. All of these factors result in greater environmental impacts in local areas than might be predicted by the MDC's used in this study. As such, our figures may underestimate the actual impacts of the various facilities. Nevertheless, since the underestimate would hold for both landfills and resource recovery facilities, the

[12] Pearce et al. rely in turn on Nordhaus (1991), Ayres and Walter (1991), Nordhaus (1994), Peck and Teisberg (1992), Fankhauser (1994), and Maddison (1994).

comparative analysis between options should remain fairly stable. Finally, it reflects the variability within the study area. The environmental costs of any facility will be determined in part by the actual location of the facility within the area. The level of impact from a unit of any pollutant is variable, and determined by local meteorological and environmental conditions, time and period of exposure, and the behavior of the local human populations, among others.

Table B1: Marginal Damage Costs of Pollutants (1997$/lb)

Pollutant	low estimate	high estimate
NO_x	1.09	4.64
SO_2	0.99	2.69
PM	0.30	2.65
CO	0.55	0.58
CH_4	0.15	0.48
CO_2	0.0016	0.0045
VOC	7	8
HCl	6	8
H_2SO_4	0.99	2.69
Cd	195	238
Pb	431	527
Hg	1,403	1,714
As	614	751
Cd	5	6
Cr	24	29
Cu	14	17
Ni	8	10
dioxins	822,253	1,004,975

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