Analysis of Municipal Solid Waste Management Alternatives for the Greater Baltimore Region

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Prepared by:
RTI International
Research Triangle Park, NC

Prepared for:
Energy Answers Baltimore, LLC

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1.0—Executive Summary

Energy Answers Baltimore, a resource recovery technology and project developer has requested a detailed and quantitative analysis of the respective relationships and tradeoffs between its Processed Refuse Fuel ^{TM} (PRF) resource recovery system and mass burn waste-to-energy (WTE) systems, and other landfill (LF) disposal alternatives for managing post-recycling municipal solid waste (MSW) in the Greater Baltimore Region of Maryland. Post-recycling MSW consists of that waste remaining after materials have been recovered for recycling and/or composting.

Energy Answers has engaged RTI to analyze the comparative net energy consumption and greenhouse gas emissions from a series of solid waste management alternatives and to present those results. RTI is an independent, nonprofit institute that provides research, development, and technical services to government and commercial clients worldwide.

This analysis was conducted using RTI's Municipal Solid Waste Decision Support Tool (MSW-DST) developed by the U.S. EPA and RTI. The data and results generated through this project provide a general assessment of the potential tradeoffs in energy and emissions associated with the management of post-recycling MSW in the Greater Baltimore Region. The following scenarios were considered in this analysis as they are viable and available alternatives:

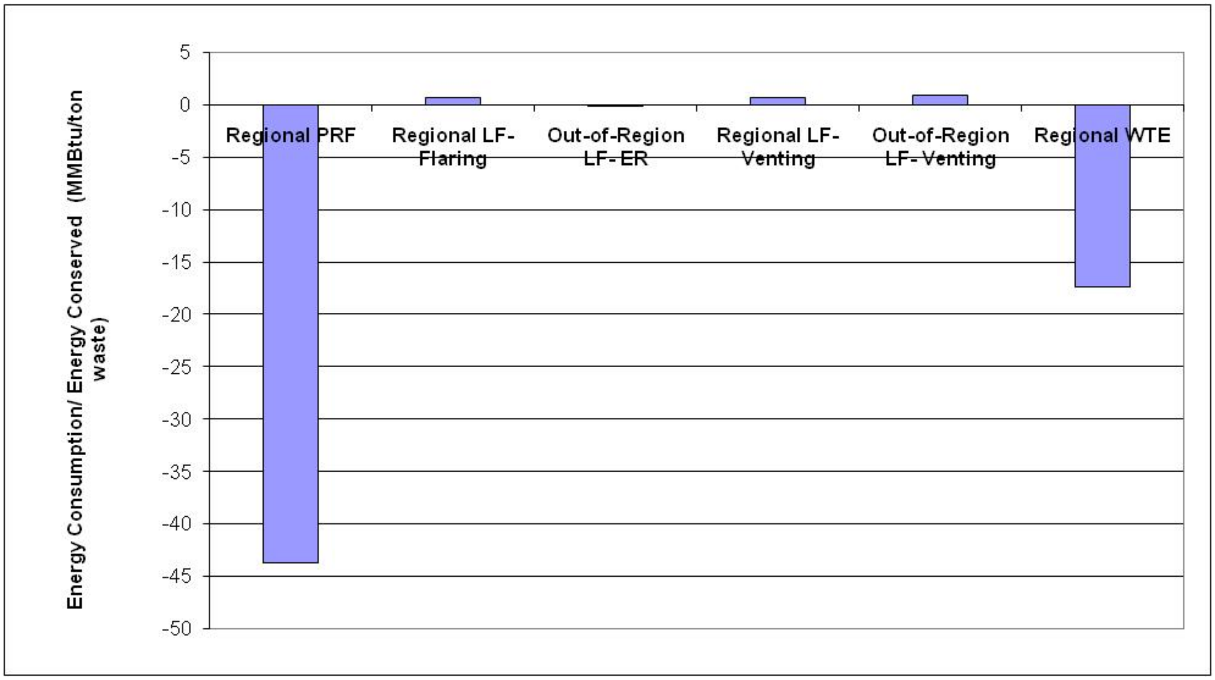
- Scenario 1: Regional PRF system with electrical energy generation and materials recovery.
- Scenario 2: Regional landfill with gas collection and flaring.
- Scenario 3: Out-of-region landfill disposal with gas collection and energy recovery (ER).
- Scenario 4: Regional landfill with no landfill gas management.
- Scenario 5: Out-of-region landfill disposal with no landfill gas management.
- Scenario 6: Regional mass burn WTE system with ferrous metals recovery.

The main findings from this analysis are:

Net Energy Consumption

On a per ton of waste basis, the energy savings from the regional PRF scenario is more than twice as large as that from the regional WTE scenario (44 MMBtu/ton of waste vs. 17 MMBtu/ton of waste) and results in a significantly larger net energy savings when compared to each of the other scenarios (**Figure 1**). This clearly speaks to the benefits of the PRF system's enhanced energy and materials recovery efficiency.

Figure 1 - Net Energy Consumption/Energy Conserved per Ton of Waste by Scenario



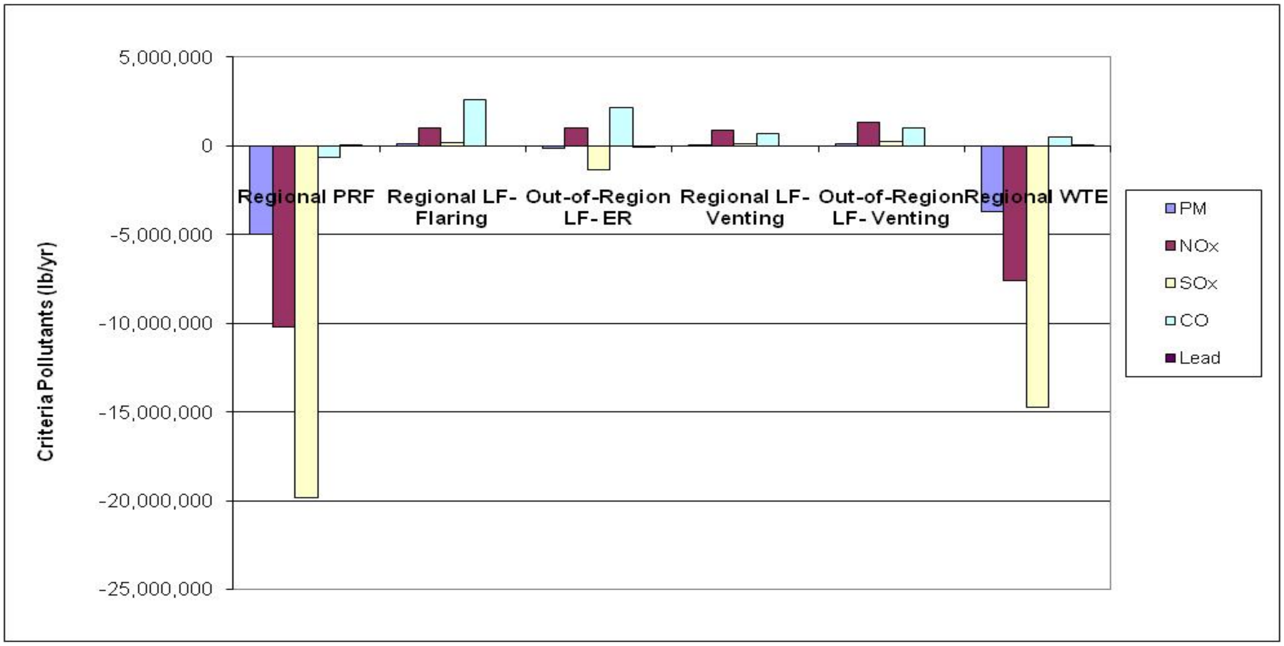
These energy savings result from the following key aspects: (1) the PRF scenario's energy production offsets the production of energy in the petroleum and utility sectors; (2) metals and aggregate recovery, and recycling from the PRF system's combustion ash offsets the consumption of energy otherwise needed to extract and process virgin materials to manufacture metals; and (3) due to the fact that PRF is burned primarily in suspension rather than completely on a traveling grate, a more complete efficient burnout is accomplished and the energy recovery per ton of waste is considerably higher.

Energy is consumed by all waste management activities (e.g., landfill operations), as well as by the processes utilized to produce energy and their material inputs, (e.g., diesel fuel, landfill liner) which are included in this analysis. Energy can also be produced by some waste management activities (e.g., PRF, landfill gas-to-energy, and mass burn WTE) and its use can be offset or avoided by other activities (e.g., metals recovery and recycling). If the energy produced and/or offset by the waste management system is greater than the energy consumed, then a net energy savings is achieved.

Criteria Pollutant Emissions

The particulate material (PM), nitrogen oxides (NOx), sulfur oxides (SOx), and carbon monoxide (CO) reductions are significantly larger in the PRF scenario due to greater utility and material recovery offsets (**Figure 2**). The WTE scenario also exhibits net emission reductions of PM, NOx, and SOx. In general, PM, NOx, and SOx reductions are mostly attributed to the utility offsets and CO reductions to the materials recovery offsets. The out-of-region landfill with energy recovery exhibits net reductions of PM, SOx, and lead (Pb) also associated with the utility offsets.

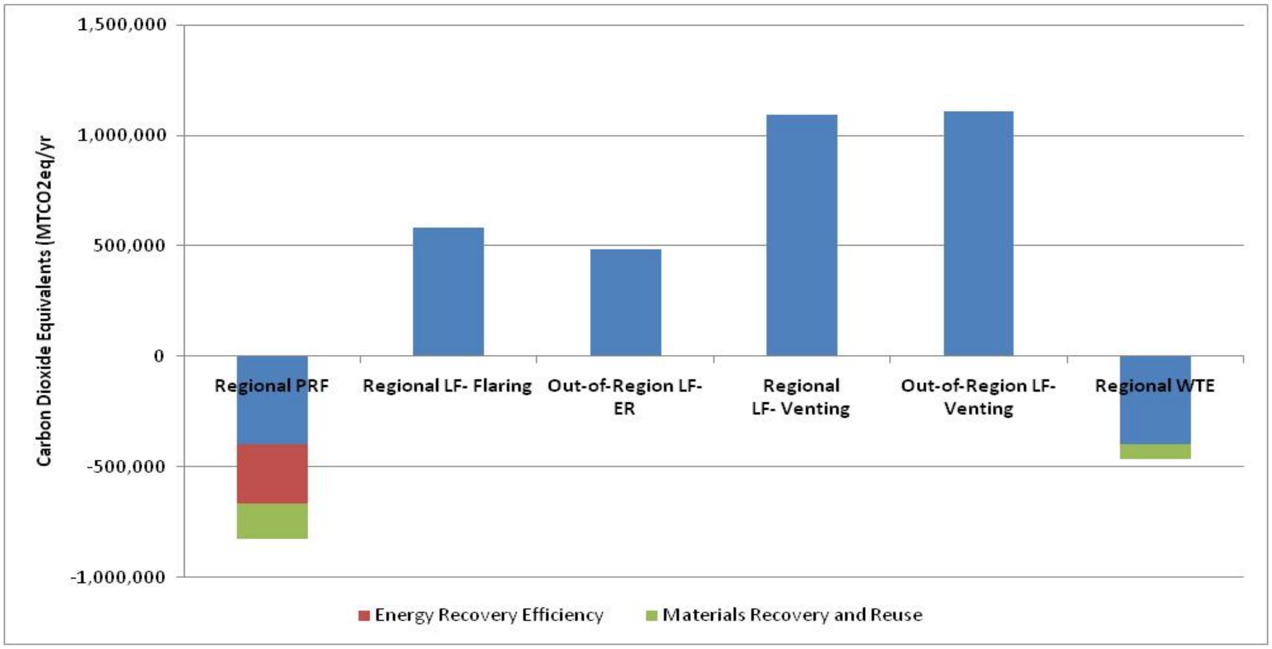
Figure 2 - Net Total Criteria Pollutant Emissions by Scenario



Greenhouse Gas (GHG) Emissions

As illustrated in **Figure 3**, the GHG emissions savings from the PRF scenario is almost double that from the WTE scenario - mostly due to enhanced energy recovery efficiency (red portion of the bars in **Figure 3**) and additional materials recovery and reuse (green portion of the bars in **Figure 3**) while all of the four landfill scenarios result in an even larger quantity of GHG emissions.

Figure 3 - Net Total Carbon Dioxide Equivalents by Scenario



this study. This means a reduction in GHG emissions of over 1.3 million MTCO2eq when the PRF system is compared to the out-of-region landfill with energy recovery and approximately 1.9 million MTCO2eq when compared to a regional or out-of-region landfill venting scenario.

GHG offsets are directly related to the following aspects: (1) electrical energy production that doesn't utilize fossil fuels offsets GHG emissions from the generation of electrical energy using fossil fuels; (2) materials recovery and recycling offsets GHG emissions by avoiding the consumption of energy that otherwise would be used in materials production processes; (3) avoidance or reduction of landfill disposal, which creates methane gas, a potent GHG; and (4) reduction of emissions associated with the additional transportation distance of waste to landfills when a PRF system is located closer to the source of waste.

GHG emissions can lead to climate change and its associated impacts. GHG emissions result from the combustion of fossil fuels and the biodegradation of organic materials (e.g., methane gas from landfills). Offsets of GHG emissions result from the displacement of fossil fuels, materials recycling, and the diversion of organic wastes from landfills. GHG emissions are reported in units of metric tons of carbon dioxide equivalents or MTCO2eq.

2.0—Methodology

Estimates for net energy consumption and GHG emissions were calculated using RTI's MSW DST. The MSW DST is a computer-based model developed by RTI in cooperation with the U.S. Environmental Protection Agency (EPA) Office of Research and Development to assist communities and MSW management planners in analyzing the full costs and life cycle environmental aspects of alternatives for MSW management. The MSW DST is populated with North American average default data, which has been modified to use site-specific data supplied by Energy Answers for its PRF technology, as well as characteristics for the Greater Baltimore Region. Users can evaluate the numerous MSW management scenarios that are feasible within a community or region and identify the alternatives that are economically and environmentally efficient, making tradeoffs if necessary. The MSW DST has undergone extensive stakeholder input and peer review (as well as a separate peer review by the U.S. EPA) and is regarded as a thorough, cutting-edge software tool that can help solid waste management planners make more informed decisions. Additional information about the MSW DST is supplied in **Appendix A** and can be obtained from RTI.

The methods used in the MSW DST to calculate the energy and environmental results are built on the principles of Life Cycle Assessment (LCA). LCA is a type of systems analysis that accounts for the complete set of upstream and downstream (cradle-to-grave) energy and environmental aspects associated with industrial systems. The technique examines the inputs and outputs from every stage of the life cycle from the extraction of raw materials, through manufacturing, distribution, use/reuse, and waste management. In the context of integrated waste management systems, an LCA tracks the energy and environmental aspects associated with all stages of waste management from waste collection, transfer, materials recovery, treatment, and final disposal. For each of the waste management operations, energy and material inputs and emissions and energy/material outputs are calculated (see **Figure 4**). In addition, the energy and emissions associated with fuels, electrical energy, and material inputs are captured.

Likewise, the potential benefits associated with energy and/or materials recovery displacing energy and/or materials production from virgin resources are captured in the life cycle results.

Energy and emissions associated with building the waste management facilities are not considered in the results. Generally, they have been found to be insignificant when compared to the energy and emissions from other life cycle stages.

Taking a life cycle perspective encourages waste management planners to consider the environmental aspects of the entire system including activities that occur outside of the traditional framework of activities from the point of waste collection to final disposal.

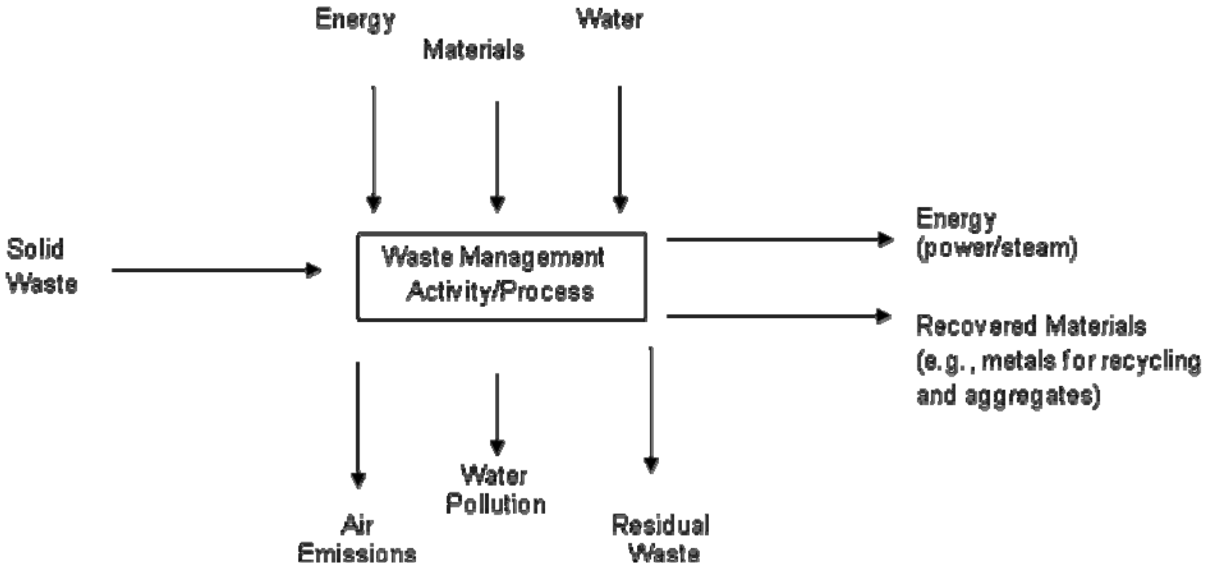


Figure 4. Life Cycle Inputs and Outputs of a Waste Management Process
All waste management processes that comprise an integrated waste management system consume energy and materials, and may produce energy, recovered materials, and emissions. Some processes, such as mass burn WTE and PRF systems, recover varying amounts of energy and materials. The benefits associated with energy and/or materials recovered are captured in the life cycle study.

3.0—Scenarios Analyzed

The primary goal of the project was to identify and quantify the net energy consumption and GHG aspects of the management of 1,460,000 tons of post-recycling MSW for the following management alternatives:

- Scenario 1: Regional PRF system with electrical energy generation and materials recovery.
- Scenario 2: Regional landfill with gas collection and flaring.
- Scenario 3: Out-of-region landfill disposal with gas collection and energy recovery, collection and transportation of waste to a transfer station, and then long-hauled to landfill using semi-tractor truck.
- Scenario 4: Regional landfill with no landfill gas management.
- Scenario 5: Out-of-region landfill disposal with no landfill gas management, collection and transportation of waste to a transfer station, and then long-hauled to landfill using semi-tractor truck.
- Scenario 6: Regional mass burn WTE system with ferrous metals recovery.

The regional PRF scenario is based on suspension combustion of PRF in a spreader-stoker boiler (as accomplished at the SEMASS Resource Recovery Facility in Massachusetts) that produces electrical energy and recovers ferrous and non ferrous metal from the combustion ash. Bottom ash is also recovered as aggregate. The electrical energy produced is used for internal power load and the remainder is delivered to the regional electricity grid. Though it is Energy Answers intent to productively utilize the fly ash recovered from the combustion process, for purposes of this study it is assumed that fly ash will be transported and disposed of in a dedicated ash landfill. Recovered metals are assumed to be recycled.

For the landfill alternatives, it is assumed that regional and out-of-region landfills are designed and operated based on the requirements established by U.S. Subtitle D landfill standards. The landfills are assumed to have a liner system, to collect and manage (i.e., treat) leachate, and to have a gas collection system. For Scenario 3, the out-of-region landfill with energy recovery, it is assumed that the MSW would be sent to the King George landfill in Virginia. This landfill is approximately 100 miles from the Baltimore area and is designed to collect and combust landfill gas in an internal combustion engine-generator that generates electricity. The electricity produced is used for internal power load and the remainder is assumed to be delivered to the regional electricity grid.

The Maryland Department of the Environment (MDE) estimates that Maryland counties and Baltimore City generated 12.4 million tons of solid waste in 2009. This total represents solid waste managed by all sources, not just Maryland permitted solid waste acceptance facilities. A total of 8.1 million tons of waste was accepted at Maryland permitted solid waste acceptance facilities. Of the 8.1 million tons, 2.7 million tons was exported to out-of-state facilities or approximately 7,400 tons per day. Therefore, the main aim of the scenarios considering transportation to out-of-state landfills is to study the environmental impacts of this waste export.

The following assumptions and conditions were applied to all scenarios analyzed (as appropriate):

- The quantity of post-recycling MSW managed in each scenario analyzed was assumed to be 1,460,000 tons per year.
- **Table 1** presents the electricity grid mix of fuels considered in this analysis. Electricity consumption, electricity offsets, and related emissions were estimated as follows:
  - For scenarios inside the Baltimore region (i.e., Scenarios 1, 2, 4 and 6), the regional grid mix (Long-Term Electricity Report for Maryland, July 15, 2011) was used.
  - For the out-of-the region landfill scenarios (i.e., Scenarios 3 and 5), the average electricity grid mix of fuels for the Mid-Atlantic Area Council, MAAC was used.

Table 1. Electricity Grid Mix of Fuels

Fuels	**MAAC** (1)	**Maryland** (2)
Coal	29%	61%
Natural Gas	37%	1%
Residual Oil	5%	0%
Distillate Oil	5%	0%
Nuclear	12%	31%
Hydro	14%	5%
Wood	0%	0%
Other	0%	2%
TOTAL(3)	**100%**	**100%**

(1) U.S. EIA (Energy Information Administration). 2011. Energy Consumption by Sector and Source, Middle Atlantic, Reference Case. Available at: http://www.eia.gov/oiaf/aeo/tablebrowser/#release=AEO2011&subject=0-AEO2011&table=2-AEO2011&region=1-2&cases=ref2011-d020911a

(2) Maryland Department of Natural Resources. 2011. Long-Term Electricity Report for Maryland. Prepared by: Exeter Associates, Inc. July 15.

(3) Values may add up to more than 100% due to rounding.

- Waste composition, as shown in **Table 2**, is based on the national average post-recycling composition developed by the U.S. Environmental Protection Agency (EPA), 2008.

Table 2. Post-Recycling MSW Composition

Waste Categories	**Percentages**
Paper and paperboard	20.7%
Glass	5.6%
Steel	6.2%
Aluminum	1.6%
Other nonferrous metals	0.3%
Plastics	16.8%
Rubber and leather	3.8%
Textiles	6.3%
Wood	8.9%
Other organic	2.0%
Food waste	18.6%
Yard trimmings	7.0%
Miscellaneous inorganic	2.3%
TOTAL	**100%**

Source: Municipal Solid Waste in the United States-2008
Facts and Figures, U.S. EPA web page at
http://www.epa.gov/epawaste/nonhaz/municipal/msw99.htm

Key assumptions used in this analysis for each waste management process are listed in **Table 3.**

Table 3. Key Assumptions by Process Used in This Analysis

Parameter	**Assumption**
General	
Waste Tonnage	1,460,000 tons
Waste Composition	See **Table 2**
Waste Collection Frequency	1 time per week
Transportation Distances	
Collection to Regional PRF	20 miles one way
Collection to Regional Landfill	20 miles one way
Collection to Transfer Station	20 miles one way
Transfer Station to Out-of-Region Landfill	100 miles one way by truck
PRF	
Basic Design	Processed Refuse Fuel^{TM} with electricity and materials recovery
Plant Heat Rate (net)	14,200 Btu/kWh
Ferrous Recovery Rate	4.86% of incoming tonnage
Aluminum Recovery Rate	0.56% of incoming waste tonnage
Assumed Offset for Energy Recovery	Average regional utility grid mix of fuels (See **Table 1**)

Parameter	**Assumption**
WTE	
Basic Design	Mass burn with electricity and ferrous metals recovery
Plant Heat Rate (net)	17,500 Btu/kWh
Ferrous Recovery Rate from Ash	4.86% of incoming tonnage (1)
Assumed Offset for Energy Recovery	Average regional utility grid mix of fuels (See **Table 1**)
Landfill	
Basic Design	Conventional, Subtitle D Type
Time Period for Calculating Emissions	100 years
Landfill Gas Collection Efficiency	50%
Landfill Gas Oxidation Rate	15%
Landfill Gas Management	Flare for regional landfill (Scenario 2). Energy recovery for out-of-region landfill (Scenario 3).
Conversion (Gas to Electricity) Efficiency for Internal Combustion Engine	33%
Assumed Offset for Energy Recovery	MAAC utility grid mix of fuels (See **Table 1**)

(1) Assumed the same recovery rate as for the regional PRF facility.

Table 4 presents the combustion emission factors used to estimate the criteria pollutant emissions from the PRF facility.

Table 4. Combustion Emission Factors

Pollutant	**Regional PRF**	**US EPA Standard**(1, 2)
SOx (ppmvd @ 7% oxygen, dry)	24	30
HCl (ppmvd @ 7% oxygen, dry)	25	25
NOx (ppmvd @ 7% oxygen, dry)	45	150
CO (ppmvd @ 7% oxygen, dry)	150	150
PM (mg/dscm @ 7% oxygen, dry)	10	20
Dioxins / Furans (ng/dscm @ 7% oxygen, dry)	13	13
VOCs (mg/dscm)	0	NA(3)

(1) U.S. EPA (2011). Title 40: Protection of Environment, PART 60—STANDARDS OF PERFORMANCE FOR NEW STATIONARY SOURCES. Subpart Eb—Standards of Performance for Large Municipal Waste Combustors for Which Construction is Commenced After September 20, 1994 or for Which Modification or Reconstruction is Commenced After June 19, 1996. e-CFR Data is current as of October 14, 201. Available at: http://ecfr.gpoaccess.gov/cgi/t/text/text-idx?c=ecfr&sid=7760d2a3d3fe46bf6ef33d3787de30fc&rgn=div6&view=text&node=40:6.0.1.1.1.15&idno=40

(2) The WTE scenario used the U.S. EPA Standard as emission factors.

(3) NA - Not Applicable. U.S.EPA does not have regulatory limits for VOCs from municipal waste combustors.

Table 5 lists the mass flow of waste for each scenario.

Table 5. Mass Flow of Waste for the Scenarios Analyzed (wet tons)

	Annual Tons Managed					
	Scenario 1— Regional PRF	Scenario 2— Regional Landfill Flaring	Scenario 3— Out-of-Region Landfill Energy Recovery	Scenario 4— Regional Landfill Venting	Scenario 5—Out-of-Region Landfill Venting	Scenario 6— Regional WTE
Collection	1,460,000	1,460,000	1,460,000	1,460,000	1,460,000	1,460,000
Long-Haul Transfer	0	0	1,460,000	0	1,460,000	0
Regional PRF	1,460,000	0	0	0	0	0
WTE	0	0	0	0	0	1,460,000
Recovered Materials	243,800	0	0	0	0	71,000
precombustion ferrous	43,500					0
post-combustion ferrous	27,500					71,000
non ferrous	9,500					0
boiler aggregate	163,300					0
Ash Landfilled	173,200	0	0	0	0	233,144
Regional Landfill	0	1,460,000	0	1,460,000	0	0
Out-of-Region Landfill	0	0	1,460,000	0	1,460,000	0

4.0—Results

The summary level results for each scenario analyzed are shown in **Table 6**. Results are presented as net totals for each scenario and waste management activity. Therefore, a positive value represents a net energy or emission whereas a negative value represents a net energy or emissions savings/avoidance. For example, a negative value for GHG emissions means that the MSW management scenario offsets (or avoids) more GHG emissions than it produces by virtue of energy and materials recovery, and displacing utility sector energy production and/or materials production from virgin resources.

Results for annual net energy consumption, criteria air pollutants, and GHG as carbon dioxide equivalents (MTCO2eq) have been charted in **Figures 5 through 8** and are discussed below.

Detailed results for each waste management process considered are presented in **Appendices B through G**.

Table 6. Summary Level Results

		Scenario					
Parameter	**Units**	**Regional PRF**	**Regional LF-Flaring**	**Out-of-Region LF-ER**	**Regional LF-Venting**	**Out-of-Region LF-Venting**	**Regional WTE**
Energy Consumption	MMBtu	-17,161,547	1,038,329	-81,882	1,038,329	1,268,238	-12,381,254
	MMBtu/ton	-44	0.7	-0.1	0.7	0.9	-17
Air Emissions							
Total Particulate Matter	lb	-4,994,624	88,764	-112,594	45,897	96,183	-3,684,839
Nitrogen Oxides	lb	-10,193,859	1,017,734	1,026,652	913,246	1,315,301	-7,583,970
Sulfur Oxides	lb	-19,804,236	150,573	-1,337,362	123,781	219,354	-14,760,331
Carbon Monoxide	lb	-651,669	2,598,662	2,133,929	669,657	983,609	527,510
Carbon Dioxide Biomass	lb	1,701,162,516	1,021,980,167	1,021,928,890	887,647,691	887,647,691	1,702,198,320
Carbon Dioxide Fossil	lb	-1,656,353,857	59,057,210	-187,398,770	59,057,210	59,057,210	-902,198,435
Carbon Dioxide Equivalents	MTCO2eq	-824,035	582,945	482,402	1,092,561	1,109,412	-466,434
Hydrocarbons (non CH4)	lb	137,619	165,378	150,875	165,378	165,378	-161,916
Lead	lb	10	1	-10	1	1	27
Ammonia	lb	-1,394	17	1	17	17	-692
Methane	lb	-6,904,503	53,310,214	52,773,067	102,158,387	102,158,387	-5,393,546
Hydrogen Chloride	lb	-476,868	32,821	10,841	7,101	7,101	384,010
Dioxins/Furans(1)	lb	NR	NR	NR	NR	NR	NR

(1) The MSW DST does not track Dioxin/Furans emissions for the all processes included in the scenarios. Therefore, the net total results are presented as Not Reported (NR).

4.1 Net Energy Consumption

Energy is consumed by all waste management activities (e.g., landfill operations), as well as by the processes utilized to produce energy and their material inputs (e.g., diesel fuel, landfill liner), which are included in this analysis. Energy can also be produced by some waste management activities (e.g., PRF, landfill gas-to-energy, and WTE) and can be offset or avoided by other activities (e.g., metals recovery and recycling). If the energy produced and/or offset by the waste management system is greater than the energy consumed, then a net energy savings is achieved. Energy use (or savings) is an important parameter in life cycle studies because it often drives the results of the study due to the significant amounts of air and water emissions associated with energy production.

For landfill gas management, this analysis assumed 50% gas capture efficiency which is the average capture efficiency of landfills in operation in the State of Maryland. This was estimated using the information in the inventory of statewide GHG emissions for calendar year 2006 available at:

http://www.mde.state.md.us/programs/Air/ClimateChange/Pages/GreenhouseGasInventory.aspx

The 50% value for capture efficiency does not take into account the periods when landfills are neither flaring nor recovering energy.

As shown in **Figures 5 and 6**, the regional PRF scenario results in the largest net energy savings, followed by the regional WTE. On a per ton of waste basis, the savings from the PRF scenario is more than twice as large as the savings from the WTE scenario. These energy savings result from the following key aspects, which are illustrated by the red and green portions of the bars in **Figure 5**:

- In the PRF and WTE scenarios, energy production offset the production of energy in the petroleum and utility sectors.
- Metals recycling and aggregate recovery from PRF combustion ash offsets the consumption of energy otherwise needed to extract and process virgin materials to manufacture metals.
- Due to the fact that PRF is burned primarily in suspension rather than on a traveling grate, a more complete efficient burnout is accomplished and the energy recovery per ton of waste is considerably higher.

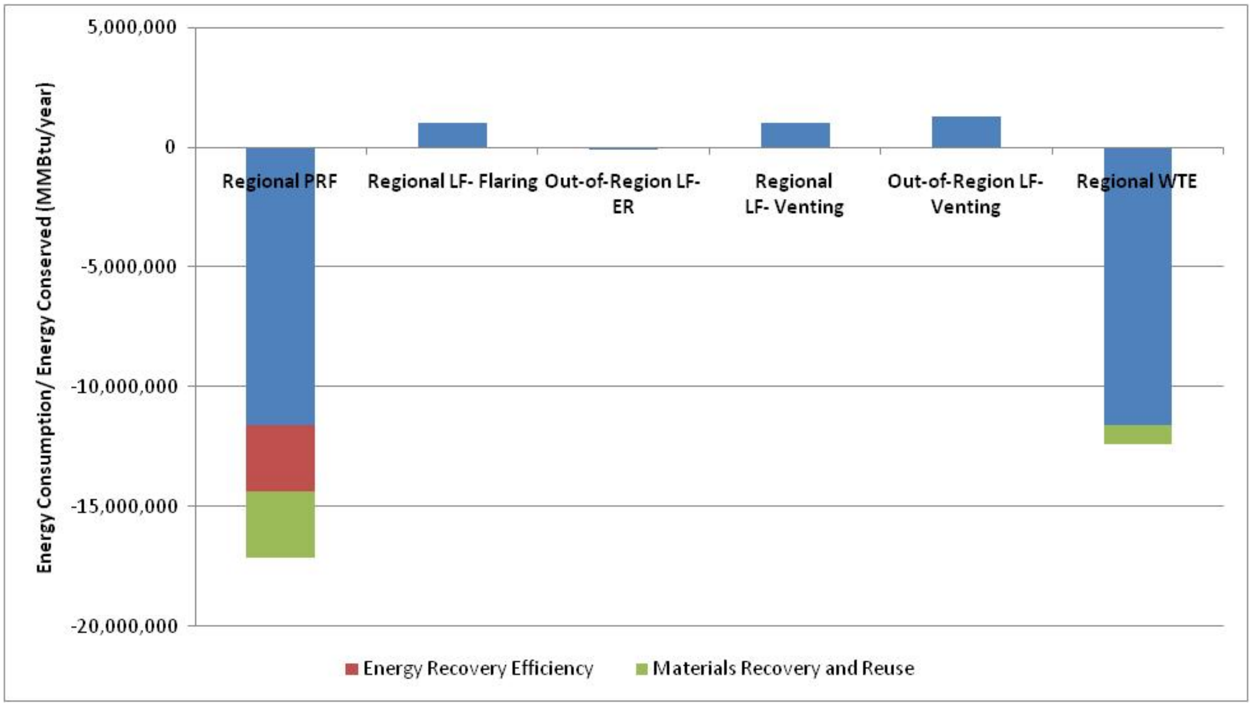


Figure 5. Net Energy Consumption/Energy Conserved by Scenario

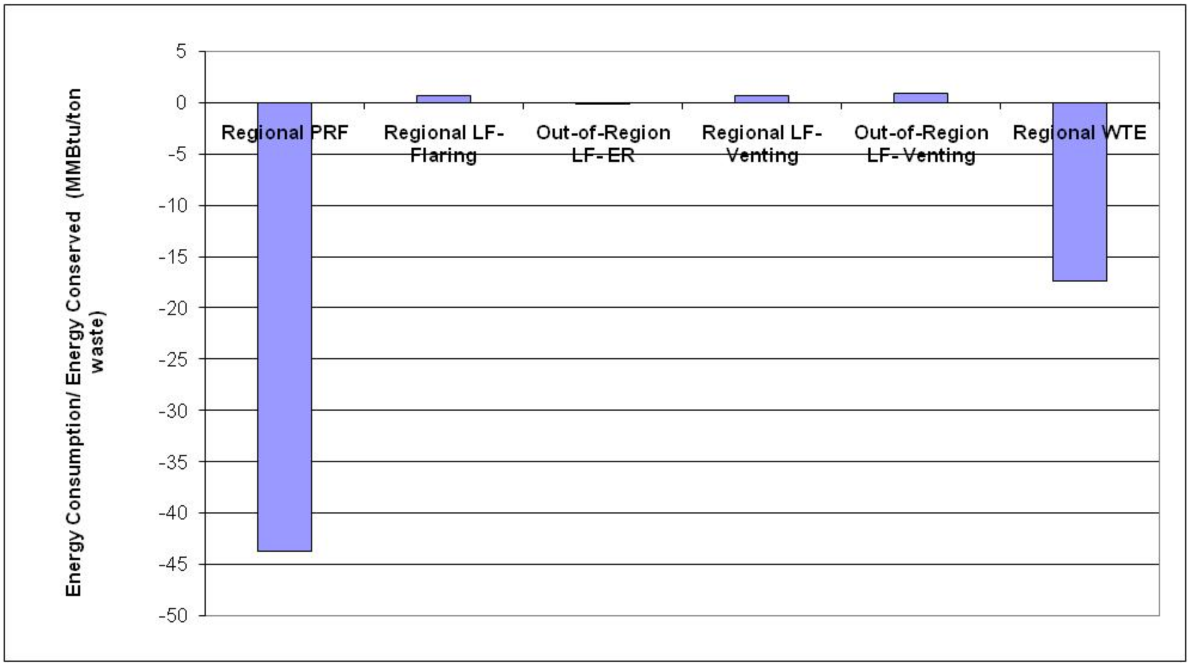


Figure 6. Net Energy Consumption/Energy Conserved per Ton of Waste by Scenario

4.2 Criteria Pollutants, Mercury and Dioxin/ Furans

The MSW DST does not provides life cycle results for mercury and dioxin/furans since there is not consistent data on emissions of these pollutants from all the processes included in the LCI for a given scenario. According to **Table 4** the PRF facility is in compliance with the regulatory standard of 13 ng/dscm @ 7% oxygen, dry for dioxin/furans. Also, the PRF resource recovery system captures 98% of the mercury in the waste, which otherwise would go to the landfill where it could be released in gases and leachate.

Figure 7 illustrates the results of the different MSW management scenarios with respect to emissions of criteria air pollutants, including particulate matter (PM), sulfur oxides (SOx), nitrogen oxides (NOx), carbon monoxide (CO), and lead (Pb). Because criteria pollutants are highly correlated to energy production, the differences in criteria pollutants generally tend to track with the differences in net energy consumption and production between the scenarios. In general, the closer the waste management alternative is to the source of waste, the lower the total emissions of PM, SOx, NOx, CO, and Pb. On a life cycle basis, transportation is a relatively insignificant factor when compared to energy and materials production (or recovery). In general, there can be significant VOCs (in addition to methane) present in landfill gas and combusting the gas can eliminate some of them. The impacts of the VOCs in landfill gas are not fully account for in this study.

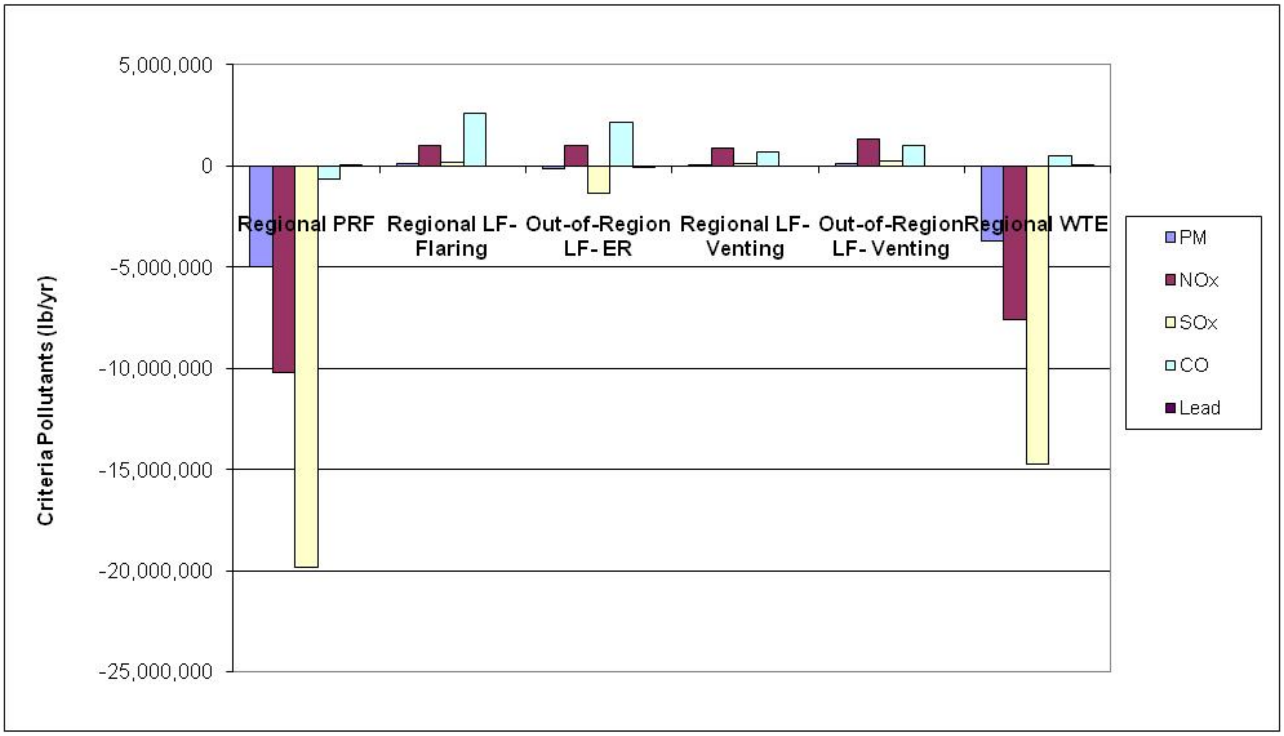


Figure 7. Net Total Criteria Pollutant Emissions by Scenario

4.2.1 Particulate Emissions

Particulate matter, or PM, is the term for particles found in the air, including dust, dirt, soot, smoke, and liquid droplets. Particles can be suspended in the air for long periods of time. They come from a variety of sources and, in the case of waste management, result largely from fuel combustion in vehicles, combustion of waste, and combustion of fuels for the production of electrical energy. PM is a major source of haze that reduces visibility, can cause erosion of structures, and can lead to health effects associated with lung and heart disease.

As shown in **Figure 7**, the regional PRF, the out-of-region landfill with energy recovery, and the regional WTE are the only scenarios that result in net PM offsets, which means a greater amount of PM emissions are avoided than created, by virtue of materials and energy recovery. No particulate dust generated from truck traffic on landfill cover has been calculated in this study.

4.2.2 Nitrogen Oxide Emissions

NOx emissions can lead to such environmental impacts as smog production, acid deposition, and decreased visibility. NOx emissions are largely the result of fuel combustion and typically are largest for waste collection activities. Offsets of NOx emissions can result from the displacement of energy production and/or the recovery and recycling of materials (which also saves energy).

According to **Figure 7** the PRF and WTE scenarios are the only ones that exhibit NOx savings. Again, the amount of NOx emissions offset by each scenario is governed largely by the NOx emissions associated with electrical energy production in the regional utility grid mix of fuels.

4.2.3 Sulfur Oxide Emissions

SOx emissions can lead to such environmental impacts as acid deposition, corrosion, and decreased visibility. Similar to NOx emissions, SOx emissions are largely the result of fuel combustion processes. Likewise, SOx emission offsets can result from the displacement of combustion activities, mainly fuels and electrical energy production, as well as the use of lower sulfur-containing fuels.

Figure 7 shows that the regional PRF, the out-of-region landfill with energy recovery, and the regional WTE scenarios result in net offsets of SOx emissions, but the PRF scenario has a larger net offset due primarily to its energy recovery efficiency and the emissions savings associated with non ferrous metals recycling.

4.2.4 Carbon Monoxide Emissions

CO is a colorless, odorless gas that is formed when carbon in fuel is not burned completely. It is a component of motor vehicle exhaust, which contributes about 56% of all CO emissions nationwide. Other sources of CO emissions include industrial processes (such as metals processing and chemical manufacturing), and power production. CO contributes to the formation of smog which can trigger serious respiratory problems.

According to **Figure 7** only the regional PRF scenario exhibits CO savings and due to the material recovery offsets. The regional landfill with gas flaring has the highest CO emissions due to the emissions from methane combustion. Complete combustion may not be achieved in flares operating outside their design conditions, and partially burned fuel may show up as carbon (smoke, soot, particulates) and/or intermediate reaction products such as CO.

4.2.5 Lead Emissions

The major sources of lead emissions have historically been motor vehicles (such as cars and trucks) and industrial sources. Due to the phase-out of leaded gasoline, metals processing is the major source of lead emissions to the air today. The highest levels of lead in the air are generally found near lead smelters. Other stationary sources are waste incinerators, utilities, and lead-acid battery recyclers and manufacturers. People, animals, and fish are mainly exposed to lead by breathing and ingesting it in food, water, soil, or dust. Lead accumulates in the blood, bones, muscles, and fat, leading to a variety of health effects. Infants and young children are especially sensitive to even low levels of lead.

As shown in **Figure 7**, lead emissions are too small for most scenarios to show up on the chart. Lead emission savings are associated with energy recovery. The out-of-region landfill with energy recovery is the only scenario exhibiting lead emission savings. In the PRF and the WTE scenarios, the lead emissions from materials remanufacturing are larger than the emission savings from energy recovery and this is the reason why these scenarios do not have overall emission savings.

4.3 GHG Emissions

GHG emissions can lead to climate change and its associated impacts. GHG emissions result from the combustion of fossil fuels and the biodegradation of organic materials (e.g., methane gas from landfills). Offsets of GHG emissions result from the displacement of fossil fuels, materials recycling, and the diversion of organic wastes from landfills. We have reported GHG emissions in units of metric tons of carbon dioxide equivalents (MTCO2eq), derived as follows:

$$\mathbf{[(Fossil\ CO_2*1) + (CH_4*21)]/2200}$$

As shown in **Figure 8**, the PRF and WTE scenarios both result in a net offset of GHG emissions, but the GHG savings from the PRF scenario is two times higher than those from the WTE scenario due to enhanced energy recovery efficiency (red portion of the bars in **Figure 8**), and additional metals and aggregate recovery and reuse (green portion of the bars in **Figure 8**). In general, GHG offsets are directly related to the following aspects:

- In the PRF and WTE scenarios, the electrical energy production offset GHG emissions from the generation of electrical energy using fossil fuels.
- Materials recovery and recycling offsets GHG emissions by avoiding the consumption of energy that otherwise would be used in virgin materials production processes.
- Landfill disposal, which creates methane gas, a potent GHG, is avoided.
- A PRF facility located close to the source of waste will reduce the associated emissions of transporting the waste to landfills.

Figure 8 also illustrates the impact on GHG emissions associated with moving from the regional landfill where gas is collected and flared (Scenario 2) to the out-of-region landfill where gas is collected and used for energy recovery (Scenario 3). The emissions offsets from energy recovery in Scenario 3 offset the additional burdens from the transfer station and long-haul transportation.

In the PRF, out-of-region landfill with energy recovery, and WTE scenarios, the amount of GHG emissions avoided via energy recovery is highly dependent on the mix of fuels that is displaced on the regional electrical energy grid. If the grid mix is largely comprised of fossil fuels, the offset will be greater than a case where the regional grid mix is comprised of significant nuclear or renewable power sources. In this analysis, the regional grid is supplied primarily by coal.

The emissions associated with long-haul transportation in the out-of-region landfill scenarios have a lesser impact in the overall results since most of the GHG emissions in these scenarios are methane emissions from landfill disposal.

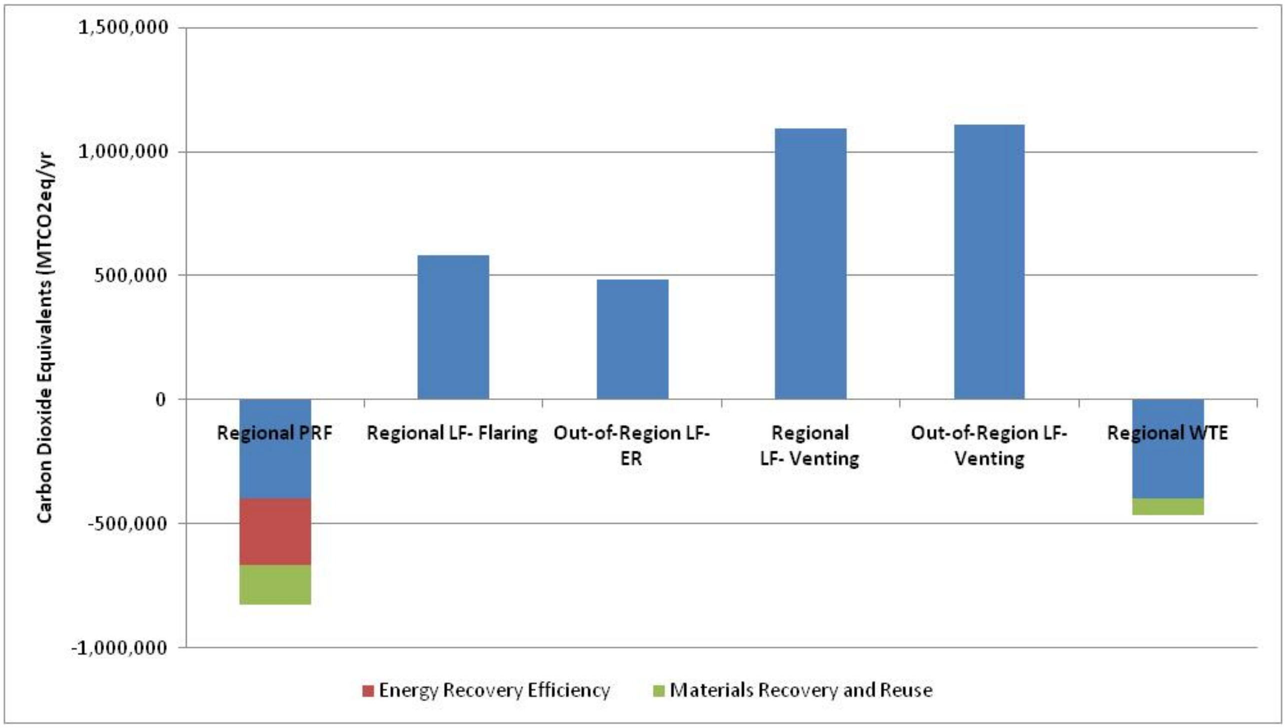


Figure 8. Net Total Carbon Dioxide Equivalents by Scenario

5.0—Conclusions

The main findings from this analysis include:

- **Energy**: <u>On a per ton of waste basis, the energy savings from the PRF scenario is more than twice as large as that from the WTE scenario (44 MMBtu/ton of waste vs. 17 MMBtu/ton of waste), which speaks to the benefits of the PRF system's enhanced energy and materials recovery efficiency.</u> The regional PRF (Scenario 1), the out-of-region landfill with energy recovery (Scenario 3) and the regional WTE (Scenario 6) are the only scenarios that offer net energy savings. The energy savings from Scenario 1 and 6 are significantly larger than those from Scenario 3 and are primarily due to the magnitude of the electrical energy generated and subsequent offsets of energy that would otherwise be consumed to mine and process fuels that the regional electric utilities rely on. The net energy savings for the PRF scenario is over 17,000,000 MMBtu per year and for the WTE scenario the savings is over 12,000,000 MMBtu per year. To a lesser degree, energy savings are also realized due to the material recovery and recycling, which is close to 2,800,000 MMBtu per year for the PRF scenario and close to 800,000 MMBtu per year for the WTE scenario. Due to the fact that PRF is burned primarily in suspension rather than on a traveling grate, a more complete burnout is accomplished and the energy recovery per ton of waste is considerably higher.

- **Criteria pollutants**: <u>The particulate material (PM), nitrogen oxides (NOx), sulfur oxides (SOx), and carbon monoxide (CO) reductions are significantly larger in the PRF scenario due to greater utility and material recovery offsets.</u> The WTE scenario also exhibits net emission reductions of PM, NOx, and SOx. In general, PM, NOx, and SOx reductions are mostly attributed to the utility offsets and CO reductions to the materials recovery offsets. The out-of-region landfill with energy recovery exhibits net reductions of PM, SOx, and lead (Pb) also associated with the utility offsets.

- **Greenhouse gas (GHG) emissions**: <u>The regional PRF will reduce GHG emissions by over 1.3 million MTCO2eq when compared to the out-of-state landfill with energy recovery and approximately 1.9 million MTCO2eq when compared to a regional or out-of region landfill venting scenario.</u> The regional PRF and WTE scenarios are the only ones that exhibit net GHG emission savings, with the PRF savings being almost twice as large as the WTE's (824,035 metric tons of carbon dioxide equivalents (MTCO2eq) vs. 466,434 MTCO2eq for the WTE). This translates to approximately 0.6 MTCOeq reduced per every ton of waste managed at the PRF facility and according to the specific data/assumptions used in this study. These savings are mostly attributed to the utility offsets.

  In comparing the net total GHG emissions from the regional PRF scenario with those from the landfill scenarios, the landfill alternative produced between 2 and 4 times more CO2-equivalent emissions than the PRF alternative. This range is based on GHG emissions, namely CH4 and CO2, and converting these emissions into CO2 equivalents using the factor of 23 for CH4 and 1 for CO2 from fossil sources. CO2 from biogenic sources are given a weight of zero. Other analyses of WTE systems versus landfills have produced different results. In particular, Eschenroeder (2001)[1] found landfills to potentially generate 45 to 115 times greater radiative forcing than WTE systems. Eschenroeder went beyond the comparison of emissions and GHG equivalents to the analysis of the atmospheric responses to the GHG emissions by conducting a "perturbation" analysis using the model data (IS92a) developed by the Intergovernmental Panel on Climate Change (IPCC) as the unperturbed solution. Such an analysis of atmospheric response was not conducted as part of this analysis.

  Thorneloe, Weitz and Jambeck (2005 and 2006)[2] analyzed different waste management scenarios including one with 30% of the waste being recycled and 70% used at a WTE facility and showed this scenario as the best overall performer according to energy and emission results. A straight comparison between the results of Thorneloe, Weitz and Jambeck (2005 and 2006) and those from this study cannot be performed since there are important differences in the input parameters and assumptions for the studies. Key differences include: different grid mix of fuels used to estimate energy and emission offsets from electricity generation, different waste composition, different energy and material recovery efficiencies for the WTE facilities, and results that represent scenarios where both recycling and combustion of post-recovery waste with energy recovery are assumed.

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[1] Eschenroeder, Alan. 2001. Greenhouse Gas Dynamics of Municipal Solid Waste Alternatives. Journal of Air and Waste Management Association. 51:1423-1427.

[2] Thorneloe, S., Weitz, K., and Jenna Jambeck. 2005. Moving From Solid Waste Disposal to Management in the United States. October.

Thorneloe, S., Weitz, K., and Jenna Jambeck. 2006. Application of the U.S. Decision Support Tool for Materials and Waste Management. Available at: http://www.wte.org/userfiles/file/Thorneloe2006.pdf

In general, scenarios that recover energy and/or materials (i.e., Scenario 1- regional PRF, Scenario 3- out-of-the region landfill with energy recovery, and Scenario 6- regional WTE) perform best on a life cycle basis. The benefits accrued from energy recovery processes are based on the avoided requirements to obtain energy from other sources, for example:

- The dirtier the displaced energy source (e.g., coal), the greater the offset/benefit.
- Alternative/renewable energy sources (e.g., wind/solar) generally have less beneficial offsets.
- Where the energy recovered replaces the use of fossil fuels, the environmental benefits are augmented, especially with regard to GHG emissions and climate change potential. Such is the case with the regional PRF where the regional grid is supplied primarily by coal.

When comparing the landfill scenarios, the results of this analysis confirm that landfill emissions will be higher from systems that mostly rely on flaring the gas as opposed to using it for energy recovery. In addition, potential variation in the energy recovery efficiency will also have a large impact on the overall GHG emissions and net energy consumption requirements. For example, high efficiency internal combustion engines (ICEs) will generate more electricity per gas volume and would displace a similar amount of electricity produced with conventional fuels. Therefore, the landfill will be credited with the avoided burdens of conventional electricity production.

6.0—Uncertainties and Limitations

The following are some limitations and sources of uncertainty identified for this study:

- Landfill collection efficiency: A vital parameter when simulating a landfill is the efficiency of the landfill gas extraction. While the captured quantities are used for electricity and/or heat production, losses inherent with this procedure determine the methane emissions from the landfill. This analysis assumed 50% capture efficiency, which is the average capture efficiency of landfills in operation in the State of Maryland, estimated using the information in the inventory of statewide GHG emissions for calendar year 2006 available at:

  http://www.mde.state.md.us/programs/Air/ClimateChange/Pages/GreenhouseGasInventory.aspx

  The 50% value for capture efficiency does not take into account the periods when landfills are neither flaring nor recovering energy. Therefore, we may be underestimating the GHG emissions of landfills in this study.

- Mercury and dioxin/furans: The MSW DST does not provide life cycle results for mercury and dioxin/furans since there is not consistent data on emissions of these pollutants from all the processes included in the LCI for a given scenario. This is an important limitation of this study since both pollutants have been identified as posing significant risk to human and ecosystem health. Mercury is found in a variety of products, such as fluorescent and other lights and batteries, much of which ends up in municipal landfills. The mercury contained in these products can evaporate into the air or leach into the groundwater from the landfills. Mercury leaching from landfills into groundwater has been studied more than air emissions. Available data show that mercury in groundwater can exceed drinking water standards from older, unlined landfills, but is less likely to leach into groundwater from landfills that are lined and use leachate collection systems. Depending on how the leachate is treated, however, mercury collected in leachate systems may reenter the environment. Also, waste combustion, in particular certain wastes such as PVC plastics with high chloride contents are potential sources of dioxin/furan emissions. However, the improvement in air pollution control technology has significantly reduced these emissions.

- <u>Energy and emissions associated with construction of the different facilities:</u> Another source of uncertainty in the results is the impact of the energy and emissions associated with construction of the different facilities. This study does not consider the energy and emissions associated with the construction of any of the waste management facilities. However, studies like Sich and Barlaz (2000)[3] have found that when landfill gas is not recovered for energy, the effect of construction on the landfill life cycle inventory (LCI) is more significant for some LCI parameters, and that it could increase the energy consumption and GHG emissions by over 3 percent and some of the criteria pollutant emissions, ranging from approximately 2% for SOx to approximately 9% for PM. RTI could not find any data/analyses to gauge how significant the impact of energy and emissions from construction of other waste management facilities such as the PRF and the WTE is.

- <u>Landfill characterization data:</u> As with any modeling results, there is inherent uncertainty in the results of this study. While this analysis uses general waste, infrastructure, and management characteristics of the landfill disposal processes/facilities, it does not reflect a highly detailed and comprehensive data collection effort specific to each process/facility. Based on uncertainty analyses performed with the MSW DST results, as a general rule-of-thumb, RTI uses a threshold of 20 percent difference in the results to indicate a significant difference between scenarios. A difference of 10 percent or less is not significant; a difference of 10 to 20 percent may be significant in some contexts. A difference greater than 20 percent could be considered significant.

- <u>Carbon storage and sequestration</u>: Another aspect of the quantitative analysis that may lead to results that differ from other, similar analyses is the treatment of carbon storage and sequestration. This MSW DST analysis presents only GHG emissions and GHG emissions offsets associated with materials and energy recovery. We did not attempt to quantify potential carbon storage and sequestration for long term storage of biogenic carbon in landfills. The impact of

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[3] Sich, Barbara and Morton Barlaz, 2000. Process model documentation: calculation of the cost and life-cycle inventory for waste disposal in traditional, bioreactor, and ash landfills, July. Available at: https://mswdst.rti.org/docs/Landfill_Model_OCR.pdf

excluding this potential benefit is that the GHG emissions for landfills are higher than they would be if the carbon storage and sequestration benefits were included. The significance of this depends on the tonnage of organic material landfilled.

- Time period over which the landfill emissions are integrated: This analysis uses 100 years as the time period over which the landfill emissions are integrated, but there is ongoing debate around this since emissions from landfills can spread over very long time periods, often thousands of years or longer. This issue is critical, especially for plastics, as they are made of fossil carbon and their degradation is very slow, so that emissions take place over a time horizon that largely exceeds 100 years.

- Landfill fires have been identified as a significant source of uncontrolled emissions. However, due to the unpredictable nature and potential variations in magnitude of this type of event we have not factored the impact of landfill fires into this study.

Appendix A

Background Information about the MSW DST

The MSW DST was developed through a cooperative agreement between the U.S. EPA's Office of Research and Development and RTI's Center for Environmental Analysis to assist communities and other waste planners in conducting cost and environmental modeling of MSW management systems. Users can evaluate the numerous MSW management scenarios that are feasible within a community or region and identify the alternatives that are economically and environmentally efficient, making tradeoffs if necessary.

The MSW DST allows users to analyze existing waste management systems and proposed future systems based on user-specified information (e.g., waste generation levels, waste composition, diversion rates, and infrastructure). The current components included in the MSW DST are waste collection, transfer stations, material recovery facilities (MRFs), mixed MSW and yard waste composting, combustion and refuse-derived fuel production, and conventional or bioreactor landfills. Existing facilities and/or equipment can be incorporated as model constraints to ensure that previous capital expenditures are not negated by the model solution.

As illustrated in **Figure A-1,** the MSW DST consists of several components, including process models, waste flow equations, an optimization module, and a graphic user interface (GUI). The process models consist of a set of spreadsheets developed in Microsoft Excel. These spreadsheets use a combination of default and user-supplied data to calculate the cost and life cycle coefficients on a per unit mass basis for each of the 39 MSW components being modeled for each solid waste management unit process (collection, transfer, etc.). Each process model describes and represents the essential activities that take place during the processing of waste items. For example, the collection model includes parameters for waste collection frequency, collection vehicle type and capacity, number of crew members, and number of houses served at each stop. Although national average default values are included in the MSW DST for such parameters, users can override the default values with site-specific information. These operational details, which are input by the user to represent an MSW management system, are then synthesized in the process model to estimate the cost of processing as a function of the quantity and composition of the waste entering that process. The resulting cost coefficients from each waste management process model are then used to estimate the cost of that option.

The MSW DST also contains models for ancillary processes that may be used by different waste management processes. These models calculate emissions for fuels and electrical energy production, materials production, and transportation. Electricity, for example, is used in every waste management process. Based on the user-specified design information and the emissions associated with generating electricity from each fuel type, the MSW DST calculates coefficients for emissions related to the use of a kilowatt hour of electricity. These emissions are then assigned to waste stream components for each facility that uses electricity and through which the mass flows. For example, MRFs use electricity for conveyors and facility lighting. The emissions associated with electricity generation would be assigned to the mass that flowed through that facility. Users can specify whether the emissions associated with generating electrical energy are based on a national, regional, or user-defined mix of fuel.

The optimization module is implemented using a commercial linear programming solver called CPLEX. The model is constrained by mass flow equations that are based on the quantity and composition of waste entering each unit process and that intricately link the different unit processes in the waste management system (i.e., collection, recycling, treatment, and disposal options). These mass flow constraints preclude impossible or nonsensical model solutions. For example, these mass flow constraints will exclude the possibility of removing aluminum from the waste stream via a mixed waste MRF and then sending the recovered aluminum to a landfill. The optimization module uses linear programming techniques to determine the optimum solution consistent with the user-specified objective and mass flow, and user-specified constraints. Examples of user-specified constraints are the use of existing equipment/facilities and a minimum recycling percentage requirement.

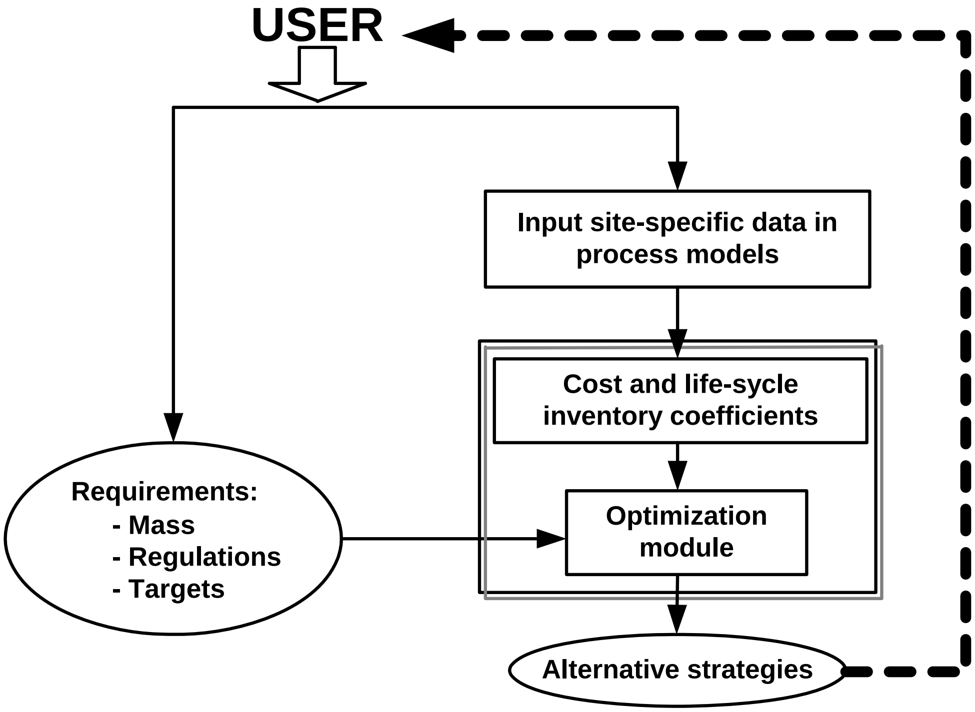

Figure A-1. Conceptual Framework for the MSW DST.

The environmental aspects associated with a defined MSW management scenario are estimated in terms of annual net cost, energy consumption, and environmental releases (air, water, solid waste). For example, waste collection vehicles consume fuel and release several types of air pollutants in their exhaust. The collection process model of the MSW DST uses information about the quantity and composition of waste generated and a host of collection route parameters to estimate the amount of fuel consumed and air emissions by waste constituent collected. In addition, the environmental burdens associated with producing the fuel used in the collection vehicles are calculated and included in the collection results. All process modules in the MSW

DST operate in a similar manner and express results as a function of the quantity and composition of the waste entering each process.

In some waste management processes, cost, energy, and emission offsets may occur. For example, diverting recycling materials from the waste stream results in a revenue stream and can displace energy consumption and emissions associated with virgin materials production. Similarly, waste management processes that recover energy (e.g., PRF, landfill gas utilization) will displace energy production in the utility sector and thereby avoid fossil fuel production- and combustion-related emissions. In applying the MSW DST, any materials or energy recovery-related benefits are netted out of the results for each process.

Appendix B. Detailed Results for Scenario 1: Regional PRF with Electrical Energy and Materials Recovery

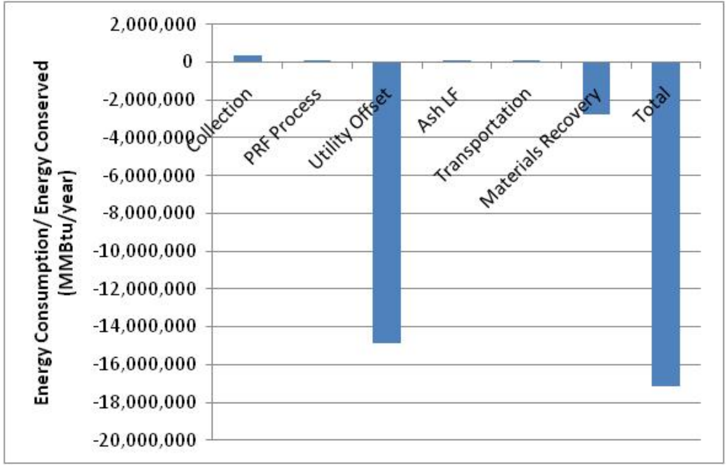

Figure B-1. Net Energy Consumption/Energy Conserved by Process

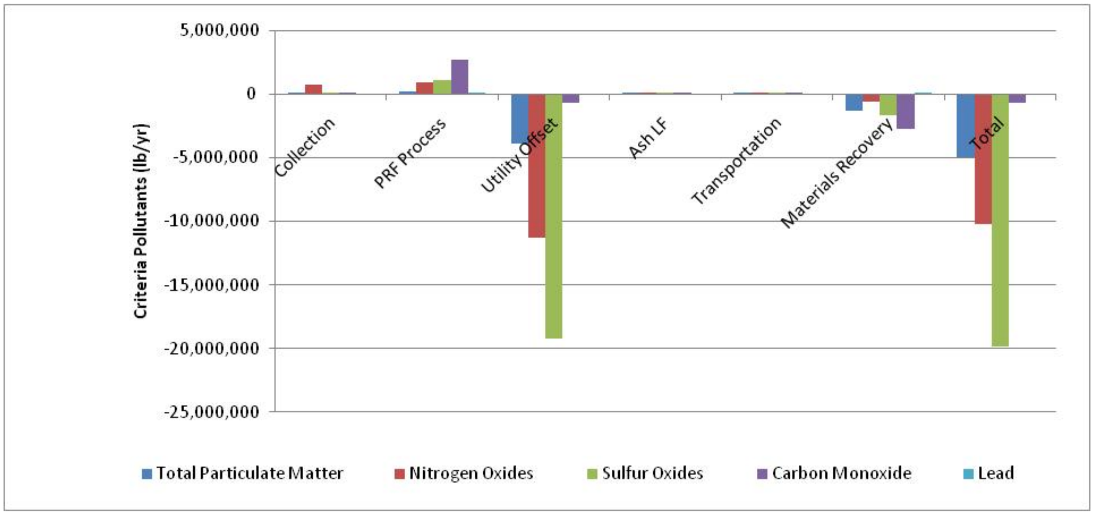

Figure B-2. Net Total Criteria Pollutant Emissions by Process

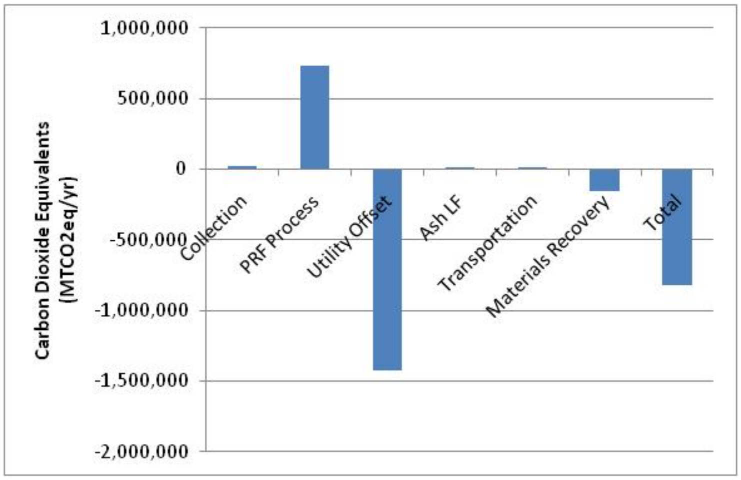

Figure B-3. Net Total Carbon Dioxide Equivalents by Process

Appendix C. Detailed Results for Scenario 2: Regional Landfill with Gas Collection and Flaring

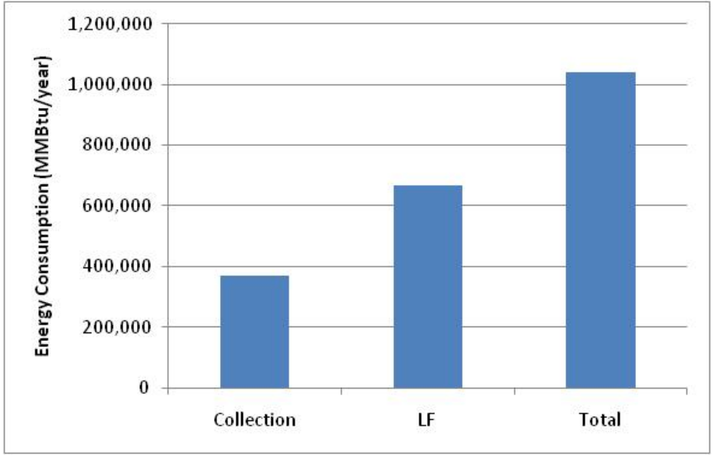

Figure C-1. Net Energy Consumption by Process

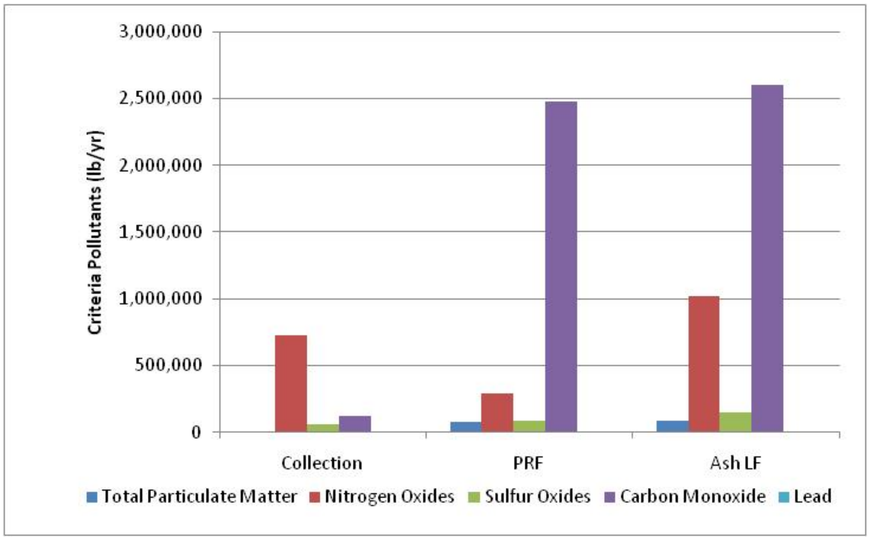

Figure C-2. Net Total Criteria Pollutant Emissions by Process

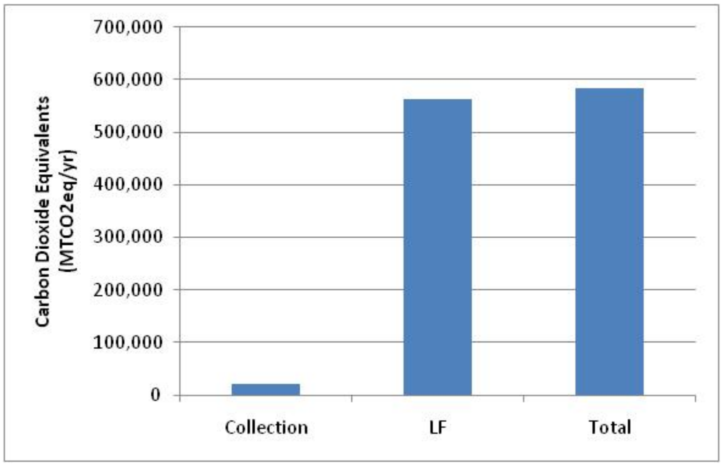

Figure C-3. Net Total Carbon Dioxide Equivalents by Process

Appendix D. Detailed Results for Scenario 3: Out-of-Region Landfill Disposal with Gas Collection and Energy Recovery

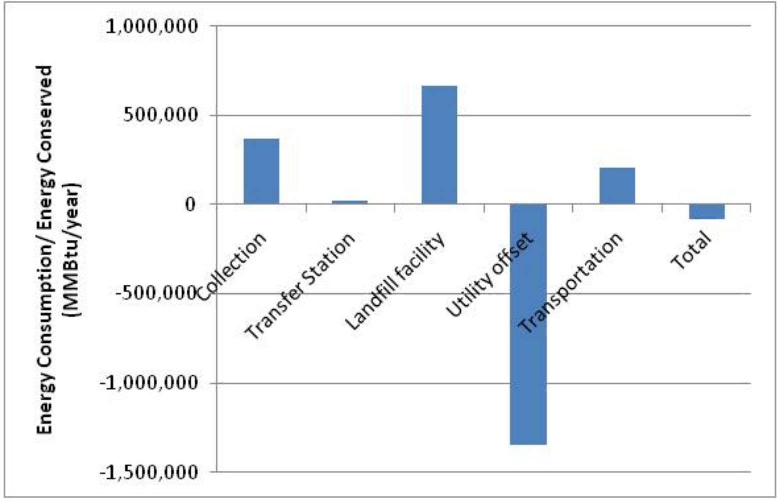

Figure D-1. Net Energy Consumption/Energy Conserved by Process

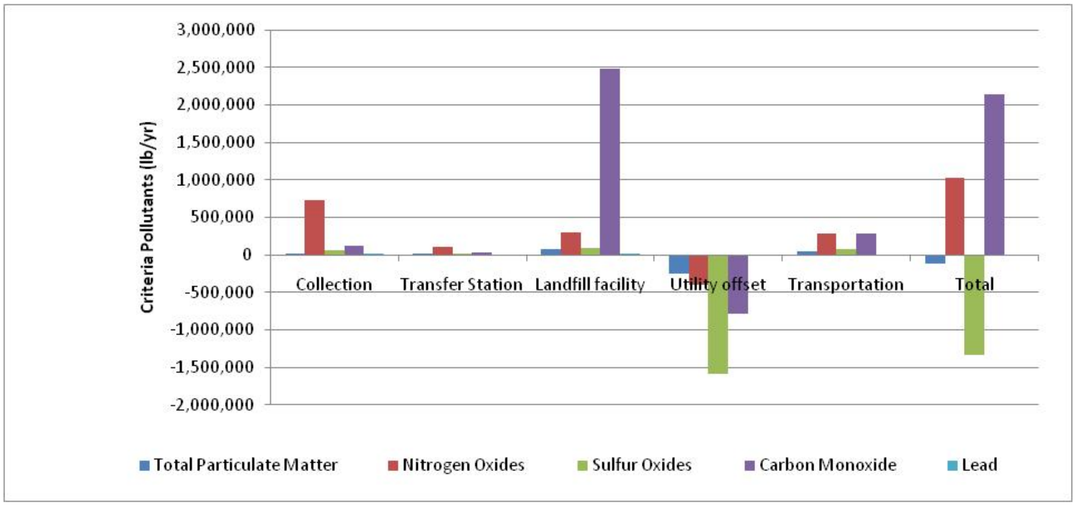

Figure D-2. Net Total Criteria Pollutant Emissions by Process

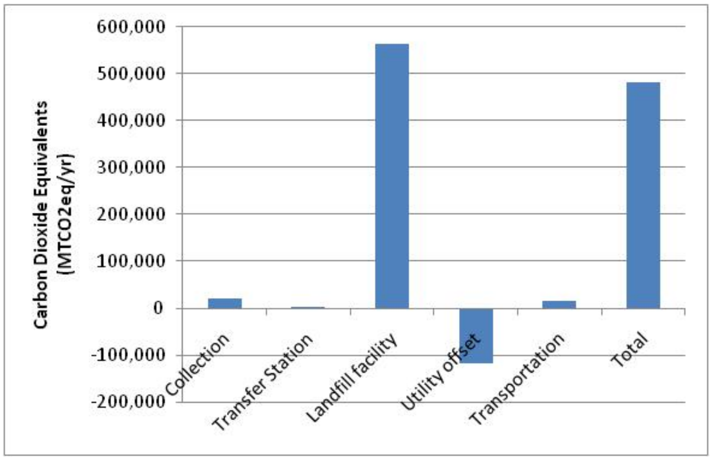

Figure D-3. Net Total Carbon Dioxide Equivalents by Process

Appendix E. Detailed Results for Scenario 4: Regional Landfill with No Landfill Gas Management

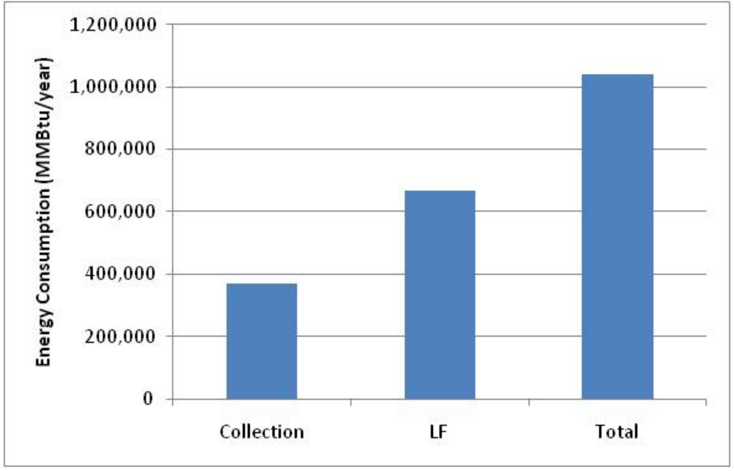

Figure E-1. Net Energy Consumption by Process

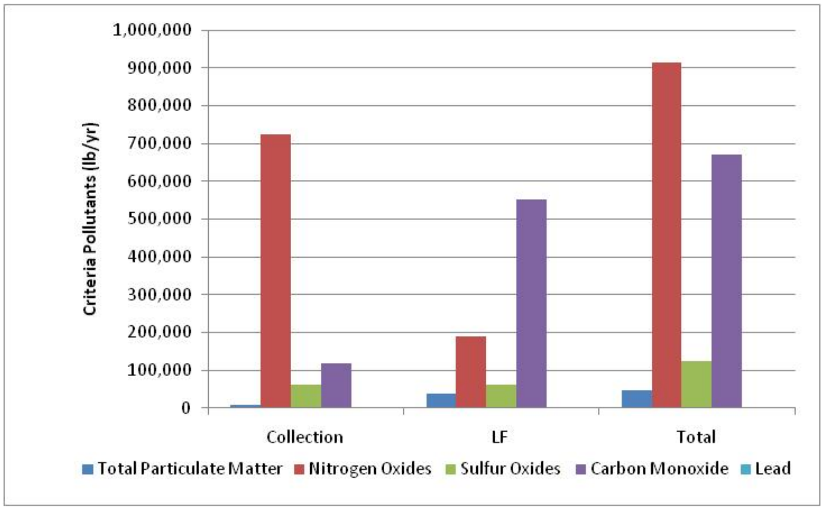

Figure E-2. Net Total Criteria Pollutant Emissions by Process

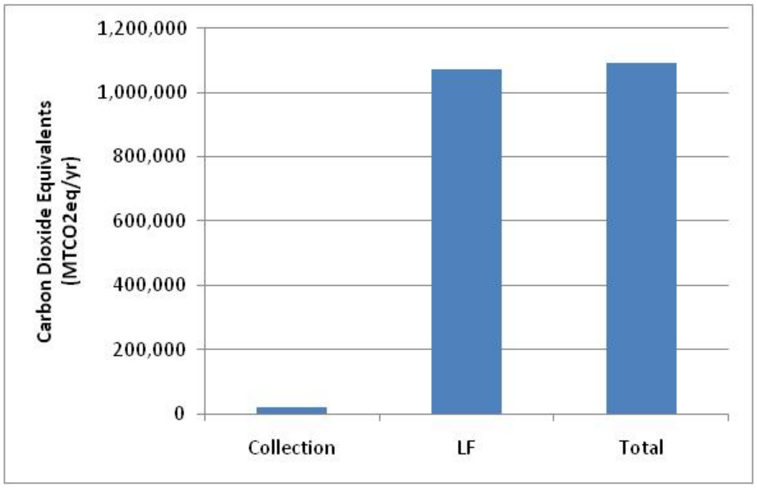

Figure E-3. Net Total Carbon Dioxide Equivalents by Process

Appendix F. Detailed Results for Scenario 5: Out-of-Region Landfill Disposal with No Landfill Gas Management

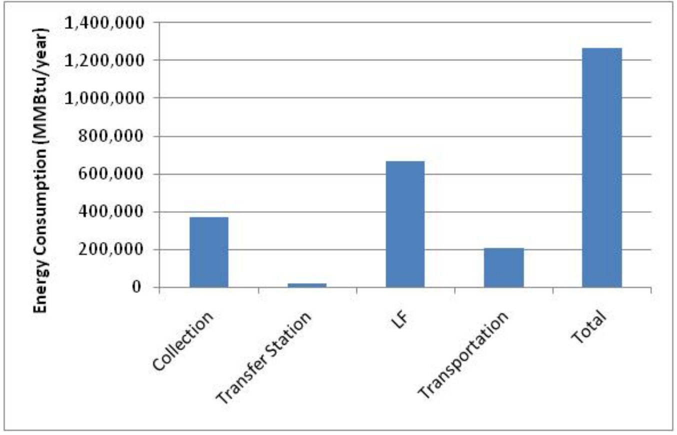

Figure F-1. Net Energy Consumption by Process

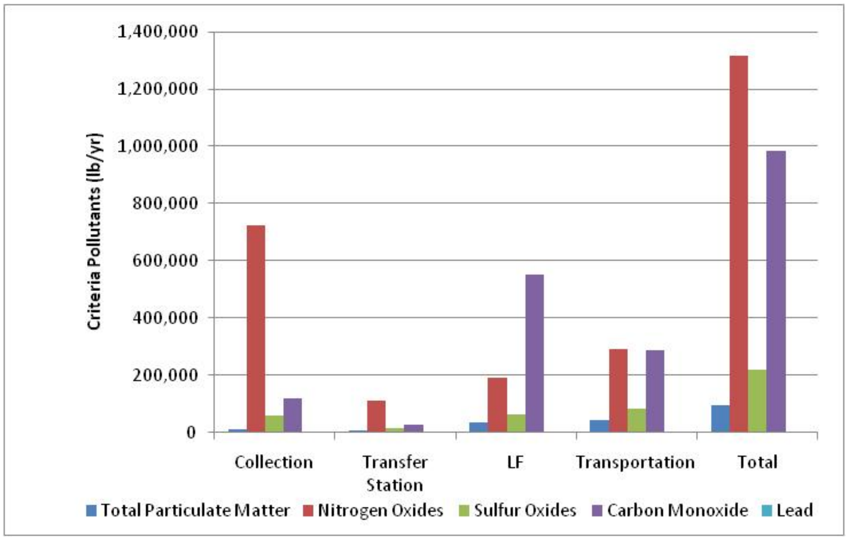

Figure F-2. Net Total Criteria Pollutant Emissions by Process

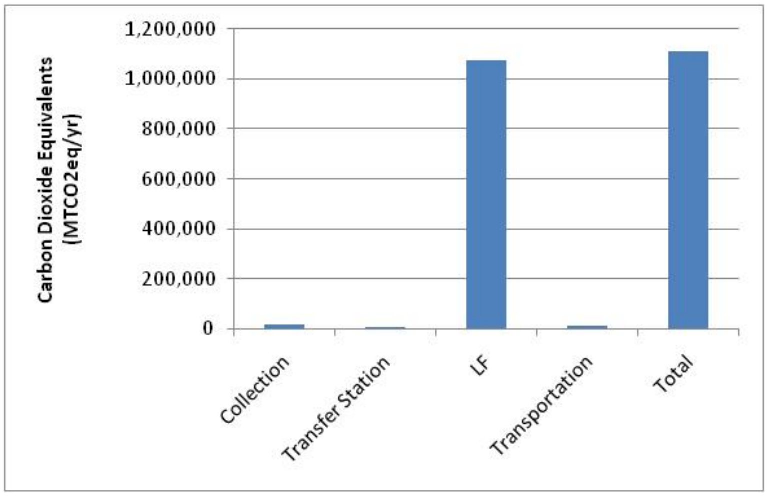

Figure F-3. Net Total Carbon Dioxide Equivalents by Process

Appendix G. Detailed Results for Scenario 6: Regional WTE

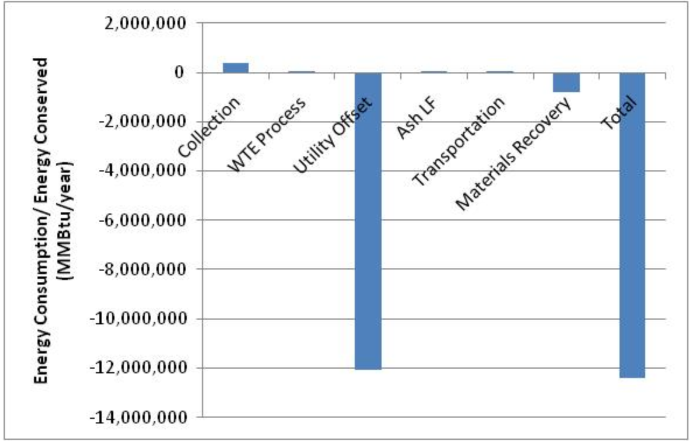

Figure G-1. Net Energy Consumption/Energy Conserved by Process

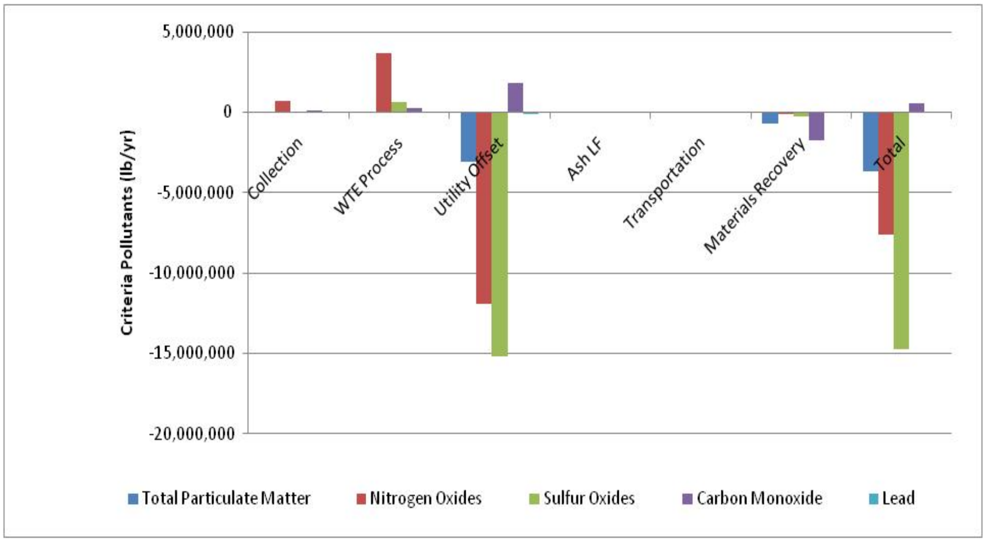

Figure G-2. Net Total Criteria Pollutant Emissions by Process

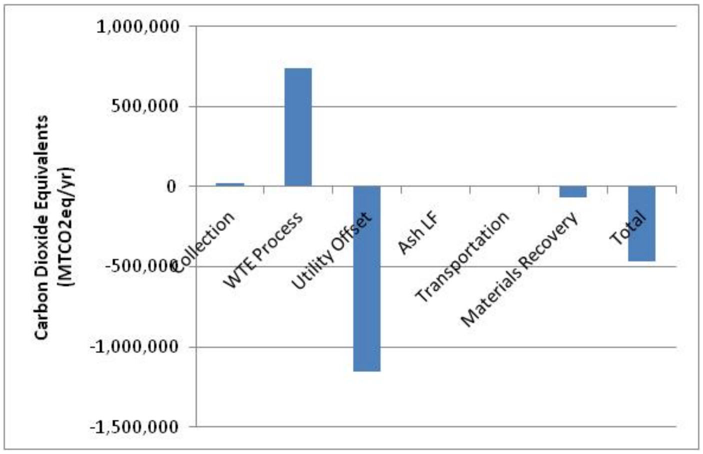

Figure G-3. Net Total Carbon Dioxide Equivalents by Process