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Sustainable Cities: Key Considerations in the Selection of Strategies to Optimize Solid Waste Management

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Contents

About the Authors i

Acknowledgments ii

Abstract ii

Introduction 1

Methods 2

Waste Composition and City-Specific Data 3

Waste Management Strategy Modeling 6

Results and Discussion 9

Minimizing GHG Emissions Results 11

Cost Results 13

Energy Consumption Results 14

Criteria Air Pollutants Emission Results 15

Limitations 17

Conclusions 18

References 20

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Abstract

Cities often have limited financial resources for sustainability planning, including sustainable solutions for municipal solid waste (MSW) management. In this paper, we investigate MSW management strategies designed to meet two common environmental goals: reducing greenhouse gas (GHG) emissions and achieving zero waste by maximizing materials recovery. We analyzed strategies using data collected from a range of low- to high-income cities around the world. We inputted these data into RTI's Municipal Solid Waste Decision Support Tool and used the tool to identify the waste management strategies for each city that best met these two environmental goals. We compared results among the cities and strategies and then highlighted the limitations of designing sustainable programs based on a single goal. Strategies for minimizing GHG emissions and for maximizing materials recovery can have significantly different environmental impacts in the same city, ranging from net savings under one strategy to net emissions under another. We were able to explain many of these differences by considering the regional differences in waste composition—in particular, the amount of recyclable commodity materials—and the energy and emissions savings associated with displacing conventional fuels in waste-to-energy processes for the strategies that included these processes.

Introduction

In general terms, a sustainable city incorporates resource conservation, social values and needs, and economic development into its infrastructure, policies, and activities. Sustainable cities continually seek ways to lower their energy consumption, greenhouse gas (GHG) emissions, and overall environmental footprint while enhancing economic growth and improving social well-being. Reducing the generation of waste and sustainably managing waste that is generated are important components of a sustainable city.

According to the World Bank (2012), each day over 1.1 million metric tons of waste are disposed of in open dump sites and engineered landfills. Consistently, the field data used in this analysis showed that in many cities, most of the waste collected was disposed of in dump sites and landfills. Depending on the management conditions of such sites, various pollutants can be emitted that pose a human and an ecological risk, and many materials that could be recycled or transformed into marketable resources are simply buried.

The World Bank (2012) reports that "GHG emissions from MSW [municipal solid waste] have emerged as a major concern as post-consumer waste is estimated to account for almost 5 percent (1,460 MTCO2e [million metric tons of carbon dioxide equivalent]) of total global greenhouse gas emissions. Solid waste also includes significant embodied GHG emissions. For example, most of the GHG emissions associated with paper occur before it becomes MSW. Encouraging waste minimization through MSW programs can have significant up-stream GHG minimization benefits" (p. 29). Furthermore, a US Environmental Protection Agency (EPA) (2006) report on the life cycle assessment of solid waste shows that 12 percent of total global methane emissions, a potent GHG, come from landfills. Initiatives from government agencies and nongovernmental organizations aim for sustainable waste management that includes reducing material demand and consumption, increasing consumer recycling and reuse, increasing materials recovery from the waste stream, and minimizing the amount of GHG emissions from the entire material life cycle.

In this study, we focused on two common MSW management initiative goals: minimizing GHG emissions from waste management and achieving zero waste by maximizing materials recovery. Our aim was to identify the strategies that best meet these goals across a wide range of cities and identify the factors that have the greatest impact on the selection of strategies and the resulting cost and environmental performance. Using the results of this study, solid waste managers and decision makers around the world can be better equipped to evaluate the viability of various waste management processes and technologies and can more efficiently use their resources on those shown to be more promising.

Many studies have evaluated the cost and GHG emissions associated with integrated solid waste management strategies in specific locations (e.g., Chen & Lin, 2008; Koroneos & Nanaki, 2012; Liamsanguan & Gheewala, 2008; Menikpura, Gheewala, & Bonnet, 2012; Menikpura, Sang-Arun, & Bengtsson, 2013). However, these studies did not compare environmental and cost impacts associated with a wide range of MSW composition and locations having contrasting geographic and socioeconomic characteristics. The World Bank (2014) conducted a study focused on cost-effective strategies for climate change mitigation and low-carbon development across various sectors of the economy such as energy, transportation, industry, and waste. However, this World Bank study followed GHG emissions inventory guidelines such as those put forth by the Intergovernmental Panel on Climate Change (2006), which account for the impact of activities such as recycled product manufacturing under different sectors of the economy (e.g., the energy sector and the industrial processes sectors). Although cities need GHG inventories, they are limited in scope. Solid waste officials and decision makers also need to know the broader range of impacts such as energy consumption, local air pollutants, and cost. In addition, the recovery of materials or energy products from waste needs to be included as part of the waste management sector to understand potential revenue streams from their sale and associated environmental benefits.

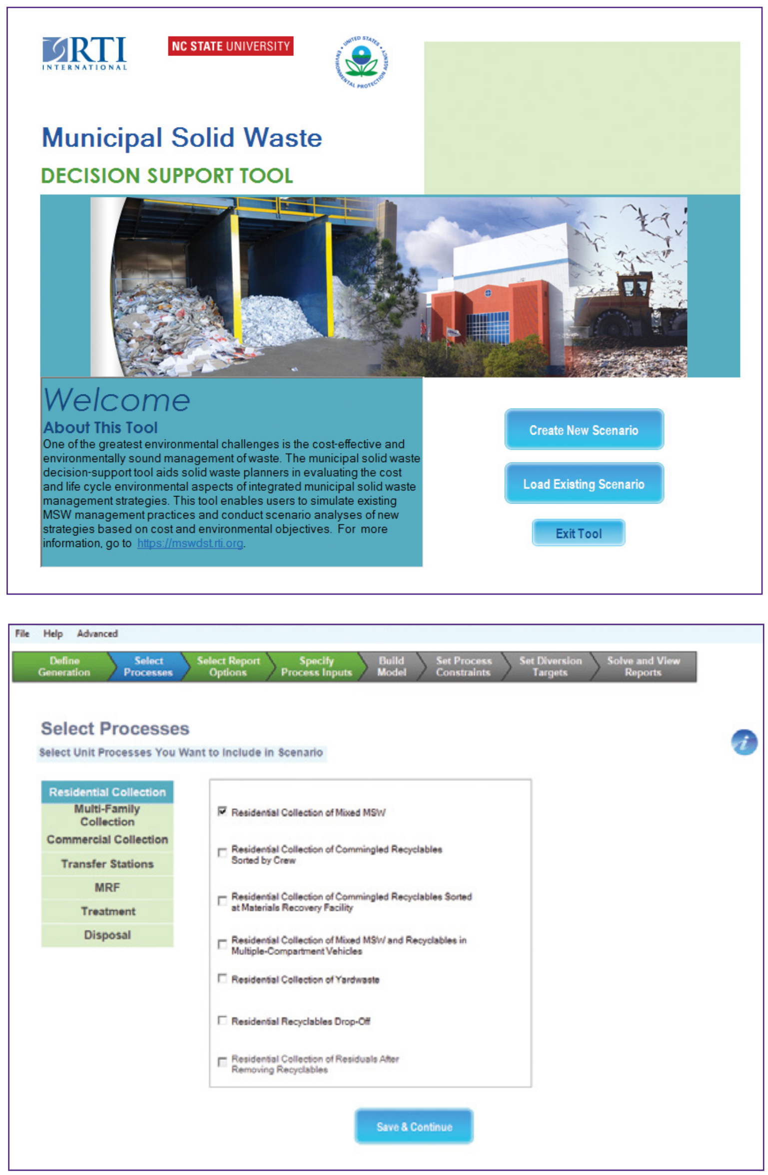
In our study, we used a more comprehensive life cycle approach that considers all upstream and downstream environmental impacts of waste management. We performed our assessment using field data from nine cities of different income levels and data from contrasting regions of the world. In addition to the life cycle assessment, we conducted a cost analysis to capture the full suite of expenses (and revenues) associated with the waste management strategies we selected for each city.

Methods

The Municipal Solid Waste Decision Support Tool (MSW DST) is a computer-based model developed by RTI International and North Carolina State University in cooperation with EPA's Office of Research and Development. The tool was designed to help communities and waste planners analyze the full costs and life cycle environmental aspects of MSW management alternatives. As Figure 1[1] illustrates, we used the MSW DST to identify parameters and assumptions that significantly influence the choice of strategies minimizing GHG emissions or maximizing materials recovery and their respective environmental and cost impacts. Using the following steps, we tailored the MSW DST for each city and identified the optimal strategies for minimizing GHG emissions and maximizing materials recovery:

1. Compiled data collected for each city, including waste quantity and composition and information about existing waste management infrastructure and costs, and updated the data to reflect 2012[2] conditions.
2. Inputted these data for each city into the MSW DST to create a tailored model that represents the unique conditions of each city.
3. Ran the MSW DST[3] (see Figure 1) to identify strategies to minimize GHG emissions or maximize materials recovery and to obtain results in terms of mass flows of materials to the selected waste management processes and estimates of net cost, energy consumption, and emissions to the atmosphere and water.

Figure 1. We used location-specific data to create tailored MSW DST builds for each city and to run scenario analyses



1 The authors generated all figures and tables in this paper.

2 We updated cost and revenue data to 2012 values using country-specific Consumer Price Indexes and gross national income (GNI) data from the World Bank Development Indicators database (World Bank, 2013).

3 See RTI International (2012) for additional information about the MSW DST.

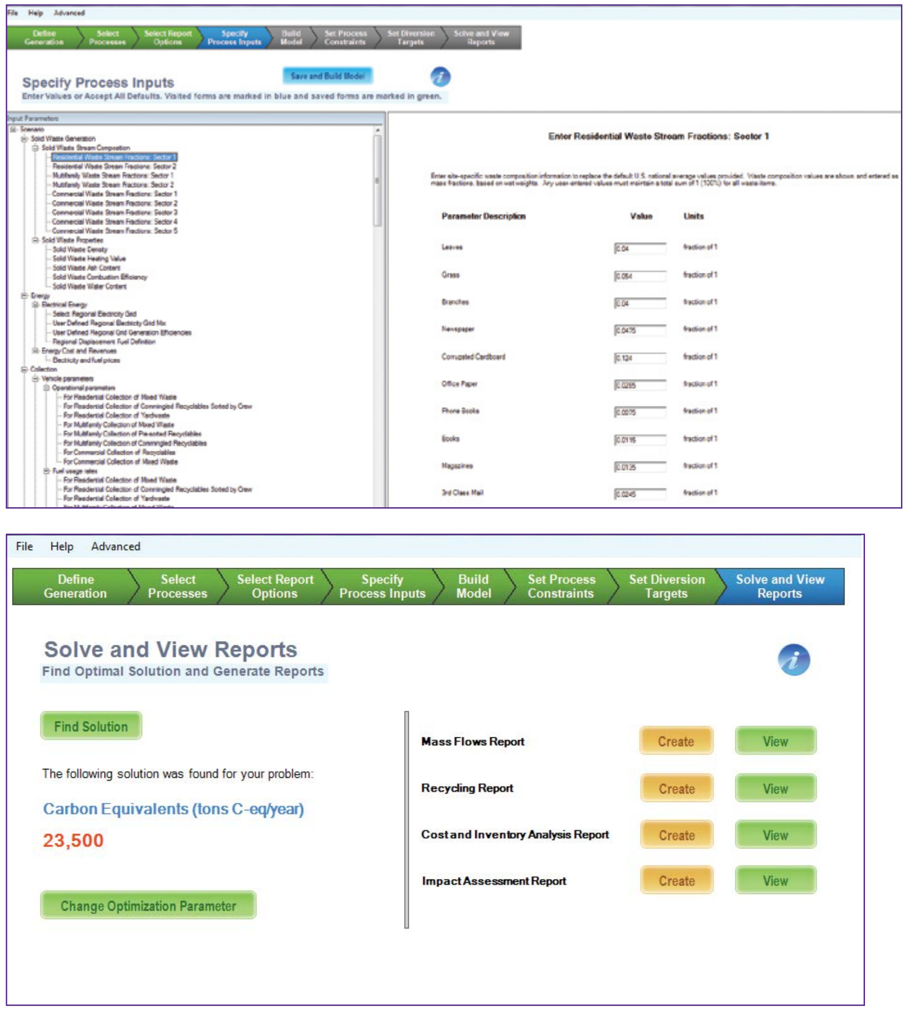
4. Compared and contrasted the results across cities to identify the key drivers behind the selection of waste management processes for each strategy and their respective environmental and cost performance.

Waste Composition and City-Specific Data

Many studies have found the composition of MSW to be highly correlated with population income and moderately correlated with geographic conditions (Akinci, Duyusen Guven, & Gok, 2012; Bandara, Hettiaratchi, Wirasunghe, & Pilapiiya, 2007; Beigl, Lebersorger, & Salhofer, 2008; Buenrostro & Bocco, 2003; Dennison, Dodda, & Whelan, 1996; Gidarakos, Havas, & Ntzmailis, 2006; Kumar et al., 2009; Li, 2013; Mazzanti & Zoboli, 2009; Sokka, Antikainenb, & Kauppia, 2007). In this study, we used waste composition for nine cities of varying income levels and geographic conditions to represent a large range of conditions worldwide. We collected these data through field meetings with waste management officials in each city as part of a study for the World Bank (2008b). We searched for more recent data in the published literature as well; the only other data source presenting waste composition data for the cities in this analysis was the 2012 *What a Waste: Global Review of Solid Waste Management* (World Bank, 2012). However, we found that the World Bank (2008b) data are the most current. We updated the waste generation data previously collected for the World Bank (2008b) with more recent estimates (World Bank, 2012; United Nations Statistics Division, 2013a, 2013b, 2013c). As noted earlier, we adjusted all previously developed cost data to 2012 values.

The nine cities included in this study are Amman (Jordan), Atlanta (United States), Buenos Aires (Argentina), Conakry (Guinea), Kathmandu (Nepal), Kawasaki (Japan), Lahore (Pakistan), Sarajevo (Bosnia and Herzegovina), and Shanghai (China). According to their 2012 GNIs per capita[4] (World Bank, 2013) and consistent with the categories in the 2012 World Bank report,[5] Conakry and Kathmandu are low income (LI); Lahore is low middle income (LMI); Sarajevo, Amman, Shanghai, and Buenos Aires are upper middle income (UMI); and Kawasaki

Figure 1. We used location-specific data to create tailored MSW DST builds for each city and to run scenario analyses ***(continued)***



[4] We used GNI per capita data that the World Bank estimated according to the Atlas method: "The Atlas conversion factor for any year is the average of a country's exchange rate for that year and its exchange rates for the two preceding years, adjusted for the difference between the rate of inflation in the country and international inflation; the objective of the adjustment is to reduce any changes to the exchange rate caused by inflation" (World Bank, n.d.).

[5] In *What a Waste*, the World Bank classified countries into four income levels according to its estimates of 2005 GNI per capita (shown here in US dollars). High: $10,725 or above; upper middle: $3,466–$10,725; lower middle: $876–$3,465; lower: $875 or less.

and Atlanta are high income (HI). Figure 2 presents information on the distribution of existing solid waste management processes as documented in World Bank (2008b), and Figure 3 presents the composition of waste in each city. Table 1 presents city-specific percentages of fuels used to generate electricity, known as the grid mix, and Table 2 presents costs, which are inputs to the model. Based on our working knowledge of the tool, we elected to use city-specific data for the parameters to which the MSW DST is most sensitive. Consequently, we used the city-specific data and information in Figure 3 and Tables 1 and 2 for this analysis.

According to Figure 2, most of the waste in the selected cities is managed using landfill disposal, with the exception of Kawasaki, where the availability of land for waste disposal is very limited and very expensive (Table 2). As Figure 2 indicates, the need worldwide for the implementation of waste disposal alternatives that promote mass and energy conservation and fulfill the sustainability paradigm is clear.

A key observation that we noted from analyzing the data presented in Figure 3 is that waste composition among the cities appears to vary significantly, for example:

- Recyclable material fractions (paper, plastics, metals, and glass) range between 12 percent and 50 percent of the total waste generated.
- Nonrecyclable organics (food and yard waste) fractions range between 20 percent and 75 percent of the total waste generated.
- High-income cities such as Atlanta and Kawasaki have a larger percentage of paper, which has a well-established recycling infrastructure and market.
- Plastic material, which has high energy value, is a relatively small fraction (on a mass basis) of the waste stream in most cities.

The composition of waste has a significant influence on the MSW DST's selection of the waste management processes (and the overall strategy), as we explain in the following sections.

Figure 2. City-specific waste management processes and income levels

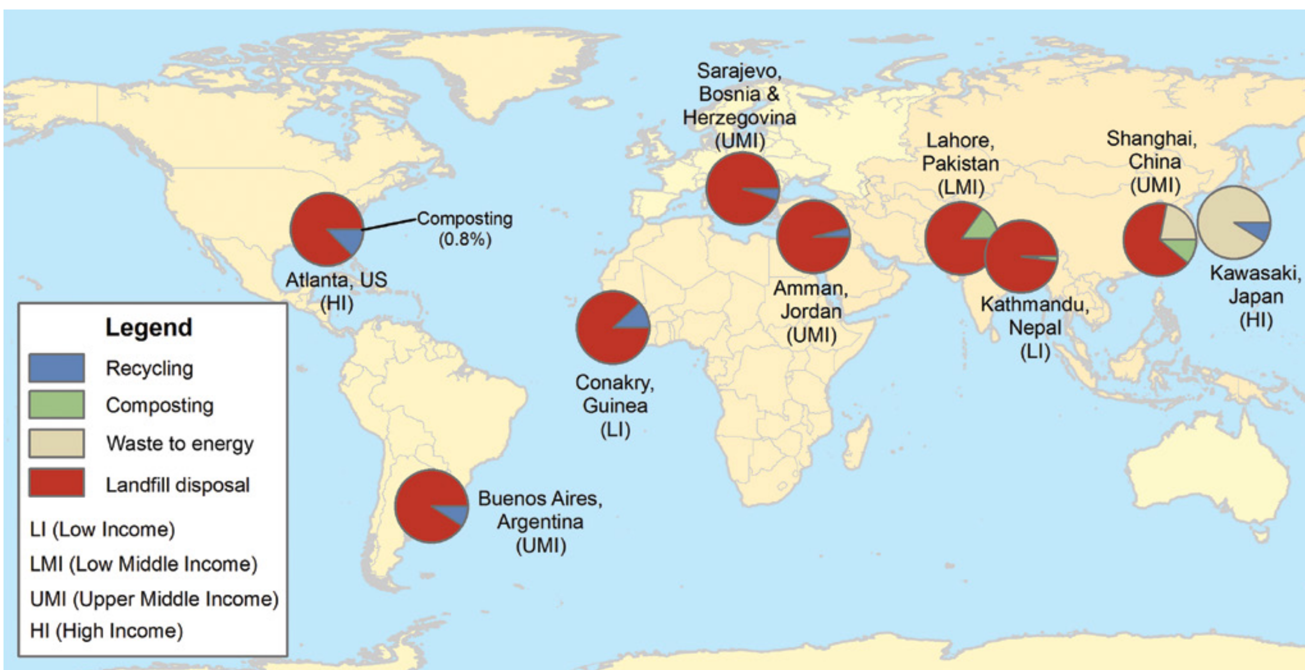


Figure 3. City-specific waste composition

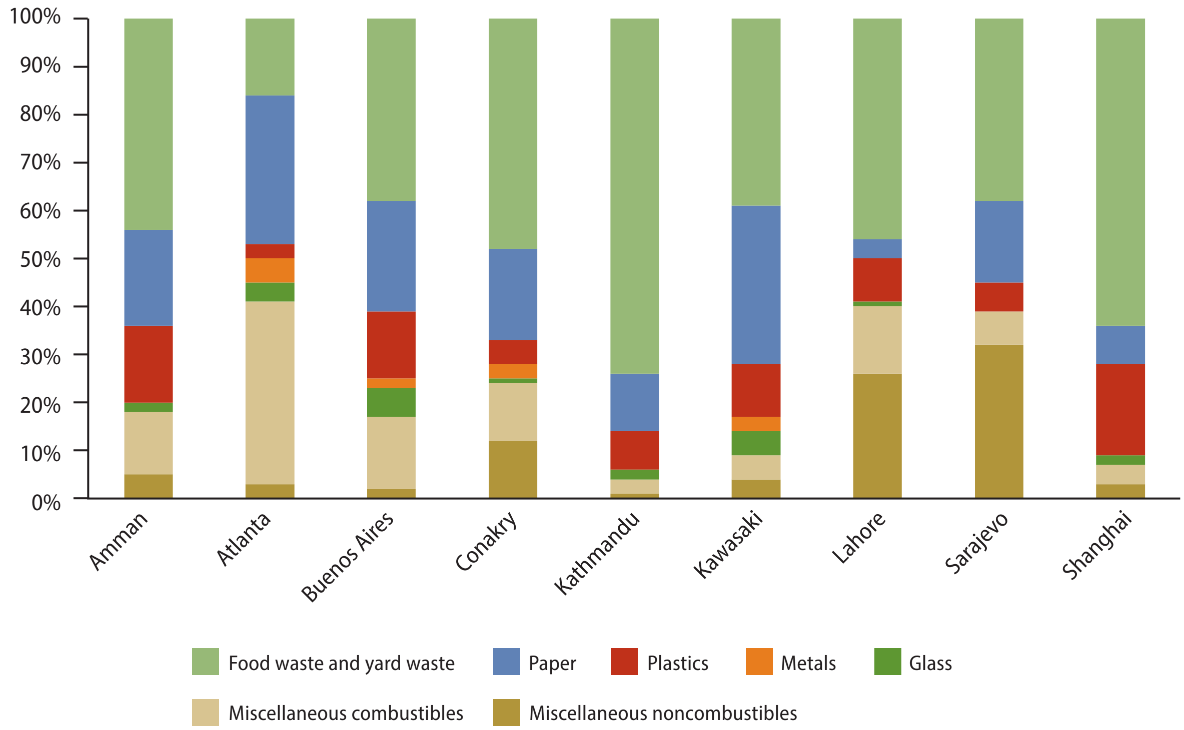


Table 1. Electricity grid mix

Fuel	Amman	Atlanta	Buenos Aires	Conakry	Kathmandu	Kawasaki	Lahore	Sarajevo	Shanghai
Coal	0%	56%	1%	0%	0%	25%	8%	47%	0%
Natural gas	94%	10%	46%	0%	0%	27%	50%	0%	33%
Residual oil	0%	3%	5%	74%	0%	0%	15%	2%	33%
Distillate oil	5%	0%	0%	0%	0%	8%	15%	0%	33%
Total fossil fuels	**100%**	**69%**	**52%**	**74%**	**0%**	**60%**	**88%**	**49%**	**100%**
Nuclear	0%	0%	9%	0%	0%	30%	1%	0%	0%
Hydroelectric	<1%	0%	39%	23%	90%	10%	11%	51%	0%
Wood	0%	0%	0%	0%	0%	0%	0%	0%	0%
Other	<1%	0%	0%	3%	10%	0%	<1%	0%	<1%
Total other fuels	**0%**	**31%**	**48%**	**26%**	**100%**	**40%**	**12%**	**51%**	**0%**

Note: Grid mix is the mix of fuels used to generate electricity.
Source: World Bank, 2008b.

According to Table 1, with the exception of Kathmandu, the electricity grid mix in most cities is dominated by fossil fuels. In Sarajevo, the split between fossil and nonfossil fuels is close to 50/50. Cities whose grid mixes have the largest percentages of fossil fuels could potentially have the largest emissions savings associated with electricity-generating waste management options such as waste to energy (WTE), as we explain in the following sections.

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Table 2. City-specific (2012) economic data to which the MSW DST is most sensitive (US dollars)

Cities	Diesel fuel price ($/l)	Electricity purchase price ($/kWh)	Electricity sale price ($/kWh)	Land price ($/m^2)[a]	Labor rates, unskilled labor ($/hour)[b]	Recyclable prices ($/metric ton)			
						Paper	Plastics	Metals	Glass
Amman	0.97	0.13	0.06	150	1.0	43	182	220[c]	47
Atlanta	1.10	0.05	0.03	1	7.2	101	492	834	17
Buenos Aires	1.33	0.10	0.03	177	1.1	53	355	402	42
Conakry	1.34	0.17	0.03	16	0.3	41[c]	44	44	6
Kathmandu	1.09	0.13	0.03	4	0.5	41	57	50	6[c]
Kawasaki	1.60	0.16	0.07	847	15.0	101[c]	75	533	6
Lahore	1.20	0.09	0.03	50	0.2	49	241	66	8
Sarajevo	1.62	0.15	0.06	560	1.7	59	121	220[c]	12[c]
Shanghai	1.28	0.10	0.07	76	0.7	92	81	220	12

[a] We obtained land prices from the World Bank's *Solid Waste Management Holistic Decision Modeling* (2008b) and the World Bank's *Report on Survey of Urban Land Prices in the Developing World* (2008a) for cities in the same region as the studied cities. The data for Kathmandu and Lahore, which came from World Bank (2008a), were estimated as the average of the land prices for cities in the same geographical region and with similar socioeconomic characteristics.

[b] We obtained the labor rates for most cities (except Kawasaki and Atlanta) from engineering costing handbooks (AECOM South Africa, 2013; Gardiner & Theobald, 2012; Turner & Townsend, 2012). We used these data sources to improve the quality of the data collected in the World Bank (2008b) study. We used data for cities in Kenya as a proxy for Conakry and data for cities in India as a proxy for Lahore. We used data from the World Bank (2008b) report for Kawasaki and the 2012 minimum wage data from the Georgia Department of Labor (2014) for Atlanta.

[c] We found no city-specific price data. We set values to the lowest price found for cities in the same income-level category.

Note: We used an average default compost price of $21.5/metric ton reported in Waste and Resources Action Programme's *Market Situation Report—April 2008* (2008). The value of the produced soil amendment varies significantly based on quality and the availability of markets. Bagged compost demands the highest price, but if markets are not available, facilities may rely solely on bulk sales. The assumed sale price of $21.5/metric ton is consistent with the values in Levis and Barlaz's *Composting Process Model Documentation* (2013), where most of the sales are bulk sales.

Key observations that we noted from analyzing the data presented in Table 2, along with our working knowledge of the factors that influence the MSW DST results, include the following:

- Sarajevo has the highest diesel fuel price, which can significantly affect the cost of waste collection.
- Conakry has the highest electricity purchase price, which does not favor processes that consume electricity, such as recycling and composting.
- Kawasaki and Shanghai have the highest electricity sale prices, which favors processes that produce electricity, such as WTE.
- Sarajevo and Kawasaki have the highest land prices, which increases the cost of management options such as landfill disposal.
- Atlanta and Kawasaki have the highest unskilled labor rates, which increases the cost of labor-intensive processes such as manual recyclables separation and recovery.
- Atlanta and Kawasaki have the highest prices for recycled paper and metals, which favors recycling these materials. Similarly, Atlanta and Buenos Aires have the highest prices for recycled plastics, and Amman and Buenos Aires have the highest prices for recycled glass.

Waste Management Strategy Modeling

We used the MSW DST to identify which strategies would best fulfill the goals of either minimizing GHG emissions or maximizing materials recovery (the primary goal of zero waste) for each of the nine cities. The MSW DST includes the following waste management processes: recycling, composting, WTE, and landfill disposal. Other less prevalent options such as anaerobic digestion and emerging conversion technologies (e.g., gasification) are not part of the MSW DST and were not considered for this analysis.

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Figure 4 depicts the life cycle flow of waste and processes included in the MSW DST from the point of collection through recycling and treatment processes to the ultimate disposal of residual waste.

The MSW DST includes an optimization function that, based on city-specific information and constraints, identifies the waste management strategy that best meets the user-defined objective, which in this study is minimizing GHG emissions or maximizing materials recovery. Waste management processes selected by the MSW DST to achieve the goals are dictated by the (1) technical feasibility of managing the various waste items and (2) contribution of each process to meeting the defined goal of minimizing GHG emissions or maximizing materials recovery. Results from the MSW DST include mass flows of materials to the selected waste management processes and estimates of net cost, energy consumption, and emissions to the atmosphere and water.

With respect to technical feasibility, certain processes may be limited in the materials they will accept. For example, aluminum cans would not be sent to an organic waste composting facility; likewise, food waste (ideally) would not be sent to a materials recovery facility. For every waste management process, the composition of the waste feedstock is an important consideration:

- Recycling is typically limited to marketable commodities (metal, paper, plastic, glass). Although it may be technically feasible to recycle or reuse additional materials present in MSW (e.g., concrete, brick, tires, textiles), the specific materials recovered for recycling are typically dictated by the presence of a market for the material.

Figure 4. Waste life cycle and key process design and operating assumptions selected for the analysis for all cities

Waste Life Cycle	Processes Included in the MSW DST		
Collection	**Collection** • Consists of both segregated (separate recyclables, organics, and residuals) and nonsegregated (mixed waste only) collection • Assumes 50% residential collection for high-income cities (i.e., Kawasaki and Atlanta) and 90% multifamily collection for other cities • Assumes 75% participation factor (percentage of population that participates in recycling) • Assumes 75% capture rate (percentage of recyclables put in bins by those participating) • Assumes biweekly collection		
Recycling and Treatment	**Recycling** • Includes both mixed waste and commingled recyclables designs • Assumes 70% separation efficiency for mixed waste and 99% for commingled waste • Assumes a semiautomated facility design powered by purchased electricity and liquid natural gas	**Composting** • Includes prescreening (79% average) to remove recyclables and contaminants • Assumes a windrow* process • Produces low- and high-quality compost • Assumes facility and equipment consume purchased electricity and diesel fuel	**Waste to Energy** • Includes a modern mass burn process with a 17,500 Btu/kWh heat rate (efficiency) • Assumes 90% steel recovery rate from combustion ash • Assumes self-generated electricity is used to run internal processes
Transportation	**Transportation**		
Remanufacturing/ Use	Recycled material that replaces virgin material in remanufacturing facility	Compost that replaces conventional soil amendments and fertilizers	Waste-generated electricity replaces fossil fuel–generated electricity
End of Life	**Landfill Disposal** • Includes a modern sanitary-type facility • Assumes 75% gas collection efficiency • Assumes gas collected is controlled by a flaring system • Assumes purchased electricity and diesel to fuel are consumed by processes and equipment	Ash landfill disposal	

*Windrow process: Compost material is arranged in lines or rows.

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- Composting is typically limited to organic materials, such as food, yard, and agricultural waste, but mixed MSW can also be composted. A key decision related to the feedstock is the desired quality of the compost product. Quality organic feedstock (namely yard waste and food waste) can yield higher-quality compost products that can be sold for higher prices. Lower-grade feedstock such as mixed MSW can yield lower-quality compost products that, although likely not saleable, may be used as cover material for landfills.
- WTE can handle combustible and noncombustible materials. Because some materials (e.g., plastics) have a higher Btu (British thermal unit) value (see Tchobanoglous, Theisen, & Vigil, 1993) than others (e.g., food waste), the specific material makeup of the combustible fraction dictates the amount of energy that a WTE plant can generate. In addition, WTE plants typically recover ferrous metal from combustion ash using a magnet and sell this metal to recycling markets.
- For landfills, all materials present in the MSW stream can be landfilled. Similar to Btu value, each waste item has a unique methane yield value that, along with other factors, dictates the potential amount of landfill gas that item might produce. Waste streams with a higher fraction of organic wastes will produce greater amounts of landfill gas.

The MSW DST models transportation to various facilities and to material manufacturing facilities where end-of-life products are recycled into the same product (commonly referred to as closed-loop recycling). For this research, we used default transportation distances and assumed those distances are the same for all the cities. We acknowledge that this parameter can be a significant source of uncertainty, in particular, for the transportation of recycled material to manufacturing facilities because often these facilities are located thousands of miles away from the waste source and their location depends on the end-product market.

As Figure 4 illustrates, the MSW DST considers the entire life cycle of a waste material; for materials that can be recycled, the life cycle includes their being manufactured into new products. The MSW DST also estimates energy, emissions, and cost savings from the displacement of virgin material consumption that is associated with closed-loop recycling, as shown in Table 3 for GHG emissions.

Table 3. GHG emissions savings from using recycled materials instead of virgin resources to produce materials (sorted in decreasing order)

Recyclable material	GHG emissions ($MTCO_2$-eq/metric ton)[a]	GHG savings equivalent to the number of miles driven per year by the average passenger vehicle[b]
Aluminum	−11.00	25,911
Low-density polyethylene	−1.85	4,362
Polyethylene terephthalate	−1.79	4,215
High-density polyethylene	−1.41	3,317
Steel	−1.05	2,479
Newspaper	−1.00	2,358
Glass	−0.40	950
Phone books	−0.19	451
Textbooks	−0.04	91
Magazines and third-class mail	−0.02	45
Corrugated boxes	0.12	−288
Office paper	0.30	−703

[a] Values are in metric tons of carbon dioxide equivalent. Negative values indicate emissions savings. These values come from the MSW DST and exclude nitrous oxides (N_2O) emissions because they are not reported consistently in the MSW DST. This issue is further explained in the Limitations section.

[b] Using equivalency factors from US EPA (2014).

For the analysis of composting systems, we assumed the production of high-quality compost for use as a soil amendment that obviates the need for conventional fertilizers. The MSW DST does not include emissions, energy, and costs associated with compost use and the offsets from the avoidance of conventional fertilizers. Therefore, we adjusted the MSW DST results using the data in Levis and Barlaz (2013). Table 4 presents the GHG emissions savings data used. The table shows the emissions saving potential of each material in the waste stream that could be potentially composted.

Table 4. GHG emissions savings from using compost as a soil amendment to provide carbon storage and replace conventional fertilizers (sorted in decreasing order)

Compostable material	GHG emissions ($MTCO_2$-eq/metric ton)[a]	GHG savings equivalent to the number of miles driven per year by the average passenger vehicle[b]
Nonvegetable food waste	–0.026	61.9
Leaves	–0.012	28.6
Branches	–0.010	23.8
Miscellaneous organic	–0.009	21.4
Wood	–0.007	16.7
Textiles	–0.007	16.7
Grass	–0.006	14.3
Vegetable food waste	–0.005	11.9

[a] Values are in metric tons of carbon dioxide equivalent. Negative values indicate emissions savings. The original data from Levis & Barlaz (2013) in kilograms of each greenhouse gas per megagram of each material were used to estimate these values. N_2O emissions were excluded to be consistent with the MSW DST.

[b] Using equivalency factors from US EPA (2014).

Table 5. Energy content of WTE feedstock

Waste item	Heating value per item[a] (megajoule/tonne)
Plastics	19.7
Newsprint	8.0
Corrugated cardboard	7.3
Yard trimmings, branches	7.0
Office paper	6.7
Books	6.6
Third class mail	6.4
Magazines	5.7
Yard trimmings, leaves	2.7
Yard trimmings, grass	2.7
Food waste	1.9
Ferrous cans	0.3
Glass	0.1
Aluminum cans	0.0

[a] These values are used in the MSW DST (RTI International, 2012).

WTE systems generate electricity and produce a revenue stream through its sale. The electricity produced also creates an environmental benefit by virtue of displacing electricity that otherwise would need to be generated by the city's energy utility. Table 5 presents the energy content of each material in the waste stream. Table 1 presents the specific mix of fuels used by the utility sector to produce electricity in each city, which could be replaced by the electricity generated from the combustion of waste.

We assumed that 75 percent of households had separate recyclables collection and that the fraction of recyclable material that was being segregated into the recycling collection bin was 75 percent. We also assumed all waste management processes use international best-available technology.

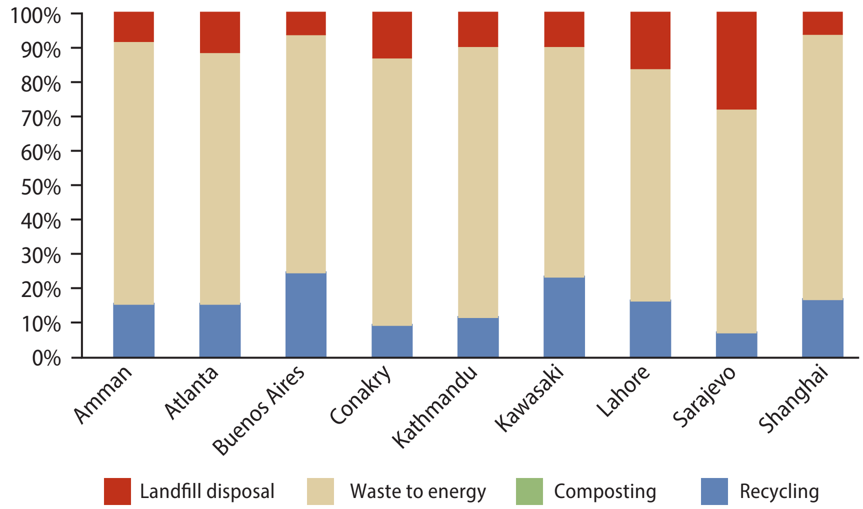
Results and Discussion

Figures 5 and 6 show the percentage of waste selected by the MSW DST to be sent to various processes to minimize GHG emissions (Figure 5) or maximize materials recovery (Figure 6) for each city. The strategies selected by the MSW DST to minimize GHG emissions show a clear pattern of using a WTE-based system along with materials recycling and disposal of any unusable residuals and combustion ash. The MSW DST did not use composting in minimizing GHG emissions. Alternatively, the strategies selected for maximizing materials recovery generally included a composting- and recycling-based system with disposal of unusable residuals.

The selection of a WTE-based system to best meet the objective of minimizing GHG emissions may come as a surprise. To help explain this selection, in Table 6 we present the results from the MSW DST for net total GHG emissions for Kathmandu under two waste management scenarios: (1) composting is the waste management option selected and (2) WTE is the waste management option selected. As shown in Table 6, GHG emissions from the composting process (on a per unit mass basis) are lower than those from the WTE process, but the additional emissions from the separate collection of organics and landfill disposal of noncompostable organics are higher. The overall result is that composting has greater net total GHG emissions.

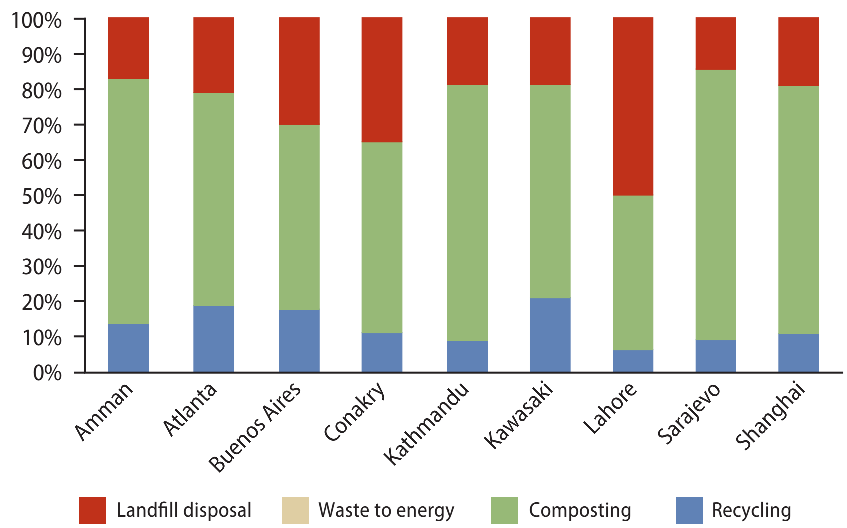
Kathmandu has the largest percentage of organics in its waste stream, which suggests its waste stream has a relatively low average Btu value. In addition, hydroelectric energy is the main source of electricity. Therefore, the energy produced by a WTE process does not have a large potential to generate GHG emissions savings by displacing fossil fuels. Despite this characteristic, Table 6 highlights the importance of considering all the life cycle stages in making waste management decisions. As shown in the table, the emissions from the end of life (i.e., landfill disposal) of the composting rejects, which could be over 40 percent of the incoming waste, negate most of the benefits of the composting process.

Figure 5. Percentage of waste sent by the MSW DST to various waste management processes in each city to minimize GHG emissions



Note: The MSW DST did not select the composting option. The label was retained to indicate zero values.

Figure 6. Percentage of waste sent by the MSW DST to various waste management processes in each city to maximize materials recovery



Note: The MSW DST did not select the composting option. The label was retained to indicate zero values.

Table 6. Comparison of MSW DST results by waste management process and strategies for Kathmandu, assuming either composting or WTE is the option selected

Life cycle stages	GHG emissions if composting is selected ($MTCO_2$-eq/metric ton waste)	GHG emissions if WTE is selected ($MTCO_2$-eq/metric ton waste)
Collection	0.01	0.01
Recycling and treatment, transportation, and remanufacturing and use	−0.05	0.03
End of life	0.3	0
Total	**0.3**	**0.04**

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The strategies selected by the MSW DST for maximizing materials recovery are governed by a number of key factors: (1) the amount of recyclable material present in the waste stream (per Table 1), (2) the number of households that participate in the recyclables collection program, (3) the fraction of recyclable material that is put by residents into the recycling collection bin (versus the trash bin), and (4) the separation efficiency at the sorting facility. Likewise, the amount of organics that can be composted depends on the amount of compostable organics in the waste stream, ability to segregate the organic material for composting, and design of the composting facility.

In addition to the analysis of waste management processes selected by the MSW DST for minimizing GHG emissions or maximizing materials recovery, we also analyzed the environmental and cost performance of the selected strategies. In the next section, we compare and contrast the results for GHG emissions, costs, energy consumption, and criteria air pollutants for the strategies that best met the two goals.

Minimizing GHG Emissions Results

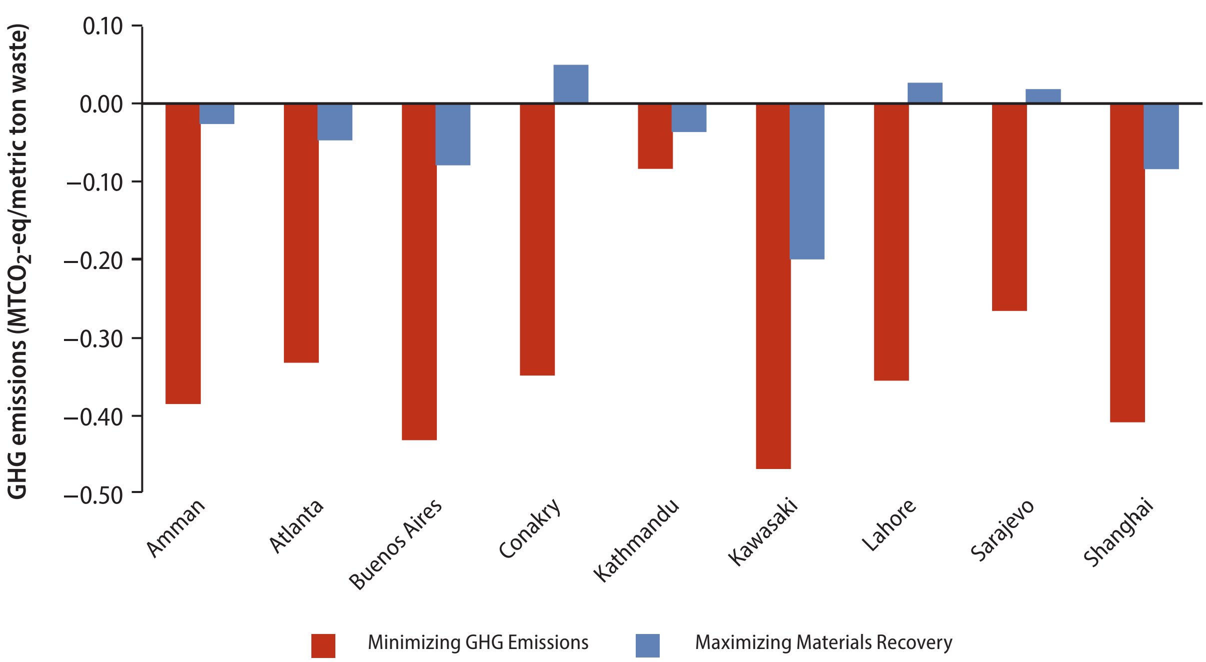
Figure 7 illustrates the net GHG emissions results for each city, expressed as metric tons of carbon dioxide equivalents per metric ton of waste ($MTCO_2$-eq/metric ton waste) according to the following equation:

$$MTCO_2\text{-eq} = MTCO_2 \text{ fossil} \times 1 + MTCH_4 \times 25$$

Please note that the equation is consistent with GHG accounting protocols and the Intergovernmental Panel on Climate Change guidelines for using the recommended global warming potentials of 1 for CO_2 fossil and 25 for methane (CH_4). However, the equation excludes nitrous oxides (N_2O) emissions and other potential GHG emissions because the MSW DST does not consistently report them, which we discuss later in the Limitations section.

The results presented in Figure 7 are the net CO_2-equivalent emissions estimated by the MSW DST for the strategies identified for minimizing GHG emissions and maximizing materials recovery. Results are presented as net total and include GHG emissions from all waste management activities, and

Figure 7. Net GHG emissions (savings), by city



Note: Negative values indicate savings.

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any GHG emissions savings resulting from energy production or materials recycling are netted out. As shown in the figure, the MSW DST found that all of these cities could achieve net GHG emissions savings for the strategies identified for minimizing GHG emissions, but overall savings are not always possible for the strategies identified for maximizing materials recovery.

Kathmandu has the smallest difference between the strategies identified for minimizing GHG emissions and maximizing materials recovery because Kathmandu uses hydropower, and relatively low GHG emissions offsets would result from displacing hydropower. The other cities rely on larger amounts of fossil fuels to generate electricity, which creates large GHG emissions offsets.

Conakry has a relatively low percentage of aluminum and plastic recyclables in its waste stream, and its electricity grid mix is approximately 75 percent fossil fuels. Therefore, Conakry's emissions savings from recycling are low and its GHG emissions from electricity consumption are high, which results in the largest net GHG emissions among all cities for the strategies identified for maximizing materials recovery.

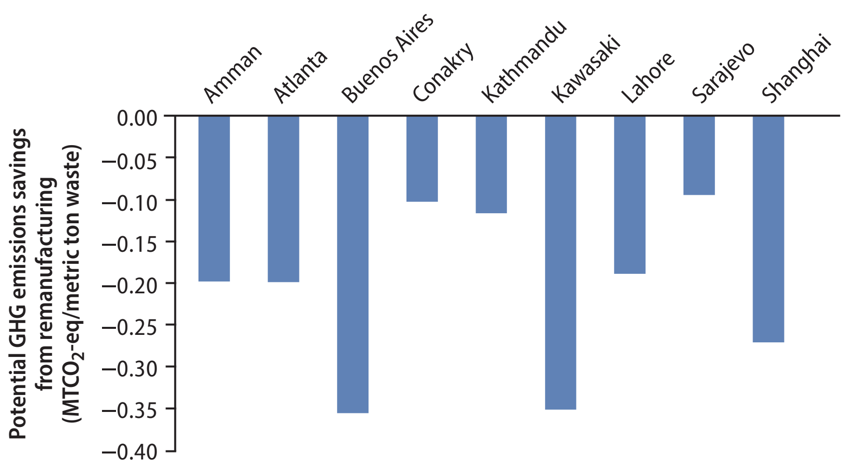
We found that the difference in CO_2-equivalent results (as shown in Figure 7) between the strategies for minimizing GHG emissions and the strategies for maximizing materials recovery is significant for most cities. WTE played a large role in the strategy to minimize GHG emissions. The benefit of WTE, with respect to GHG emissions, is realized in its ability to produce energy (typically in the form of electricity) and recover metals (and possibly other materials) for recycling. The methodology used by the MSW DST assumes that any electricity produced displaces an equivalent amount of electricity that otherwise would be produced in the utility sector, along with its associated GHG emissions. An important aspect that determined the amount of emissions displaced is the specific mix of fuels in the utility sector. That is, cities that rely on electricity produced from fossil fuels (see Table 5) such as coal or oil would save more emissions per unit of electricity produced by WTE than cities using electricity produced from non-fossil-fuel sources (e.g., nuclear, hydropower, solar and wind power).

In addition, GHG benefits result from recovering metals and possibly other materials from WTE systems. Metals are among the most energy-intensive materials to produce. Recovering and recycling metals from the waste stream can create large environmental benefits, namely from avoiding energy use and associated emissions from the extraction and processing of virgin resources. The greater the amount of metals in the WTE feedstock, or in the waste stream in general, the greater the potential for GHG emissions savings. This statement is not meant to encourage the use of WTE or to increase metals waste. Reducing waste at the source is an overarching goal, followed by recovering and recycling valuable materials from the waste stream.

The other key GHG-related benefit of WTE is that it avoids landfill disposal of waste and associated emissions of methane that result from the biodegradation of organic materials. Combusting these same organic materials in a WTE plant will result in GHG emissions (in the form of CO_2), but this form of CO_2 is currently considered biogenic in nature and thus does not factor into CO_2-equivalent results. Therefore, the main source of GHG emissions from WTE plants is the (fossil-based) CO_2 emissions that result from the combustion of fossil fuel–based products such as plastics.

For the nine case study cities, the amount of material selected by the MSW DST for recycling in the strategies for minimizing GHG emissions is affected not only by the amount of recyclable material in the waste stream, but also by the GHG emissions savings that could result from recycling specific materials rather than using the other available options (composting and landfill). Again, metals have the largest GHG emissions savings per ton because of the energy-intensive nature of manufacturing. Therefore, recycling metal creates a greater GHG emissions benefit. Other materials may have a negligible benefit or even a net GHG emissions impact when recycled and thus were not selected for recycling in the strategies for minimizing GHG emissions. Figure 8 shows the potential GHG emissions savings that could be realized by recycling the average per-ton mix of available recyclable materials in each city. Greater emissions savings potential was determined by the mix of recyclables available and their respective GHG emissions savings per unit (metric ton) recycled. Cities such as Buenos Aires, Kawasaki, and Shanghai have average mixes of recyclable materials with larger GHG emissions savings potential; thus, a larger percentage of the recyclable material waste is recycled.

Figure 8. GHG emissions savings from materials recycling for each city



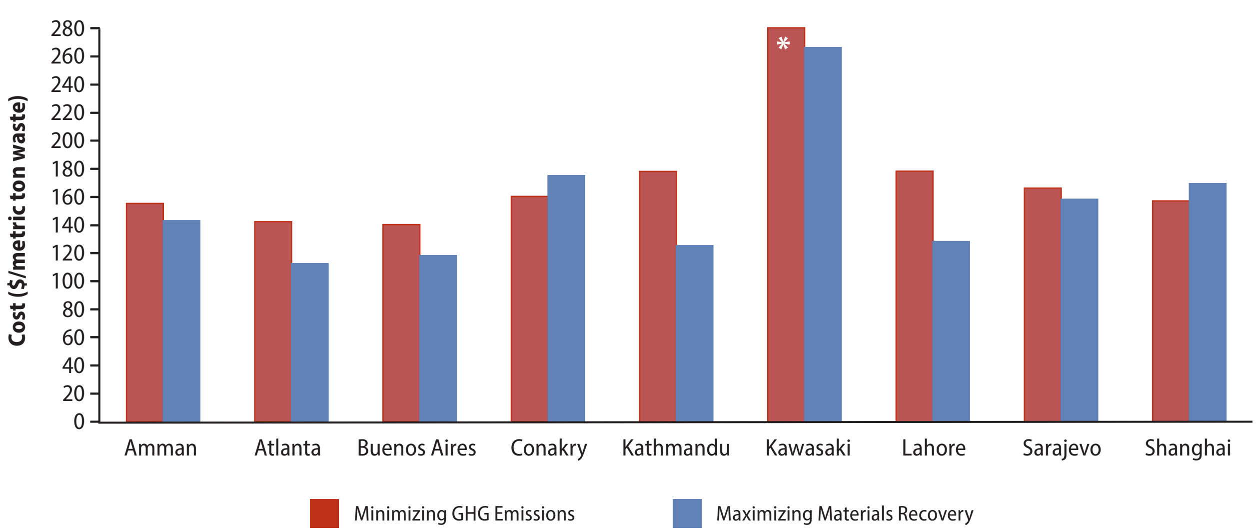
Note: Negative values indicate savings.

Cost Results

As stated, focusing on minimizing GHG emissions or maximizing materials recovery to achieve zero waste is a common goal for sustainable-city initiatives. However, city planners should also consider the cost of strategies that can achieve that goal as well as co-benefits or unintended impacts. Figure 9 shows the net cost results as generated by the MSW DST by city for the strategies identified for minimizing GHG emissions and maximizing materials recovery. The net cost accounts not only for the capital, operating, and maintenance costs of each waste management option, but also for any revenue received from the sale of recyclables, electricity, or compost products. Costs are expressed in US dollars (US$) per metric ton of waste managed.

As shown in Figure 9, with the exception of Conakry and Shanghai, the strategies selected by the MSW DST for minimizing GHG emissions cost between approximately 5 and 40 percent more than the strategies selected for maximizing materials recovery. This result is not unexpected because a WTE facility has relatively high capital and operating costs. Note that these estimates do not take into account indirect

Figure 9. Net total cost, by city



* The MSW DST estimated a cost of $605/metric ton for Kawasaki. However, for the purposes of better displaying the cost results, we are setting the upper limit for this figure at $280/metric ton.

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impacts such as health costs associated with GHG emissions and costs to implement national GHG emissions reduction strategies or the Kyoto Protocol. For Conakry and Shanghai, the net cost of the strategy for minimizing GHG emissions is lower than the net cost of the maximizing materials recovery strategy. Key aspects and parameters that affect the net cost results are as follows:

- **Electricity price.** The city-specific sale price (as shown in Table 2) for the electricity generated via WTE (or landfill gas to energy) systems directly affects the revenue that could be generated and the overall net cost of a strategy where such systems were used. The composition of waste also is important because waste with low energy content produces less electricity and thus less revenue from the sale of electricity to offset the cost of the WTE facility. For example, Shanghai has the lowest net costs because it has a waste stream with high energy value, which leads to greater electricity production, coupled with a high sale price per unit of electricity.
- **Market prices for recovered materials and compost products.** Prices paid for recovered materials and compost products vary widely from location to location. Conakry has a weaker materials market that yielded lower prices. Therefore, it exhibits higher net costs because the revenue from the sale of recovered materials does not offset the cost of recycling. In contrast, Buenos Aires has strong markets for recovered materials and high prices paid, which results in a lower overall net cost.
- **Land price.** The price of land in a city/region has a significant impact on the cost of waste management, particularly for landfill operations that require large land footprints.
- **Labor rates.** The cost of labor—in particular, unskilled labor—varies considerably from location to location and affects the determination of the preferred waste management strategy. In cities with high labor wage rates, the results from the MSW DST show that more automated (and more expensive) systems might be merited, such as the use of optical sorting technology for plastics recycling. In cities with low labor wage rates, less technical and less costly manual labor–based approaches such as handpicking of plastics might be merited.

Because the goal of the waste management strategies modeled with the MSW DST was either minimizing GHG emissions or maximizing materials recovery, we report only the associated costs of achieving those objectives. We made no attempt to balance the costs of the resulting strategies and their associated benefits/impacts. One approach to balancing the costs and benefits is to work with each city to identify an acceptable cost range and then set the MSW DST to find the solution that would minimize GHG emissions or maximize materials recovery for that acceptable cost range constraint. Such an approach could produce significantly different results.

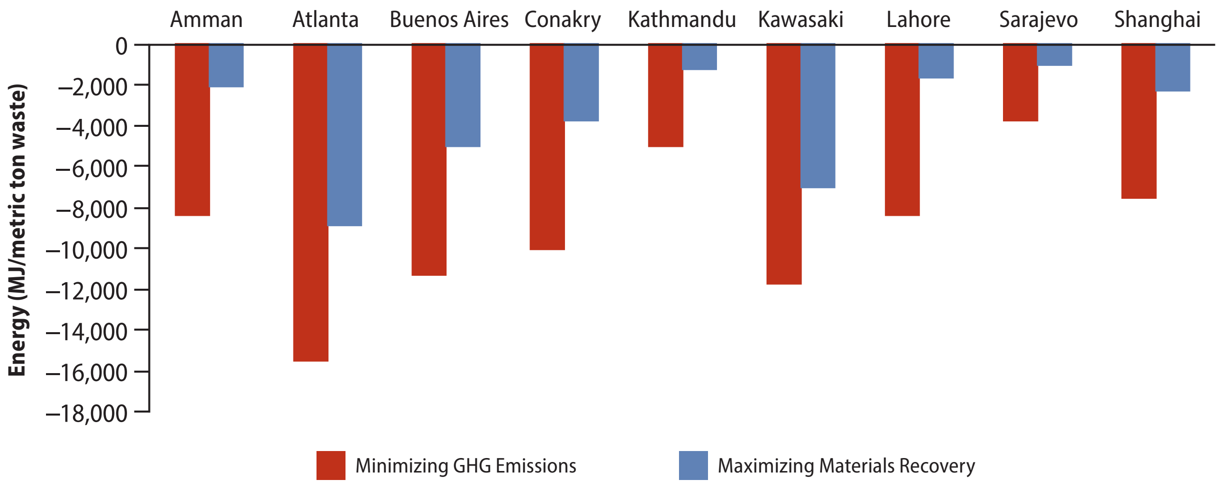
Energy Consumption Results

Figure 10 shows the total net energy requirements by city for the strategies identified for minimizing GHG emissions and maximizing materials recovery. Similar to net costs, the net energy results account for any energy savings associated with materials recycling and energy production. Results are expressed in megajoules (MJ) per metric ton of waste managed.

Similar to costs, we report only the net energy consumption for strategies minimizing GHG emissions or maximizing materials recovery. We did not attempt to balance energy and other parameters (e.g., cost, GHG emissions, criteria pollutants). However, in general, we have found that solutions for minimizing GHG emissions also achieve the lowest energy consumption (or greatest energy savings). Again, in terms of the displaced electricity, not only are the energy and emissions from the combustion of different fuels in utility boilers avoided, but also any energy consumed and emissions from the “upstream” activities of extracting and processing the fuels.

Energy in the form of fuel or electricity is consumed by all processes in the optimization strategies. Some processes (e.g., WTE) produce energy, while others (e.g., recycling) may avoid (or reduce) energy use. Key factors that influence energy production and energy avoidance potential include the electricity grid

Figure 10. Net energy consumption (savings), by city



Note: Negative values indicate savings.

mix, the waste-heating content (i.e., Btu value), and the quantity and composition of recyclable materials available for recovery.

Criteria Air Pollutants Emission Results

In addition to GHG emissions, the MSW DST reports air emissions results for pollutants commonly regulated to protect the health of sensitive populations such as asthmatics, children, and the elderly. For the purposes of this analysis, we selected a group of pollutants classified as "criteria air pollutants" in the United States because they were the first pollutants included in air quality standards at a national level. The criteria air pollutants include particulate matter, ground-level ozone, nitrogen oxides, sulfur oxides, carbon monoxide, and lead, although the MSW DST does not estimate results for ozone. Figures 11 and 12 show the net total criteria air pollutants that would be emitted by each of the case study cities under their optimal strategy identified for minimizing GHG emissions (Figure 11) and maximizing materials recovery (Figure 12). Results are expressed in kilograms (kg) per metric ton of waste managed.

Operating equipment and vehicles and combusting waste or waste-related products (e.g., landfill gas) generally result in positive emissions of criteria air pollutants. Materials recycling and energy production from waste result in emission offsets. Similar to GHG emissions, cities can achieve significant criteria pollutant savings by producing energy (electricity) from waste and by displacing electricity produced in the utility sector.

Significant criteria pollutant savings can also result from materials recycling, because it avoids the need to extract and process virgin resources to manufacture products. It is worth noting that, as shown in Figures 11 and 12, the strategies identified for minimizing GHG emissions create larger amounts of criteria pollutants than the strategies identified for maximizing materials recovery. This result is directly related to criteria pollutant emissions from WTE plants, which are not present in the strategies to maximize materials recovery.

One key consideration with respect to criteria pollutant emissions is the location where they may be emitted. Unlike GHG emissions, which contribute to the global GHG effect, criteria air pollutants contribute more to local impacts and are primarily due to fuel combustion activities. For cities, this means that criteria pollutants emitted from waste collection and transportation vehicles and local waste management options contribute to local criteria pollutants. However, energy and materials production facilities may be located outside of the local area (or even country, in the case of materials

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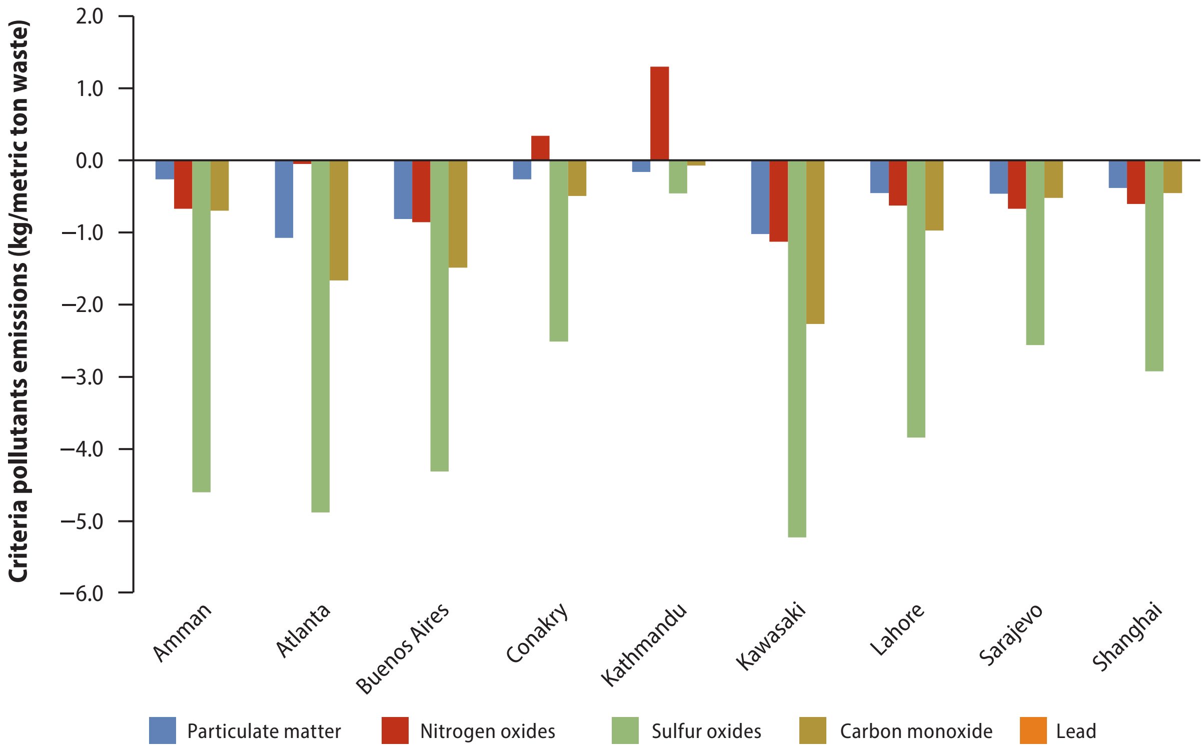
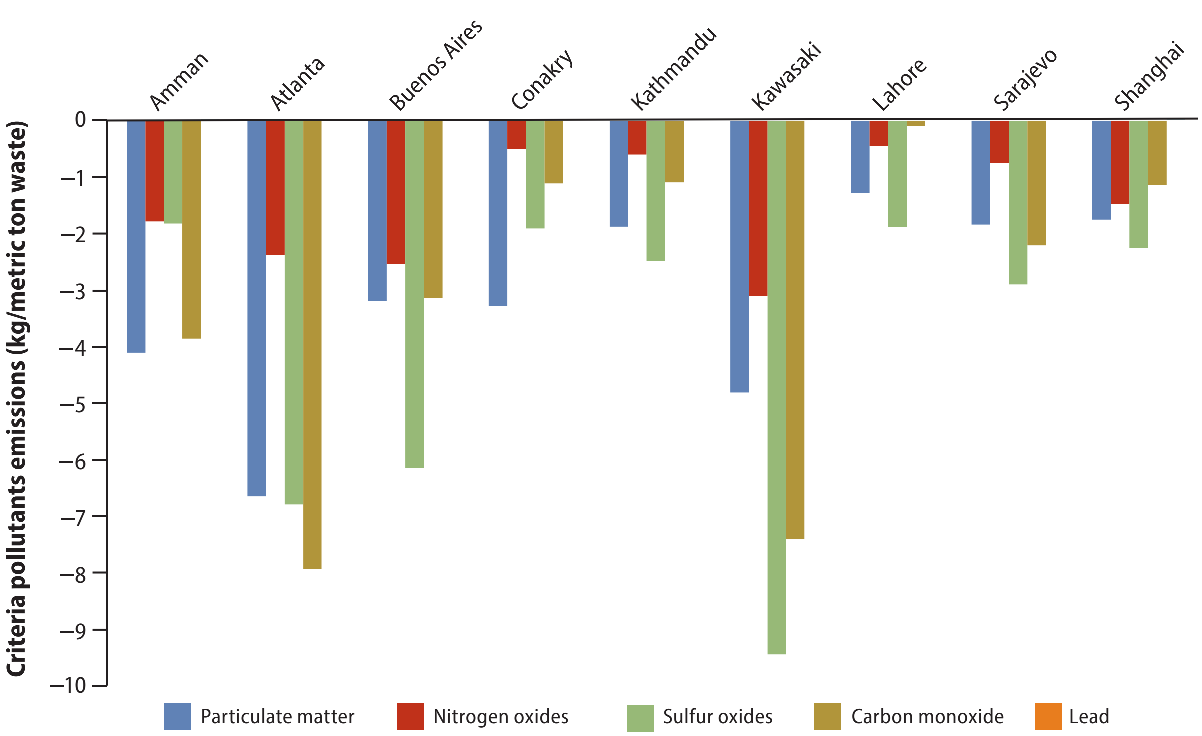
Figure 11. Net criteria air pollutant emissions, by city, for the minimizing GHG emissions strategies



Note: Negative values indicate savings.

Figure 12. Net criteria air pollutant emissions, by city, for the maximizing materials recovery strategies



Note: Negative values indicate savings.

production); thus, the city may not realize any local emissions "savings" in terms of reduced criteria pollutants. For example, recovered material from Sarajevo is shipped to manufacturing facilities in China. Sarajevo may see an increase in local criteria pollutants because of increased recycling collection and transport activity, while the larger emissions savings associated with using recycled rather than virgin raw materials are realized in China. Therefore, when considering recycling and its benefits in terms of emissions avoidance, we acknowledge that the locations where the recyclables are collected and separated do not incur most of those benefits.

Limitations

In modeling the waste management strategies for the nine cities, we used a number of assumptions and generalizations. The MSW DST itself has limitations in its methodology and applicability to different locations around the world. We acknowledge the following key assumptions and limitations of the analysis:

- Studies to characterize the quantity and composition of MSW are often cited as a key factor in selecting waste management processes (Burnley, 2007; Kumar et al., 2009). We included waste characterization data available for each city in this analysis, but we had difficulty determining the data quality. Ideally, cities would collect characterization data on a frequent (yearly) basis to identify trends in quantities and composition. Cities may find it cost prohibitive to conduct waste characterization studies regularly because they are estimated to cost $100,000 or more for large cities (Coyle, 2011).
- We assumed that all waste management facilities and operations use modern technology and best practices. However, in some cities, labor wage rates are very low, so it may be preferable to employ labor-based rather than technology-based process designs.
- The MSW DST does not include models for all possible waste management technologies. We did not consider less used technologies, such as anaerobic digestion, or new or emerging technologies, such as waste gasification and pyrolysis.
- We did not place a limit on the amount of waste that any process could accept. In reality, facilities are designed to handle a certain minimum or maximum capacity of waste and, therefore, would be limited in the amount of waste they could process.
- The MSW DST assumes that all recovered material is recycled into new products and all electricity generated from WTE is delivered to the local electricity grid. Environmental benefits are estimated based on these amounts of material and energy recovery. If infrastructure or markets are not available for handling these products, the benefits associated with them may not be realized.
- The MSW DST includes the primary GHG emissions of CO_2 and methane. Consistent with the MSW DST, other potential GHGs, such as N_2O and hydrogen fluoride, were not included in the calculation of CO_2-equivalent emissions. EPA's (2006) life cycle accounting of GHG emissions from solid waste management systems has shown CO_2 and methane to be the primary contributors to total GHG emissions for waste systems.
- Our analysis did not include constructing a baseline cost for each waste management process in each city or constraining the cost to an upper limit. Rather, the goal of this analysis was to identify key considerations in selecting strategies to minimize GHG emissions or maximize materials recovery. If different goals were analyzed or if we set up the strategy analysis differently—for example, minimizing GHG emissions and constraining cost to a defined upper limit—different results could be produced.

Conclusions

Focusing on the waste management goals of minimizing GHG emissions or maximizing materials recovery to achieve zero-waste targets can result in significantly different strategies and environmental impacts. In addition, strategies that meet those desired goals may not meet other goals, such as budgetary, land use, or economic development goals.

In this paper, we answered three general questions to identify key considerations in selecting strategies to optimize solid waste management: (1) What waste management processes can be used to develop strategies for minimizing GHG emissions or maximizing materials recovery as potential policy goals? (2) What key factors affect the distribution of waste among the different processes used in those strategies? (3) What are key cost and environmental input parameters for evaluating the performance of the waste management processes?

The following are key considerations when identifying specific waste management processes that comprise strategies for minimizing GHG emissions or maximizing materials recovery:

- The resulting strategies for minimizing GHG emissions may not necessarily adhere to the waste management hierarchy (i.e., where recycling and composting are preferred over WTE and landfill disposal) because WTE was selected as the main process for meeting this goal.
- Landfill disposal plays a smaller role in strategies to minimize GHG emissions than in strategies to maximize materials recovery because all nonrecyclable waste is sent to WTE and only the (inert) combustion ash is landfilled. Efficiencies for recovering recyclable and compostable material from the waste stream govern the amount of material that can be recovered and the amount of residuals sent to a disposal facility.
- When compared with the existing management systems (Figure 2), the optimization results present significant changes in the waste distribution among the different processes. In particular, most of the waste should be treated or recycled rather than disposed of at a landfill.

Table 7 summarizes the key factors affecting the selection of the various waste management processes for a given strategy and defining the environmental and cost performance of the strategy.

Table 7. Key factors affecting the emissions, energy, cost, and revenue results for the optimal strategies

Category	Key drivers	Minimizing GHG emissions strategy		Maximizing materials recovery strategy	
		Recycling	WTE	Recycling	Composting
Emissions	Fossil fuels in electricity grid mix	–	+	–	
	Amount of metals	+	+	+	
	Amount of plastics	+	–	+	
	Source-segregated collection requirements	–		–	–
	Landfill disposal requirements	–		–	–
Energy	Fossil fuels in electricity grid mix	–	+	–	
	Amount of metals	+	+	+	
	Amount of plastics	+	+	+	
Cost	Commingled waste collection cost	–		–	–
Revenue	Compost price				+
	Electricity price		+		
	Recyclable prices	+		+	

\+ means a positive impact on results
– means a negative impact on results

We observe differences in the quantity of GHG emissions reduced or avoided—as well as differences in cost, energy consumption, and criteria air pollutants—when comparing the results for the strategies identified for minimizing GHG emissions and maximizing materials recovery strategies for each city. Specifically, some cities exhibit a very large difference in the amount of environmental emissions achievable from the different strategies, ranging from net savings to net emissions.

Furthermore, the strategies identified by the MSW DST for minimizing GHG emissions do not necessarily minimize other emissions. A few cities exhibit net positive amounts of criteria pollutant emissions, mainly associated with WTE. In these cases, the model results suggest that reallocating waste material from WTE to recycling options might reduce the amount of net emissions as observed in the results of the strategies for maximizing materials recovery.

Cost was not a consideration in identifying strategies for minimizing GHG emissions. Although the WTE-based strategy resulted in minimum GHG emissions, the cost of such a strategy is higher than other options and may not be financially sustainable. In addition, a WTE-based strategy may drive increases in other pollutants at the local level where the WTE financial cost is incurred.

In evaluating the results from the MSW DST, we found that materials recycling creates significant benefits in terms of GHG emissions (and other emissions) reductions and significantly influences the overall results. Recycling of metals and plastics, for example, produces the most significant energy and emissions savings because of the avoided energy consumption in manufacturing processes using virgin materials. Consistently, we found that the differences in the recyclables composition often play a large role in explaining the differences in the emissions, energy, and cost results among the cities.

It is important to note that the feasibility of recycling depends on the composition of materials in the waste stream and how efficiently they can be recovered. As our analysis indicated, many cities have large amounts of food and other organic materials in their waste streams that could not be recycled but could be composted. Thus, in the strategies for maximizing materials recovery, the MSW DST sent a significant amount of waste (organics) to composting.

We also found that the burdens attributed to collection activities, in particular when commingled collection is required, play an important role in understanding the net emissions, energy, and cost results of the strategies.

Like recycling, energy recovery (from WTE) also creates significant emissions reductions. The electricity grid mix of fuels for each city appears to have the most significant role in explaining the results for strategies to minimize GHG emissions. Cities with electricity grids that rely on greater amounts of fossil fuels have greater potential to reduce GHG (and other) emissions from WTE or landfill gas-to-energy systems than cities with electricity grids that have significant fractions of nonfossil fuels.

The study was designed to capture variability in waste composition by considering data for cities of various income levels and geographic conditions. These data were collected through site visits as part of the *World Bank Solid Waste Management Holistic Decision Modeling* study (2008b). Other key data included default data and assumptions that are built into the MSW DST or came from the literature. Therefore, the net costs, energy, and emissions of the waste management strategies selected by the model to minimize GHG emissions and maximize materials recovery are not an accurate reflection of the actual costs, energy, and emissions for a given city if a particular optimization scenario is implemented. Furthermore, to get a better picture of potential socioeconomic impacts, analysts should consider indirect costs and benefits. These estimates would consider the health outcomes resulting from emissions reductions or increases.

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