

# Impact Assessment of Waste Management Options in Singapore

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## ABSTRACT

This paper describes the application of life cycle assessment for evaluating various waste management options in Singapore, a small-island city state. The impact assessment method by SimaPro is carried out for comparing the potential environmental impacts of waste treatment options including landfilling, incineration, recycling, and composting. The inventory data include gases and leachate from landfills, air emissions and energy recovery from incinerators, energy (and emission) savings from recycling, composting gases, and transport pollution. The impact assessment results for climate change, acidification, and ecotoxicity show that the incineration of materials imposes considerable harm to both human health and the environment, especially for the burning of plastics, paper/cardboard, and ferrous metals. The results also show that, although some amount of energy can be derived from the incineration of wastes, these benefits are outweighed by the air pollution (heavy metals and dioxins/furans) that incinerators produce. For Singapore, landfill gases and leachate generate minimal environmental damage because of the nation's policy to landfill only 10% of the total disposed wastes. Land transportation and separation of waste materials also pose minimal environmental damage. However, sea transportation to the landfill could contribute significantly to acidification because of the emissions of sulfur oxides and nitrogen oxides from barges. The composting of horticultural wastes hardly imposes any environmental damage. Out of all the waste strategies, the recycling of wastes offers the best solution for environmental protection and improved human health for the nation. Significant emission savings can be realized through recycling.

## INTRODUCTION

Economic development and industrialization are often accompanied by the generation of large amounts of

### IMPLICATIONS

The environmental burdens of waste management have become a major concern in many countries. The life cycle assessment method was used to compare the waste disposal options in Singapore. This system-side approach, which includes life cycle impact assessment for incineration, landfilling, recycling, and composting, provided an overview of the environmental burdens and benefits of the nation's waste management strategy.

wastes that must be recovered or disposed off. Environmental burdens of solid waste management systems, such as pollution of air, land, and water and degradation of natural habitat have become increasingly important issues to private citizens, businesses, and the government. A waste management system includes waste collection and sorting, followed by one or more of the following options: recovery and recycling of secondary materials, biological treatment of organic materials, thermal treatment, and landfill.<sup>1</sup>

Different waste strategies will impose, directly or indirectly, different impacts on the environment. The "waste management hierarchy" (minimization, recovery and transformation, and disposal) has been adopted by most industrialized nations as the bedrock of strategy development for achieving sustainable waste management systems.<sup>2</sup> The waste strategies that are adopted by various countries are influenced by a number of factors, such as geographical area, population density, transportation infrastructure, and environmental regulations.<sup>3</sup>

## Study Area: Singapore

This paper investigates the present solid waste management situation in Singapore and compares it with other waste options. Modern urban integrated waste management practices are fundamentally reliant on two core technologies: landfilling and incineration. Solid waste management in Singapore is administered by the National Environmental Agency (NEA).<sup>4</sup> With limited territory available for the landfilling of disposed wastes, the NEA policy for waste disposal gives top priority to the incineration of all incinerable wastes that are not recovered, reused, or recycled. There are presently four incineration plants and one sanitary landfill in Singapore.

## Incineration

Excessive burning of wastes can generate pollutants such as sulfur oxides (SO<sub>x</sub>) and nitrogen oxides (NO<sub>x</sub>), cadmium (Cd), copper (Cu), lead (Pb), mercury (Hg), and dioxins/furans, which potentially could contribute to environmental problems, like acidification, human toxicity, and ecotoxicity.<sup>5</sup> That is why modern incinerators must be equipped with pollution control systems to minimize these harmful emissions. These pollution control technologies are capable of removing up to 90% of NO<sub>x</sub> emissions and 99% of the toxic metals and acid gases.<sup>6</sup> All of the incinerators in Singapore are also equipped with the same type of pollution control technologies.<sup>4</sup> In the country,

incineration still takes top priority for waste disposal because of a lack of available land for landfills.

**Incinerator Ash.** A portion of the bottom ash and fly ash from the incineration is landfilled. With complete combustion, the ash is assumed to contain no organic carbon and will not generate any landfill gases.<sup>6</sup> The rest of the bottom ash is being tested to be used as road pavements. The chief benefit of using ash for roads is not just for economical reasons but also for reducing the amount of material sent to landfills. This is the same practice used in countries such as Japan<sup>7</sup> and Norway.<sup>8</sup>

### Landfill

Presently, Semakau Landfill is Singapore's only landfill for waste disposal. Nonincinerable wastes are transferred into barges at this station and transported to Pulau Semakau. Commissioned in the year 1999, the life span of the landfill is expected to last until the year 2040.

In general, municipal solid waste (MSW) landfills are not considered environmentally sustainable because of the potential hazard of organic releases.<sup>9</sup> As waste decomposes, the combination of chemical, thermal, and microbial reactions release gases. However, in Singapore, very minimal or zero traces of these gases exist at the landfill. The first reason is because organic wastes are not landfilled. The second is because of the NEA scheme to landfill a very minimal portion (at most, 10%) of the total solid waste generated.

### Recycling

Wasteful consumption patterns exploit and diminish natural resources. To preserve the natural environment and conserve natural resources, there is an obligation for the community to minimize waste output and to recycle as much waste as possible. In Singapore, several recycling companies are located at an industrial area called Sarimbun Recycling Park. Waste materials, such as construction and demolition waste, horticultural wastes, and tires, are sent there by trucks for additional reprocessing.

Recycling saves energy and helps mitigate carbon dioxide (CO<sub>2</sub>) emissions.<sup>10</sup> Singapore recycled ~48% of its waste in the year 2004.<sup>4</sup> Most of the materials recovered came from the industrial and commercial sectors. Recycling activities in Singapore include the following: (1) local recycling of tires, ferrous metals (steel), plastics, and wood; (2) conversion of construction wastes (mixtures of cement, aluminum, steel, sand, and wood) into aggregates; (3) recovery of steel slag and Cu slag; and (4) conversion of food (soya) wastes into animal feed. Other waste materials, such as paper and cardboards, are baled and sent overseas for processing. Glass, textiles, and non-ferrous metals are also sent overseas for recycling.

### Singapore Green Plan 2012

The Singapore Green Plan (SGP) 2012 marks a new milestone in Singapore's journey toward environmental sustainability for the next few decades.<sup>11</sup> The target is to raise the overall current recycling rate from 48% (in year 2004) to 60% by the year 2012.

**Toward Zero Landfill.** The excessive generation of wastes and the overuse of land for landfills pose an increasing environmental burden for the society. When developing the Semakau landfill, care was taken to protect the marine ecosystem as much as possible. With a growing population and expanding economy, waste generation and disposal is likely to increase.

Singapore's challenge is to make more optimal use of land and strive for more intensive development without compromising on human health and the environment. Singapore's policy toward waste management covers the entire spectrum from generation to recycling to disposal. Because of limited space, Singapore aims for "zero landfill" by minimizing the amount of waste generated and recycling as much as is feasible.

### Biological Treatment

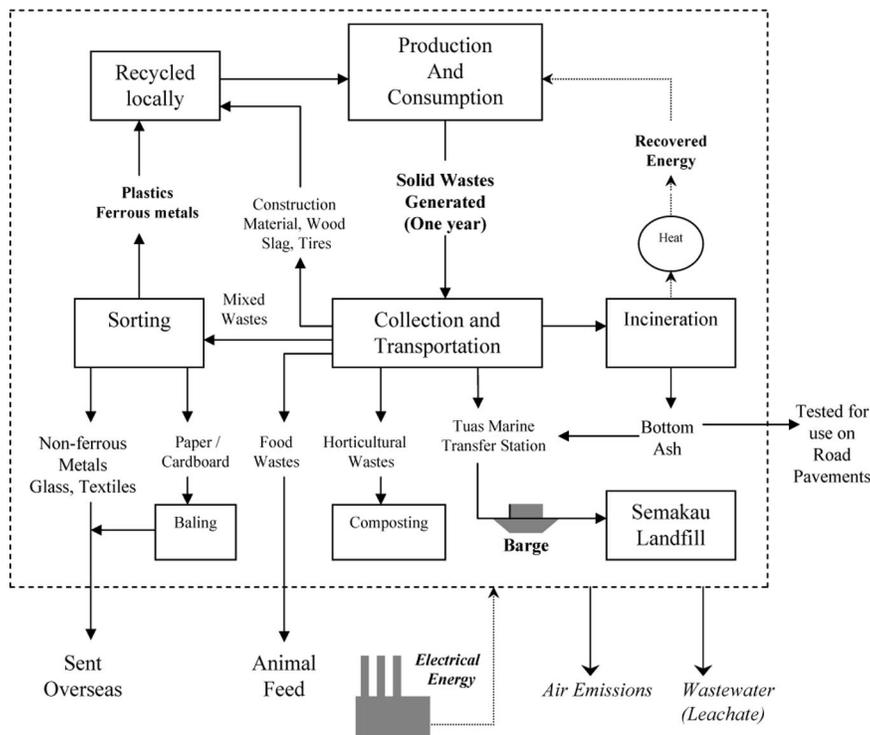
Biological treatment involves using naturally occurring microorganisms to decompose biodegradable wastes. In Singapore, the only form of biological treatment of wastes is the composting of horticultural wastes, which is the simplest form of biological treatment. Pruned tree trunks and leaves are sent to various companies at Sarimbun Park to be transformed into garden compost, including soil fertilizers and biochips. Emissions to air from composting are available from measurements performed at composting plants. The detailed process of producing compost and fertilizers for soil use can be found in Bjarnadóttir et al.<sup>9</sup>

### Life Cycle Assessment

Evaluating the environmental performance of solid waste management options is a complex task. Different waste management options will result in different environmental impacts for the country. The evaluation of these potential impacts is extremely important for the purpose of protecting the community at large, as well as preserving the natural environmental settings of a small island. To perform this complex task, the application of a life cycle assessment (LCA) for waste management is introduced.

Initially, LCA was developed as a tool for investigating the environmental impacts of products. However, more recently, considerable interest has been shown in applying the technique to waste management systems.<sup>1,5,9,12</sup> This is largely because the comparative environmental performance of waste management options is unclear, particularly when indirect effects, such as transport, infrastructure, and the benefits of recovered materials and energy are taken into account for materials or products during their end-of-life stages. Another example of the use of LCA to compare the overall environmental burdens of the end-of-life scenarios of products can be found from Tan and Khoo.<sup>13</sup>

**Functional Unit and System Boundary.** Typically, a waste management system would be described in terms of the disposal of a quantity of waste, which allows the comparison of alternative systems that might perform this service in different ways.<sup>13</sup> For the present case, the system boundary is illustrated in Figure 1. It starts with the annual amount of solid waste generated in Singapore, waste collection, and transportation. Subsequently, some of the wastes are sent by trucks to the incinerators and recycling



**Figure 1.** LCA system boundary for waste management in Singapore.

centers by trucks or to Semakau landfill by truck and barge. Approximately 90% of disposed wastes are incinerated, except for construction materials, glass, and slag, which are all presently sent to the landfill.<sup>4</sup> At the incinerator, air pollution is generated and at the same time energy is recovered for use. Gases and leachate are generated from Semakau landfill. The composting of horticultural wastes also generates gases.

Energy is required for the sorting and baling processes. After the sorting of mixed wastes, the materials that are recycled locally are ferrous metals, slag, plastics, construction material, and tires. Paper and cardboard are baled and sent overseas. Other waste materials, such as glass, nonferrous metals, and textiles, are also sent overseas for processing. The emission savings from the overseas processing of recycled wastes will not be included in the system boundary.

Within the LCA waste system, the following waste management strategies are compared: (1) present waste scheme (for year 2004): recycling rate of 44%, and waste disposed will be 90% incinerated and the rest (10%) landfilled; (2) SGP 2012: recycling rate of 60%, all waste disposed will be incinerated (100%), and zero landfill; (3) 100% landfill; (4) 100% incineration; and (5) 100% recycling.

To be able to compare the LCA results in an objective fashion, it is important that a functional unit is identified to provide a point of reference for obtaining the system inputs and outputs.<sup>14</sup> This allows for meaningful comparisons between alternative scenarios and identifies the environmental elements that should be included in the study. In most LCA studies, the functional unit has been related to the service (function) of a product and expressed in terms of a system output. The function of a

waste management system, in contrast, deals with the amount of waste generated in a given area<sup>6</sup> or the total waste of a defined geographical region in a given time (e.g., 1 yr).<sup>15</sup> The functional unit for the LCA study is defined as the total waste generated in Singapore geographic area per year (2004).

### Life Cycle Inventory

In the LCA technique, the inputs and outputs of a system are systematically identified and quantified. These input-output flows are then assessed in terms of their potential to contribute to specific environmental impacts.<sup>12</sup> As a start in identifying the comprehensive environmental burdens associated with the waste management strategies, the inventories for the unit operations included in the system boundary (Figure 1) must be listed. The simple method used is as follows: (model LCI waste data [pollutants in kg/t for specific material, for example, plastics] from various references)  $\times$  (amount of waste material [plastics] in tons generated in Singapore for selected year [2004]) = total emissions (kg) because of disposed material in the country. In the method, the "model LCI waste data" are sourced from various references, but the "amount of waste material" is according to the country's situation.

**Incineration and Landfill.** With the help of the waste management department in NEA, an inventory analysis for the total amount (tons) of various types of wastes (e.g., plastics, paper, wood, etc.) sent to landfills, incineration, and recycling is compiled. Specific emissions to air from waste incineration and landfills applied in an LCA of waste should be given as weight of pollutant emitted per

**Table 1.** Total air emissions attributable to the amount of waste incinerated in Singapore for the year 2004.

All in kg	Food Wastes	Paper/ Cardboard	Mixed Plastics	Construction Debris	Wood/ Timber	Horticultural Waste	Ferrous Metals	Non-ferrous Metals	Glass Wastes	Textile/ Leather	Tires	Slag
CO	4.02E + 04	1.04E + 05	1.55E + 05	0	3.07E + 04	2.37E + 04	0	0	0	1.53E + 04	1.39E + 03	0
CO <sub>2</sub>	3.02E + 08	7.91E + 08	1.46E + 09	0	2.21E + 08	1.73E + 08	0	0	0	1.16E + 08	1.05E + 07	0
SO <sub>2</sub>	2.83E + 04	7.05E + 04	1.50E + 05	0	2.09E + 04	1.63E + 04	0	0	0	5.35E + 02	3.08E + 01	0
NO <sub>x</sub>	2.25E + 04	5.86E + 04	1.25E + 05	0	1.73E + 04	1.34E + 04	0	0	0	8.58E + 04	7.38E + 03	0
HCl	1.80E + 04	4.45E + 04	1.00E + 05	0	1.32E + 04	1.03E + 04	0	0	0	6.80E + 02	6.15E + 01	0
Dioxins/furans	N.A.	4.02E - 02	8.92E - 02	0	1.19E - 02	6.38E - 03	0	0	0	6.12E - 03	5.54E - 04	0
PM	4.64E + 03	1.24E + 04	5.68E + 04	0	3.66E + 03	2.80E + 03	0	0	0	1.90E + 03	1.64E + 02	0
Arsenic	5.95E - 03	1.02E - 02	5.76E - 03	0	3.02E - 03	2.10E - 03	3.78E + 00	2.39E - 01	0	1.17E + 00	1.06E - 01	0
Cadmium	1.47E - 01	2.52E - 01	2.43E + 00	0	7.46E - 02	5.19E - 02	2.07E + 00	4.54E - 01	0	2.83E + 00	2.56E - 01	0
Chromium	3.39E - 01	5.81E - 01	4.54E - 01	0	1.72E - 01	1.20E - 01	7.62E - 01	4.00E - 01	0	1.17E + 00	1.06E - 01	0
Copper	1.78E - 02	3.05E - 02	3.06E - 02	0	9.02E - 03	6.27E - 03	3.61E + 00	2.21E - 02	0	1.08E + 00	9.76E - 01	0
Hg	9.20E - 01	1.58E + 00	5.33E - 01	0	4.67E - 01	3.24E - 01	1.85E + 00	4.09E - 02	0	6.89E - 01	6.23E - 02	0
Ni	5.77E - 01	9.90E - 01	6.81E - 01	0	2.93E - 01	2.04E - 01	1.06E + 00	7.80E - 02	0	4.53E - 01	4.09E - 02	0
Lead	9.56E + 00	1.64E + 01	1.73E + 01	0	4.85E + 00	3.37E + 00	1.37E + 01	4.40E - 01	0	1.72E + 01	1.56E + 00	0
Zinc	5.41E + 00	9.28E + 00	1.59E + 01	0	2.74E + 00	1.91E + 00	7.15E + 01	3.89E - 01	0	3.02E + 01	2.73E + 00	0

weight of waste incinerated (e.g., g CO<sub>2</sub>/t waste). Because most of the specific pollutant levels were unavailable from NEA, calculations for these emissions were taken from several LCI models.<sup>6,9,16</sup>

The total air emissions because of the tons of various waste types incinerated in Singapore (for the year 2004) are displayed in Table 1. The LCI data required for the type of grid electricity used to power (start up) the incinerators is available from a local national LCI database.<sup>17</sup> The emissions from incineration of waste can be determined by using the LCI model from other countries because of the same type of technology that is adopted by Singapore.<sup>6</sup> The total landfill gases for the country is displayed in Table 2. The landfill emissions are calculated using the LCI model provided by White et al.<sup>16</sup> and Bjarnadóttir et al.<sup>9</sup> As with landfill gas, it is not easy to predict the exact values for leachate generation from all sorts of wastes. For this case, it is assumed that each waste material generates 0.15 m<sup>3</sup>/t of leachate, with the leachate composition extracted from White et al.<sup>16</sup> They are displayed in Table 3.

*Recycling.* Details of the specific amounts of energy conserved because of recycling are not available in the country. Energy conserved because of recycling is shown in Table 4. For performing impact assessment, the reduction of energy use is directly associated with less air emissions from fossil fuel power plants. All of the data were extracted from McDougall et al.,<sup>6</sup> except for the recycling of

tires, which was obtained from Cornell Cooperative Extension<sup>18</sup> and Dunlop Tires.<sup>19</sup> The energy required for the central sorting of mixed wastes (of paper/cardboard, glass, ferrous metals, and nonferrous metals), based on a horizontal conventional moving conveyor machine equipped with magnetic separator, is estimated to be 0.2 kWh/t. The energy estimated for the baling of paper/cardboard is 16.5 kWh/t of waste material.

Details of energy consumed or conserved for the recycling of food into animal feed is unavailable and is left out of the LCA. The total air and water emissions because of composting of horticultural wastes in Singapore is displayed in Table 5. The data are calculated based on the LCI models from Bjarnadóttir et al.<sup>9</sup> and Hassan et al.<sup>15</sup>

*Transportation.* Presently, diesel-driven vehicles in Singapore are regulated according to the EURO 2 standards. Therefore the EURO 2 standards are used for generating truck emissions.<sup>20</sup> The transportation data for both barges (marine transportation) are adopted from the Organization for Economic Cooperation and Development and Hetch.<sup>21</sup> Both types of transportation emissions are shown in Table 6. For the disposal of waste in landfill, waste is transferred by truck for a distance of 28 km to Tuas Marine Transfer Station and then delivered to Semakau landfill by barge. The estimated distance traveled by the barge from the shore to the island is 25 km. The distance to the incinerators and Sarimbun Park (recycling

**Table 2.** Total air emissions due to the amount of waste landfilled in Singapore for the year 2004.

All in kg	Food Wastes	Paper/ Cardboard	Mixed Plastics	Construction Debris	Wood/ Timber	Horticultural Wastes	Ferrous Metals	Non-ferrous Metals	Glass Wastes	Textile/ Leather	Tires	Slag
CO	0	0	1.70E + 03	2.06E - 01	3.12E + 03	1.57E + 03	1.04E - 01	3.02E - 01	3.78E - 01	0	N.A.	1.70E - 01
CO <sub>2</sub>	0	0	2.12E + 06	1.46E + 04	3.84E + 06	2.62E + 06	2.08E + 05	2.13E + 04	5.34E + 05	0	N.A.	9.62E + 04
CH <sub>4</sub>	0	0	5.91E + 05	6.48E + 03	1.31E + 06	9.12E + 05	7.53E + 04	9.48E + 03	1.96E + 05	0	N.A.	3.56E + 04
SO <sub>x</sub>	0	0	3.94E + 03	4.12E - 01	2.64E + 03	1.34E + 03	2.08E - 01	6.03E - 01	7.56E - 01	0	N.A.	3.41E - 01
NO <sub>x</sub>	0	0	1.66E + 03	1.65E + 00	5.19E + 03	2.66E + 03	8.30E - 01	2.41E + 00	3.02E + 00	0	N.A.	1.36E + 00
HCl	0	0	2.81E + 00	1.07E + 00	2.90E - 01	4.23E + 01	5.40E - 01	1.57E + 00	1.97E + 00	0	N.A.	8.86E - 01
HF	0	0	5.61E - 01	2.14E - 01	5.80E - 02	8.46E + 00	1.08E - 01	3.14E - 01	3.93E - 01	0	N.A.	1.77E - 01
H <sub>2</sub> S	0	0	3.94E + 03	3.30E + 00	3.03E + 02	2.81E + 02	1.66E + 00	4.83E + 00	6.05E + 00	0	N.A.	2.73E + 00

**Table 3.** Leachate composition for landfills.<sup>16</sup>

Leachate Composition in Landfill in g/m <sup>3</sup> (for all waste types)												
Dioxins/furans	Phenol	Ammonium	Arsenic	Cadmium	Chromium	Copper	Lead	Mercury	Nickel	Zinc	Chloride	Fluoride
3.20E - 07	0.38	210	0.014	0.014	0.06	0.054	0.063	0.0006	0.17	0.68	590	0.39

facilities) are estimated to be 25 km and 30 km, respectively, by the use of truck transportation.

### Impact Assessment

The impact assessment method by SimaPro<sup>22</sup> includes the three main environmental damage categories described below.

*Human Health.* This is measured in disability-adjusted life years, that is, the different disabilities caused by diseases are weighted. Climate change, which is an international concern, is categorized under this damage category.

*Ecosystem Quality or Ecotoxicity.* This is measured in PDF  $\times$  m<sup>2</sup> year, which is the potentially disappeared fraction of plant species. The impact category of acidification is listed under this environmental category. In terms of ecotoxicity, the measured aspect is the percentage of all species present in the environment living under toxic stress (potentially affected fraction or PAF  $\times$  m<sup>2</sup> year).

*Resources.* The last category measures the additional energy requirement to compensate lower future ore grade, and the unit of measurement is in megajoule (MJ) surplus.

The following four categories are selected: climate change, acidification, ecotoxicity, and resource use. The four types of impact categories selected were based on their environmental relevance to Singapore, as well as the types of emissions presented in the LCI results. For example, the impact category of eutrophication is not relevant, because there are no sizable freshwater systems of rivers and lakes in Singapore. Similarly, radiation is not an issue for any of the wastes considered. Therefore, the four impact categories were chosen to be representative of the potential environmental impact of solid waste management in the Singapore context.

## RESULTS AND DISCUSSION

The results for climate change, acidification, ecotoxicity, and resource use are presented below.

**Table 4.** Energy savings because of recycling of selected materials.<sup>6,18,19</sup>

Estimated Energy Savings (GJ/t) from the Recycling of Selected Waste Materials									
Paper/Cardboard	Mixed Plastics	Wood/Timber	Ferrous Metal (Iron)	Ferrous Metal (Steel)	Nonferrous Metal (Aluminium)	Nonferrous Metal (Copper)	Construction Material	Slag (Steel/ Copper)	Tires
5.6	20.5	6.6	223.0	12.6	174.0	7.9	19.5	10.2	9.8

### Waste Disposal

The results for the present waste management strategy for the waste disposed (landfill and incineration) in Singapore, for year 2004, are displayed in Figures 2 (climate change), 3 (acidification), and 4 (ecotoxicity).

*Climate Change.* Waste treatment and management has been studied together with the intention of reducing greenhouse gases in many countries. This is because global warming or climate change has become a worldwide concern.<sup>12</sup> Moreover, Singapore, as a small island, is vulnerable to any sudden changes in sea levels.<sup>11</sup> In Figure 2, the largest amounts of greenhouse gases are generated from the incineration of plastics and, next, from paper/cardboards. The explanation for the results shown is because of, first and foremost, the chemical properties of the material. Plastics are made from oil, and although the material has a high-energy content, burning plastics contributes to climate change through CO<sub>2</sub> release. Oil is a fossil fuel, and so incineration of plastic releases carbon previously held in long-term storage in oil deposits.<sup>23</sup> Paper or cardboard, on the other hand, originates from wood, which contain elements of carbon that are released as CO<sub>2</sub> when burned.<sup>13</sup> Another explanation for the peaks shown in Figure 2 is the large volumes of paper/cardboard and plastics that are sent for incineration. Paper/cardboards and plastics each make up 25% and 24%, respectively, of the total waste disposed in Singapore. With increased recycling rates and less incineration of plastics and paper/paperboard in the near future, the levels of CO<sub>2</sub> from incinerators will also be expected to decrease. This trend is similar to the waste treatment study performed in Sweden.<sup>24</sup> The incineration of food, horticultural wastes, wood, and textiles also contributes to climate change. The transportation of wastes to incinerators hardly causes any environmental impact.

Figure 2 shows that the landfilling of wastes creates minimum harm to the environment. Although other countries report that, in general, large amounts of greenhouse gases are found in most landfills,<sup>9,12</sup> this is not the case for Singapore. The reason is because organic wastes, such as food waste, are not sent to the Semakau landfill.<sup>4</sup> Plastics, glass, construction materials, metals, and slag are

**Table 5.** Total air and water emissions attributable to the composting of horticultural waste in Singapore for the year 2004.

Emissions Attributable to Composting	
Parameter	Total kg
CO <sub>2</sub>	4.84E + 06
CH <sub>4</sub>	1.04E + 05
CO	3.11E + 04
NH <sub>3</sub>	1.84E + 04
N <sub>2</sub> O	1.96E + 04
NO <sub>x</sub>	2.52E + 04
VOC	1.96E + 05
Water emissions	Totalg
BOD	1.86E + 07
COD	3.15E + 07
Ammonium	3.22E + 06

practically inert in landfills. Compared with incineration, the landfilling of wastes does not pose much environmental threat. This is because of the nation's policy to incinerate most of the disposed wastes (up to 90%). The transportation of waste by truck and barge to the Semakau landfill also creates minimal environmental damage.

**Acidification.** SO<sub>x</sub> and NO<sub>x</sub> are significant pollutants that can cause acidification and nutrient forcing of terrestrial and freshwater ecosystems. Figure 3 shows that the incineration of plastics contributes significantly to this impact category. The second highest contribution comes from the incineration of paper/cardboard. Next comes food, wood, horticultural wastes, and textiles. For many years, incineration or heat treatment technologies equipped with waste-to-energy systems have been used by many countries for the disposal of wastes; however, pollution control devices are required to monitor and reduce the release of harmful gases from incinerators. These pollution prevention measures include the control of the amount of NO<sub>x</sub> gases that are generated.<sup>5</sup> The environmental impacts of truck transportation to the incineration plants are highly insignificant.

Figure 3 also shows that, compared with incineration, the landfilling of wastes hardly causes any environmental damage. However, the contribution of acidic gases from the transportation of wastes by barge from Tuas Marine Station to Semakau landfill is quite significant for nearly all materials, except for metals and tires. In this case, the pollution comes from the volumes and weights of the material that needs to be ferried across the sea to the landfill site, as well as the release of acidic gases from

**Table 6.** Transport pollution.<sup>20,21</sup>

Pollutants	CO	CO <sub>2</sub>	HC	SO <sub>2</sub>	NO <sub>x</sub>	PM	VOC
Truck Emissions							
Class III (g/km)	0.27	47.0	0.075	N.A.	0.48	0.17	N.A.
Marine Emissions							
g/(tkm)	109	35000	60	35	420	30	75

marine transport systems. These gases may be a threat to the continued existence of various species of vegetation and aquatic life forms, which can be found around the island's coastal areas.<sup>25</sup>

**Ecotoxicity.** MSW incinerators are found to be one of main sources of airborne metal pollution, including Cd, Cr, Cu, Pb, and zinc (Zn) in Singapore.<sup>26</sup> Incinerator emissions also contain dioxins and furans, which can be transported for considerable distances downwind from the incinerator facilities and have become major environmental and social concerns.<sup>27</sup> Stringent laws and regulations have been imposed in many countries to minimize the harm caused by such emissions.<sup>5</sup>

The results displayed in Figure 4 are generated after the removal of 99% of heavy metals from the incinerator gases, which is the removal efficiency found in new incinerators.<sup>4,16</sup> Although ferrous metals make up only a small proportion of the total waste disposed (~2%), these materials generate large amounts of toxic metals when incinerated.<sup>6</sup> According to the same study, materials such as paper, wood, textiles, and plastics also produce a significant amount of harmful gases, including dioxins and furans, when incinerated. These are known to be very toxic compounds that can adversely affect human health by entering the food chain after being emitted into the air.<sup>28</sup> This makes the strategy of minimizing waste and maximizing recycling even more pertinent in the context of Singapore. With increased recycling of wastes, future environmental burdens from incinerators, as well as harm caused to human health and nature, can be expected to lessen.

Landfill leachate can hardly be noticed in the results shown and has minimal contribution to ecotoxicity. Moreover, the perimeter bund around the Semakau landfill is lined with an impermeable membrane, as well as a layer of marine clay, to ensure that the leachate generated is contained within the landfill area. After passing through a leachate treatment plant, the treated effluent is discharged into the sea. It was reported that the quality of the treated affluent complies with watercourse standards.<sup>29</sup>

**Resources.** Singapore lacks natural resources and relies on the import of fossil fuels from other countries for energy.<sup>11</sup> The advantage of the incineration plant in the country is its ability to generate electricity from the burning of wastes. Of this electricity generated, 80% is made available for the public. The energy result from the incineration of wastes is displayed in Figure 5. The negative peaks illustrate the potential net savings of fossil fuels that are required to produce energy or electricity, that is, the total amount of energy consumed minus the amount generated. In terms of resource savings, plastics have 60% higher thermal values than paper/cardboard,<sup>13</sup> thus making them more environmentally beneficial to incinerate. Other types of combustible wastes (wood, food, horticultural wastes, and textiles) can also provide a considerable amount of energy savings from incineration.

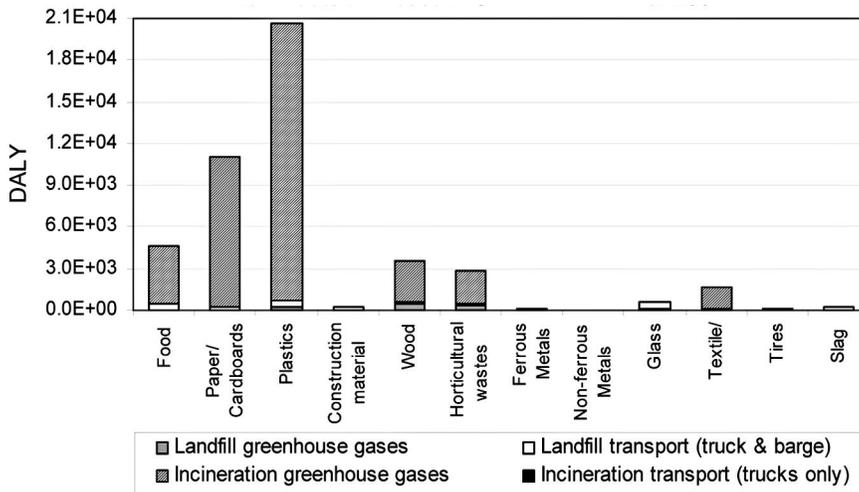


Figure 2. Climate change results for total waste disposed.

### Recycling and Composting

The results of waste recycling/composting are displayed in Figures 6 (climate change), 7 (acidification), and 8 (ecotoxicity).

*Climate Change.* It can be observed from Figure 6 that the recycling of materials provides the best environmentally sound solution for the management of wastes. The negative values show the potential amount of climate change that can be avoided, which is the amount of emissions saved by producing the same products from secondary materials. Also, recycling saves more energy (from manufacturing) than incinerators produce,<sup>30</sup> and helps mitigate climate change.<sup>12</sup> Recent studies by U.S. Environmental Protection Agency confirmed that for every ton of mixed material recycled, 0.8 million t of carbon equivalent are saved, which is four times as much as by incineration.<sup>31</sup>

Figure 6 shows that the largest benefit comes first of all from the recycling of ferrous metals (steel/iron). The recycling of construction materials is also widely assumed to be environmentally beneficial.<sup>32</sup> In the present year, Singapore's industry generated 856,700 t of ferrous metal

wastes and 422,900 t of construction debris, where as much as 93% and 94% were recycled, respectively. Construction materials consist of a mixture of cement, wood, aluminum, steel, and cardboard, which can be turned into aggregates. The number of recycling companies in Singapore has been increasing and will be expected to additionally increase in future.<sup>4</sup>

The waste materials that require sorting activities include ferrous and nonferrous metals, plastics, glass, paper/cardboard, and textiles. After the sorting process, paper and cardboard are baled and sent overseas. Compared with the benefits of emission savings from recycling, the contribution to climate change from the waste separation and baling processes, as well as transportation, are minimal.

The environmental impact of climate change from the composting of horticultural wastes is rather insignificant. Presently, ~40% of horticultural wastes, which consist of pruned branches, trunks, and leaves, are sent directly to composting facilities. From the waste material, only 1.5–2% of the biologically available carbon is emitted as methane during composting.<sup>9</sup>

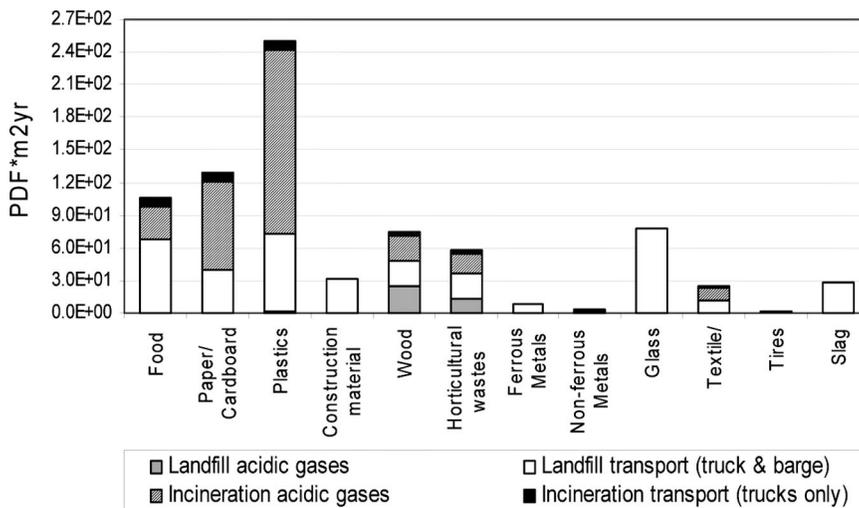
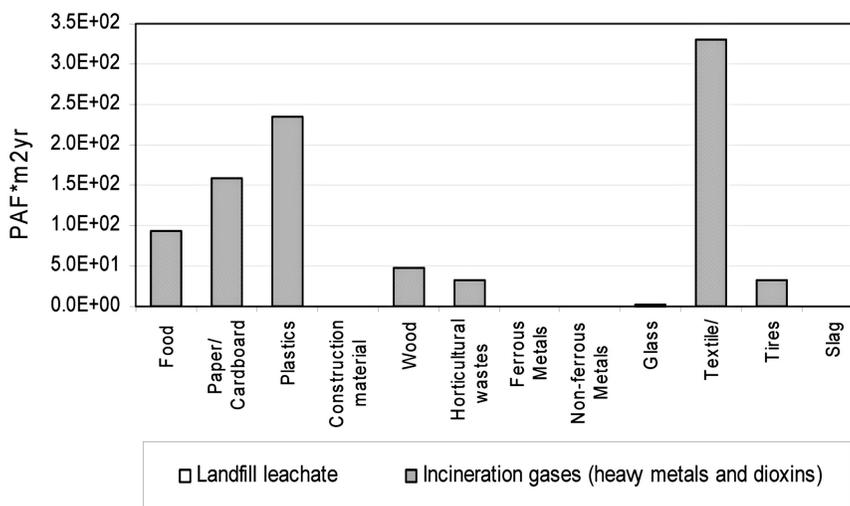


Figure 3. Acidification results for total waste disposed.



**Figure 4.** Ecotoxicity results for total waste disposed.

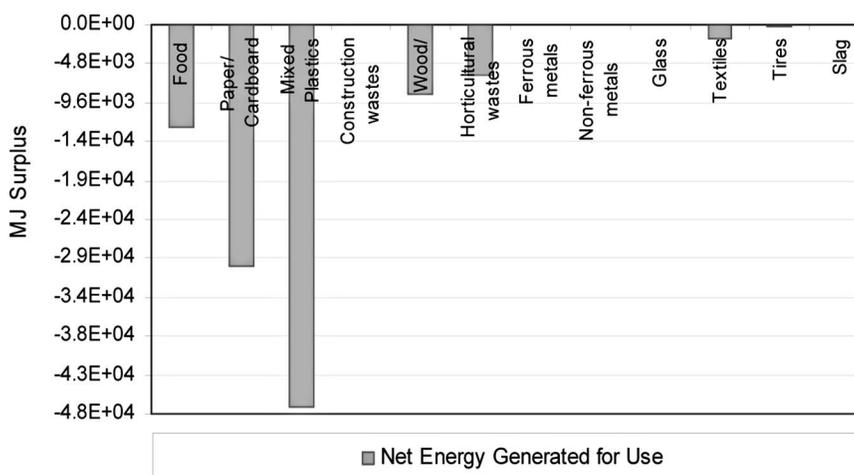
*Acidification and Ecotoxicity.* The results shown in Figures 7 (acidification) and 8 (ecotoxicity) follow the exact same trends as those displayed in Figure 6. The emission-saving patterns exhibit the same inverted peaks for each recycled material; the highest comes from ferrous metals, next, construction material, then slag, plastics, and so forth. This is because the same proportions of emission savings are generated for each material recycled.

Many types of air pollution have important negative health and environmental effects. Therefore, the reduced amounts of NO<sub>x</sub>, SO<sub>x</sub>, and toxic metals will place the country in a better position for achieving environmental protection and health.<sup>11</sup> Although it may be argued that environmental management and technology in Singapore has already been actively pursued, this was predominantly concerned with cleaning up pollution and the huge amount of solid wastes created.<sup>25</sup> The recycling of materials offers a more proactive approach to environmental sustainability, which recognizes well in advance the damaging effects that pollution from waste can cause to the natural ecosystem, and minimizes and mitigates their consequences.

Transportation contributes insignificantly to acidification. These results are consistent with a local case study performed for plastics and paperboard wastes in Singapore.<sup>13</sup> Also for acidification results (Figure 7), slightly higher peaks from composting gases can be noticed. In the present year, a total of 119,300 t of horticultural wastes was sent for composting. The composting process generates NH<sub>3</sub> and NO<sub>x</sub> gases that contribute to this environmental impact category.

### Final Comparisons

A comparison between the present waste strategy for Singapore in the year 2004 (landfill, incineration, and recycling rates) and SGP 2012 is given in Figure 9. It can be seen that the environmental burdens from landfilling and transportation of wastes are the least significant issues in the overall waste management scheme. **It can also be confirmed that any gains in energy from the incineration of wastes are outweighed by the production of harmful emissions. This fact is also true with state-of-the-art incinerators.** However, because Singapore is faced with the



**Figure 5.** Fossil fuel results for energy generation because of incineration of wastes.

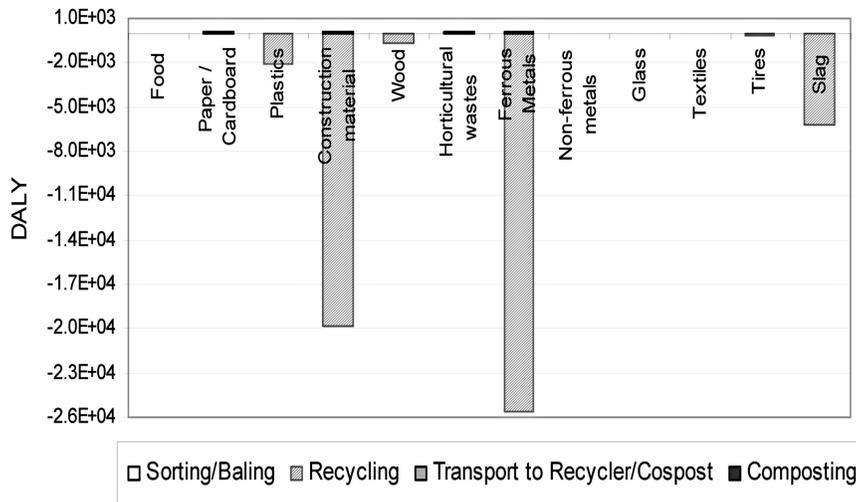


Figure 6. Climate change results because of recycling/composting.

scarcity of space for landfills, the remaining option for the treatment of disposable wastes has been incinerators.

The previous results have shown that air pollution from the incineration of wastes has contributed significantly to climate change, acidification, and ecotoxicity. Because Singapore is a small island country with high population density, high humidity, and low-lying coastal areas, the nation is especially vulnerable to unfavorable health effects from pollution, as well as climate change and sea level rise.<sup>13</sup> To prevent the detrimental effect of incinerator emissions on human health and the environment, the country has to either reduce the amount of waste generated or increase recycling rates.

Recycling of wastes offers the best solution for environmental protection and improved human health. In fact, it was reported that recycling plastic saves 3.7–5.2 times more energy, recycling paper saves 2.7–4.3 times more energy, and recycling metal saves 30–888 times more energy than is gained through incineration.<sup>33</sup>

Finally, an overall comparison of five waste management options is displayed in Figure 10. From the results, it can be highlighted that the environmental impact caused

by the 100% landfilling of waste would have been overwhelming. This hypothetical scenario would have resulted if all solid waste mixtures (including organics and foods waste) were dumped at the landfill. Fortunately, this is not permitted in Singapore. It is also shown on the graphs that the benefits of incinerating 100% of wastes would be very much outweighed by the pollution it creates. From the present waste management strategy (44% recycling, 90% incineration, and 10% landfill) to the implementation of the SGP 2012 (60% recycling, 100% incineration, and zero landfill), ~45% environmental improvement can be appreciated. The benefits will additionally improve by 70% if all waste materials were to be recycled.

### CONCLUSIONS

The sustainability of any country, especially a small island-state like Singapore, begins with ensuring that physical land resources and air are not overwhelmed by pollution from wastes. The investigation of the environmental burdens and benefits of a waste management is a complex task and, hence, requires the use of a

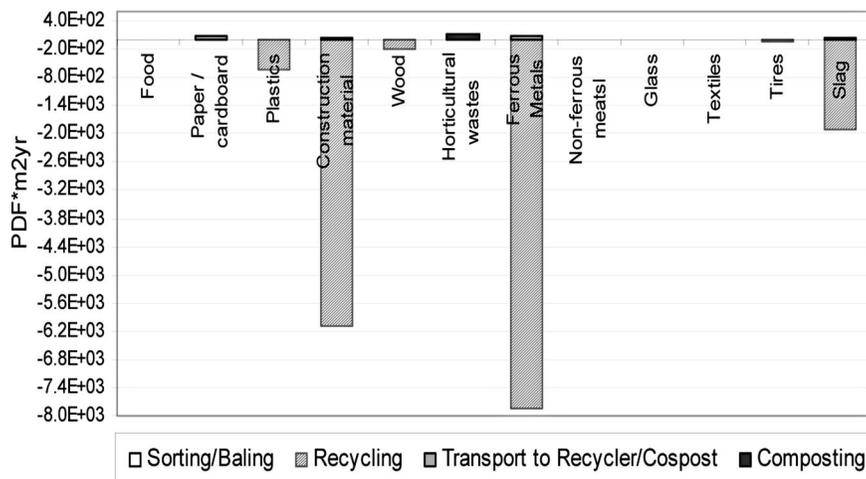


Figure 7. Acidification results because of recycling/composting.

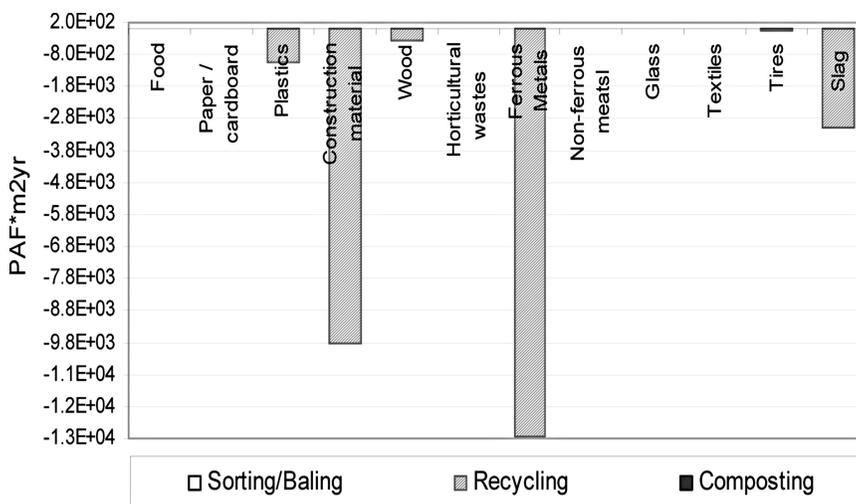


Figure 8. Ecotoxicity results because of recycling/composting.

scientifically sound environmental assessment tool. For this case study, LCA was applied to perform an environmental impact assessment of the entire waste management system and eventually to help select suitable options for dealing with solid wastes. In summary, the LCA results for the waste management strategy in Singapore concluded the following: (1) the incineration of plastics and paper/cardboard both contribute significantly to climate change and acidification; (2) apart from organic wastes, most materials are practically inert in landfills and hardly contribute to climate change or acidification; (3) transportation to Semakau landfill hardly contributes to climate change; however, sea transportation to the landfill contributes quite significantly to acidification because of NO<sub>x</sub> and SO<sub>x</sub> emissions from barges; (4) the incineration of materials generates large amounts of heavy metals and dioxin/furans, (especially from ferrous metals, plastics, textiles, and paperboard), which contribute significantly to ecotoxicity; (5) the energy gained from the incineration of waste materials is outweighed by the air pollution generated from the incinerators; (6) recycling proves to be the best solution to “get rid” of wastes, especially for

ferrous metals, construction materials, and slag (containing Cu and steel) when recycled, all three materials exhibit huge amounts of potential emission savings, which mitigate climate change, acidification, and ecotoxicity; (7) in the overall waste management scenario, the transportation of trucks to incinerators and recycling centers causes minimal damage to environment.

The final results also concluded that from the present state of Singapore’s waste management strategy (for year 2004) to implementing SGP 2012, as much as 45% environmental improvement can be achieved. Because part of SGP 2012 is also to “strive for the Pollutant Standards Index to be within the ‘good’ range for 85% of the year, and within the ‘moderate’ range for the remaining 15%,”<sup>11</sup> the nation’s quest to maximize recycling while minimizing waste has become even more important.

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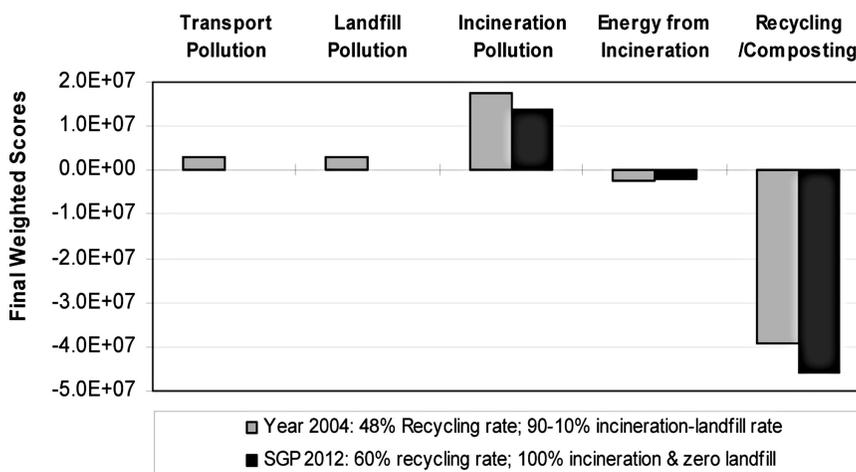


Figure 9. Comparison of present waste strategy (year 2004) and SGP 2012.

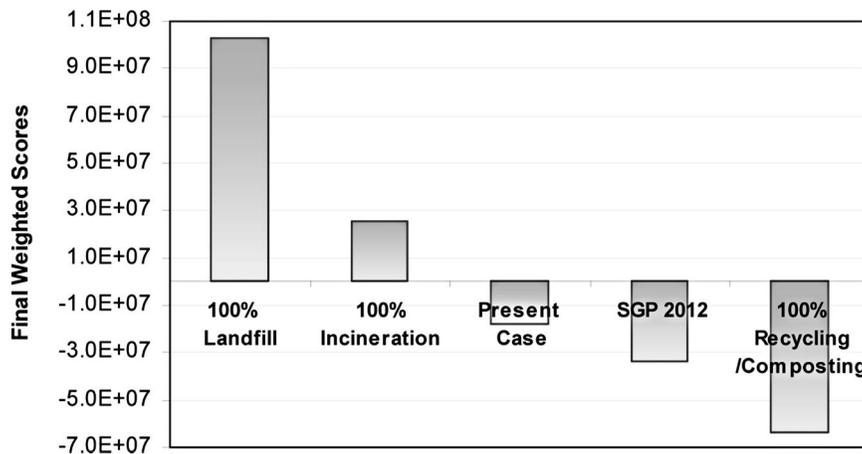


Figure 10. Overall Comparison of waste management options.

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