Life Cycle Assessment of Municipal Solid Waste Management Methods: Haifa Case Study

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Abstract

Eight solid waste management system scenarios were developed and compared for the Municipal Solid Waste Management System of the city of Haifa, Israel, by using the life cycle assessment (LCA) methodology. The solid waste management methods considered in the scenarios were the household participation of waste separation, the mixed and separate collection of dry recyclable waste and wet biowaste, recycling by material banks (MB) and material recovery facility (MRF), composting, biogasification, incineration, refuse derived fuel (RDF) production, and landfilling. The goal of the study was to determine the most sustainable option of municipal solid waste management system for Haifa. The waste management scenarios were compared using the LCA computer model known as "Integrated Waste Management – IWM-2". The inputs and outputs of each management stage were defined and the inventory analyses calculated by the model were presented as waste flows, quantities of solid waste landfilled, the key emissions to air and water, main contributions to climate change, fuel consumption and recovery, and economic cost. The impacts were then quantified with valuation method to evaluate and compare their importance. Sensitivity analysis has been used to test household source separation rate used in the initial life cycle model. The results showed that household participation of keeping the dry recyclable waste clean is more effective than keeping the wet biowaste clean; and introduction of the combination of MRF recycling and biogasification is the most environmentally and economically feasible option for Haifa.

Keywords: life cycle assessment, recycling, composting, biogasification, incineration, landfilling

Introduction

What is the correct balance between environmental and economic factors of one waste treatment system compared to another? What is the correct mix of waste recycling, composting, and energy recovery options? These are some of the key questions that should be addressed before

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commencement of any waste management operation (Nilsson-Djerf and McDougall, 2000). The application of life cycle assessment (LCA) in the waste management sector has become a useful tool in comparing the environmental and economic cost of alternative waste treatment systems and identifying the most favorable one for system performance improvement.

Israel Ministry of Environmental Protection has prepared a wide range of laws and regulations on solid waste. However, municipal solid waste management is still a continuous challenge in Israel. Since 2003, the Central Bureau of Statistics (CBS) of Israel began conducting survey on the quantities of domestic, commercial and yard waste collected by local authorities. The information collected by the CBS and the Ministry of the Environment has improved the available waste data (CBS, 2006). Haifa is the largest city in Northern Israel and the third-largest city in the country, with a population of about 267,700. According to the latest survey conducted in 2005, the amount of total waste generated in Haifa is 160,736 ton/yr and waste generation rate is 1.65 kg/capita/day (or) 601 kg/capita/yr. The organic materials are the main components of the waste stream, in terms of weight, constituting 38% of Haifa's solid waste, followed by paper 28% (paper 22%, cardboard 6%) and plastic 13% (film 12%, rigid 1%). The rest are glass 5%, textile 3%, diapers 3%, metal 2% (Fe 1%, nonFe 1%), and miscellaneous 8% (Israel Ministry of Environmental Protection, 2006).

LCA has a lot to offer in terms of selection and application of suitable MSW management techniques, technologies, and programs to achieve specific waste management objectives and goals. Thus, several studies in the literature used the LCA as a tool for municipal solid waste management (Sonesson et al., 2000; Arena et al., 2003; Dahlbo et al., 2005; Aye and Widjaya, 2006; Bovea and Powell, 2006; Ozeler et al., 2006; Emery et al., 2007; Lee et al., 2007)

The objective of this study was to use the LCA as a tool to compare different solid waste management system options and determine the most feasible system for Haifa, Israel. To this purpose, eight different scenarios of municipal solid waste management (MSWM) systems that include different municipal solid waste processing and disposal methods were developed and, then, compared with respect to their environmental impacts and costs by using the Integrated Waste Management – IWM-2 Model developed by McDougall et al. (2001).

Methodology

Scope Definition

Eight different scenarios of municipal solid waste management system that include different solid waste processing and disposal methods were developed and compared with respect to their environmental impacts and economic cost. The solid waste management methods considered in the scenarios were the household participation of waste separation, the mixed collection or the separate collection of dry recyclable waste or wet biowaste, recycling by material banks (MB) or material recovery facility (MRF), composting, biogasification, incineration, refuse derived fuel (RDF) production, and landfilling. Environmental impacts were evaluated by considering their waste flows, quantities of solid waste landfilled, key emissions to air and water, contributions to climate change, fuel consumption and recovery, and economics. The results take into account the upstream and downstream emissions and resource consumption associated with energy recovery, avoided use of conventional fertilizers, and the avoidance of virgin materials due to recycling.

The Functional Unit and System Boundaries

The function of the system under study is to manage household solid wastes in the area of study. The functional unit selected for the comparison of the alternative scenarios is the management of 1 tonne of municipal solid waste. The system boundaries selected for the life cycle of solid waste were defined as the moment when material ceases to have value, becoming waste and when waste becomes inert landfill material or is converted to air and/or water emissions or regains some value.

Waste Management Scenarios

There are eight waste management scenarios analyzed in the study. Full description of the scenarios is given in Figure 1.

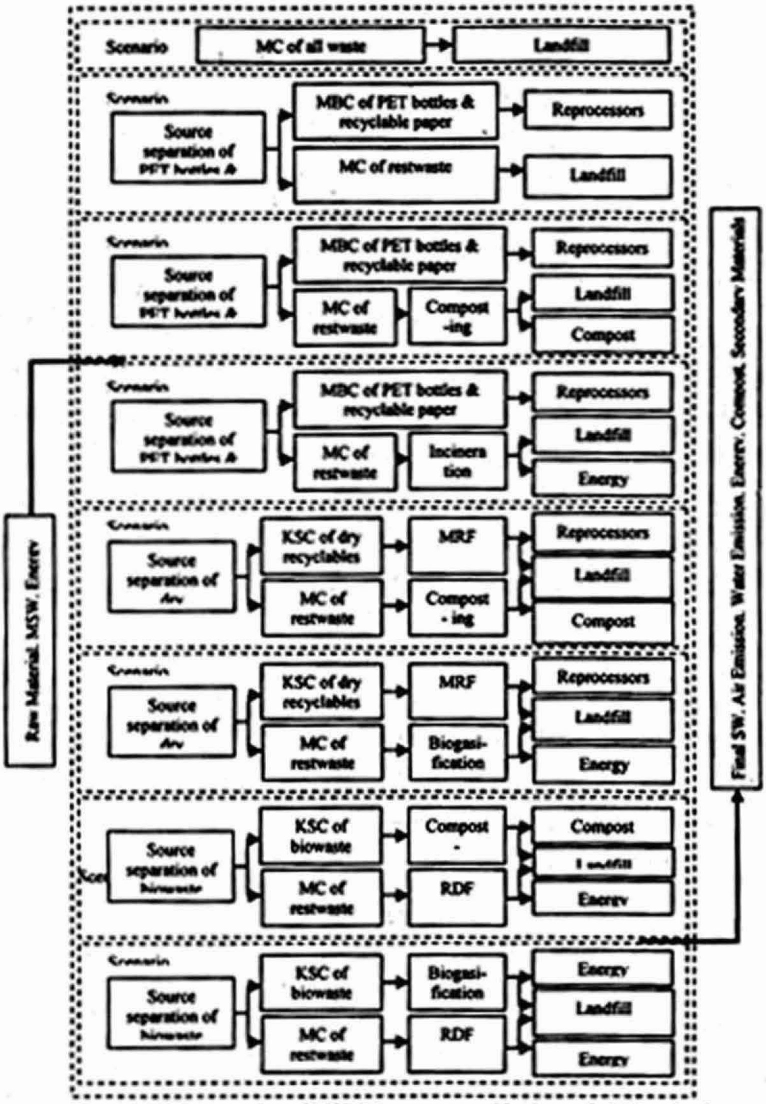

Figure 1. Eight scenarios of MSWM systems used in the study MC- mixed collection, MBC- material bank collection, KSC- kerbside collection, (----) system boundary, (→) inputs and outputs

Life Cycle Inventory

The data collection was mainly based on the projects conducted by Israel Ministry of Environmental Protection and Shaldag Environmental Solutions and Management Ltd. (Israel Ministry of Environmental Protection, 2006), CBS of Israel (CBS, 2006) and the resources available online at the website of Israel Ministry of Environmental Protection, http://www.sviva.gov.il. These data include population, waste generation rate, waste characteristics and composition, waste management application, uses of transfer stations and landfill sites, the cost calculations for the alternatives and operational recommendations for the landfill site.

The Life Cycle Inventory (LCI) constitutes a detailed compilation of all environmental inputs (material and energy) and outputs (air, water and solid emissions) during each stage of the life cycle of the waste. An LCI has been completed for all the activities required to manage the waste from the time it leaves the household to its ultimate disposition: the household participation of waste separation, the mixed collection or the separate collection of recyclable/dry waste or bio/wet waste, the management of the waste in a material bank, transfer station and/or in a material recovery facility, the recycling process of recovered fractions, the composting or biogasification process of the biowaste fraction, the incineration process or resource derived fuel production process, and the management of the waste in the landfill. The savings from energy generation from electricity, compost (avoiding fertilizers) and recycled material (avoiding virgin material) have also been included in the model.

Valuation

The environmental impacts resulted from the model were quantified and converted into monetary units by valuation method. The externalities for global warming potential and air emissions were estimated from the findings of the work of Eshet et al., 2005.

Sensitivity Analysis

Sensitivity analysis has been used to test the assumption used in the initial life cycle model by varying household participation/source separation rate. The effect of changing the percentage of source separation rate of waste from 80% to 60% has been studied.

Results and Discussion

Waste Disposal

Table 1 presents MSW flows in a classical way (a "local perspective", not considering life cycle thinking).

Table 1 Waste flow and its ultimate destination

Scenario	Recycled materials*		Combusted**		Landfilled***	
	Quantity (tonne/yr)	% of total waste input	Quantity (tonne/yr)	% of total waste input	Quantity (tonne/yr)	% of total waste input
1	0	0.0%	0	0.0%	160,888	100%
2	30,518	19.0%	0	0.0%	130,370	81.0%
3	68,233	42.4%	37,715	23.4%	54,940	34.2%
4	30,518	19.0%	100,607	62.5%	29,736	18.5%
5	74,064	46.0%	37,748	23.5%	49,076	30.5%
6	58,965	36.7%	52,847	32.9%	49,076	30.5%
7	28,642	17.8%	85,435	53.1%	46,810	29.1%
8	18,246	11.3%	95,831	59.6%	46,810	29.1%

*Recycled Materials: collected recyclables + marketable products from RDF, composting and biogasification. This can be also named as Overall Material Recovery Rate.

**Combusted figures include: RDF fuel lost due to drying and pelletising; composting and biogasification process lost due to moisture loss and degradation.

***Landfill: waste sent for landfilling without pre-treatment + residues after any treatment processes.

Table 2 presents the amounts of waste being sent for disposal to landfill taking into account a "life cycle perspective" – i.e. considering also upstream and downstream reductions, or increases, in wastes going to landfill associated with the production of compost, the generation of energy, and the avoidance of extracting virgin materials due to recycling.

Table 2 Net amounts originating from waste management operations and final solid waste destined for landfill (in tonnes)

Scenario	Sorting	Biological	Thermal	Landfill	Recycling	Total	LDR*
1	-	-	-	160,888	-	160,888	0%
2	-	-	-	130,190	-27,731	102,460	36.3%
3	-	55,158	-	75	-27,731	27,502	82.9%
4	-	-	25,601	60	-27,731	-2,070	101.3%
5	18,368	30,959	-	11	-39,650	9,688	94.0%
6	18,368	30,238	-	11	-39,650	8,967	94.4%
7	36,208	4,232	1,773	96	-4,499	37,719	76.6%
8	36,208	3,717	1,773	96	-4,499	37,204	76.9%

* Landfill Diversion Rate

Climate Change

The "Global Warming Potential" (GWP) is expressed in CO_2 equivalents and calculated for CO_2, CH_4 and N_2O using the following relationship: 1 CO_2 = 21 CH_4 = 310 N_2O.

Table 3 Effect on the climate change, reflected as Global Warming Potential [in tonnes of CO_2 equivalent]

Scenario	Collection	Sorting	Biological	Thermal	Landfill	Recycling	Total GWP (ton/yr)	GWP (kg/ton)
1	-	-	-	-	170,427	-	170,427	1059
2	236	-	-	-	126,277	2,764	129,277	804
3	236	-	1,880	-	10,395	1,157	13,667	85
4	236	-	-	106,583	55	2,764	109,638	681
5	169	685	1,504	-	24,975	-14,651	12,682	79
6	169	685	-4,352	-	24,975	-14,007	7,469	46
7	374	1,082	770	-37,165	24,931	-7,791	-17,827	-111
8	374	1,082	-3,416	-37,165	24,931	-7,348	-21,570	-134

Air Emission

The results here take into account both the direct air emissions associated with the waste management practices, as well as those avoided due to composting, biogasification, energy generation, and recycling.

Table 4 presents air emissions according to the scenarions. It is worth noting that this analysis was carried out also in terms of other emissions, e.g. for dioxins/furans, cadmium, manganese and mercury, but the resulted impacts were relatively negligible or zero, hence not presented.

Table 4 Air emissions according to the scenarios

Scenario	Emissions (kilograms)			Emissions of metals (grams)		
	PM	NO_x	SO_x	Arsenic	Lead	Nikel
1	-4,918	15,937	-22,104	-	-908	-6,190
2	8,139	15,656	-76,201	-	-316	-1,416
3	13,478	5,706	-54,471	-	660	5,026
4	-26,439	-63,264	-228,780	47	-4,458	-38,229
5	-964	-45,330	-19,393	-256,789	202,578	-1,276
6	-7,587	-55,903	-47,631	-256,789	201,388	-8,690
7	-49,681	-80,811	-214,317	-	2,499	-53,964
8	-54,415	-88,404	-234,530	-	1,648	-59,264

Water Emission

Table 5 presents the water emissions from a life cycle perspective estimated using the IWM-2 model. It is worth noting that for emissions to water the analysis was carried out not only in terms of BOD/COD, TOC, suspended solids, chloride, nitrate, sulphate, but also e.g. for dioxins/furans, phenols, ammonium, arsenic, barium, cadmium, chromium, copper, cyanide, fluoride, iron, lead, mercury and phosphate. However, the resultant emissions were either relatively negligible compared to those reported or were zero, hence not presented.

Table 5 Water emissions according to the scenarios

Scenario	Emissions (kilograms)						
	BOD	COD	TOC	SS	Cl^-	NO_3^-	SO_4^{2-}
1	10,019	9,998	-331	-310	-10,156	-58	-21,770
2	18,481	-1,112,640	69,239	71,820	370,416	19,701	176,977
3	17,784	-1,109,092	69,588	72,601	385,411	19,761	199,780
4	11,084	-1,120,023	69,483	72,013	377,634	19,744	193,083
5	14,913	-733,354	46,130	18,027	221,370	13,115	120,148
6	10,231	-738,212	46,723	16,217	195,460	13,046	93,602
7	5,687	8,569	-159	-1,061	7,105	-12	-12,910
8	2,463	5,223	-450	-2,355	-11,415	-61	-31,886

Fuel

Table 6 presents the total fuel from a life cycle perspective estimated using the IWM-2 model. The results of this analysis take into account both the amount of fuel used associated with the waste management practices, as well as those avoided due to generating energy, and recycling.

Table 6 Total fuel, considering a life cycle perspective

Scenario	Collection	Sorting	Biological	Thermal	Landfill	Recycling	Total Fuel (10^3GJ/yr)	Fuel (MJ/ton)
1	-	-	-	-	-86	-	-86	-534
2	4	-	-	-	-62	-472	-528	-3276
3	4	-	41	-	-5	-472	-432	-2666
4	4	-	-	-749	1	-472	-1,216	-7541
5	3	15	35	-	-15	-988	-952	-5875
6	3	15	-97	-	-15	-988	-1,082	-6686
7	6	24	17	-871	-15	-255	-1,148	-6799
8	6	24	-76	-871	-15	-255	-1,217	-7378

Economic Cost

Table 7 presents the direct economic cost for waste management scenarios from a life cycle perspective estimated using the IWM-2 model. The values used for the revenue of dry recyclables were (paper – \$28.5/tonne, glass- \$7.5/tonne, ferrous metal - \$294.5/tonne, plastic - \$430/tonne).

Table 7 Economic cost of waste management alternatives in Haifa

Sce-nario	Collec-tion	Sort-ing	Biolo-gical	Ther-mal	Land-fill	Recyc-ling	Total cost (10^3\$/ year)	Costs (\$/tonne)
1	-	-	-	-	10,045	-	10,045	62
2	-1,567	-	-	-	8,177	224	6,834	39
3	-1,567	-	3,726	-	3,582	-522	5,219	33
4	-1,567	-	-	2,763	2,194	-522	2,868	19
5	4,369	-4,836	2,919	-	3,149	-2,936	2,665	17
6	4,369	-4,836	2,050	-	3,149	-2,999	1,733	11
7	5,107	811	915	-2,983	3,052	-	6,902	43
8	5,107	811	840	-2,983	3,052	-	6,827	42

Environmental Cost

Table 8 shows the environmental cost for the pollutants of global warming potential and air emissions caused by waste management operations of each scenario. The unit values used were (CO_2 – \$0.0238/kg, CH_4 – \$0.6242/kg, N_2O – \$6.334/kg, Particulate Matters– \$36.156/kg, NO_x – \$6.8104/kg, SO_x – \$5.383/kg, Heavy metals - \$293/kg), following Eshet et al., 2005.

Table 8 Environmental cost of waste management alternatives in Haifa

Scenario	Externalities (10^3\$/year)								Costs (\$/tonne)
	CO_2	CH_4	N_2O	PM	NO_x	SO_x	HM	Total	
1	791	4,078	0	-178	108	-119	-2	4,680	29
2	651	3,026	0	294	106	-410	-1	3,569	23
3	135	258	-13	487	39	-293	1	614	4
4	2,601	7	0	-956	-431	-1,232	-12	-23	0
5	-159	598	-12	-35	-309	-104	-16	-37	0
6	-284	590	-6	-274	-381	-256	-19	-630	-4
7	-881	587	-12	-1,796	-550	-1,153	-15	-3,820	-24
8	-970	581	-6	-1,967	-602	-1,262	-17	-4,243	-26

Net Cost (Environmental and Economic Cost)

Table 9 indicates the environmental and economic cost for waste management operations of each scenario.

Table 9 Net cost of waste management alternatives in Haifa

Scenario	Economic cost (10^3\$/year)	Environmental cost (10^3\$/year)	Net cost (10^3\$/year)	Net Cost (\$/tonne)
1	10,045	4,680	14,725	92
2	6,834	3,569	10,403	61
3	5,219	614	5,833	37
4	2,868	-23	2,845	18
5	2,665	-37	2,628	16
6	1,733	-630	1,103	7
7	6,902	-3,820	3,082	19
8	6,827	-4,243	2,584	16

General Discussion

The IWM-2 model indicated that scenario #4 seems to be the best alternatives when considering the amount of waste going to the landfill and fuel. But this scenario has a great negative environmental impacts on global warming potential. Again, scenario #8 also seems to be the best alternative when considering environmental impacts on global warming potential, air emissions and water emissions for solid waste treatment. Nevertheless, the operating cost for this scenario is very high. Scenario #6 is the best choice that cost least in all the scenarios, and it still involves environmental improvements. Therefore, if the budget is tight and the environmental situation demands improvements, scenario #6 could be a right choice. The model also showed that biogasification is more attractive than composting in the case of biological treatment methods. But comparing to other waste treatment methods, composting scenario #5 is still an interesting option which cost the second least after scenario #6 and it also has low negative environmental impacts.

In order to clearly define the most favourable alternative, the environmental impacts resulted from the model were converted into monetary units by using the values estimated from the previous research. By involving these values, we can conclude that scenario #6 is the most environmentally and economically feasible option for Haifa. Scenario #5 and #8 are second favourable options and scenario #4 is the third one. We can also concluded that household participation of keeping the dry recyclable waste clean (Scenario #5 and #6) is more effective than keeping the wet biowaste clean (Scenario #7 and #8).

Expanding the studied system by changing the source separation rate made the results more comprehensive compared to the original case study. The sensitivity analysis indicated that source separation rate would play an important factor if one of the intensive recycling scenarios (#5 or #6), where the dry waste is kept clean, is introduced to the city. But, source separation rate would not significantly affect the system if one of the intensive biological treatments (#7 or #8), where the wet is kept clean, is introduced to Haifa.

Conclusion

Management options vary in terms of preference when considering a local perspective of e.g. landfill reductions versus the potential for more global environmental benefits achieved through recycling, compost production, and energy recovery. Life cycle assessment helps quantify these potential benefits and trade-offs. In this study, eight alternative scenarios to the existing waste management system have been studied in order to find out the most environmentally and economically favorable waste management system for Haifa.

The baseline scenario #1 stands for modern landfill, with gas and leachate collection and energy recovered from landfill gas. Scenario #2 is introduction of material banks for PET bottles and recyclable papers. Scenarios #3 and #4 present material bank recycling followed by composting and incineration. Scenarios #5 and #6 are introduction of MRF for dry recyclables and followed by composting and biogasification. Scenario #7 and # 8 stand for composting and biogasification which are followed by RDF production.

The results showed that household participation of keeping the dry recyclable waste clean is more effective than keeping the wet biowaste clean; and introduction of the combination of MRF recycling and biogasification is the most environmentally and economically feasible option for Haifa. Even though the case study is Haifa, the results can be copied to other cities characterized with same waste generation rate and waste composition.

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