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A Life-Cycle Inventory Model of Municipal Solid Waste Combustion

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ABSTRACT

Evaluation of alternate strategies for municipal solid waste (MSW) management requires models to calculate environmental emissions as a function of both waste quantity and composition. A methodology to calculate waste component-specific emissions associated with MSW combustion is presented here. The methodology considers emissions at a combustion facility as well as those avoided at an electrical energy facility because of energy recovered from waste combustion. Emission factors, in units of kg pollutant per metric ton MSW entering the combustion facility, are calculated for CO_2-biomass, CO_2-fossil, SO_x, HCl, NO_x, dioxins/furans, PM, CO, and 11 metals. Water emissions associated with electrical energy offsets are also considered. Reductions in environmental emissions for a 500-metric-ton-per-day combustion facility that recovers energy are calculated.

INTRODUCTION

Recent estimates indicate that 208 million tons of municipal solid waste (MSW) are generated annually in the United States.[1] Approximately 57% of this waste is buried in a sanitary landfill, and the remainder is managed through combustion (16%), recycling (23%), and composting (4%).[1] MSW generation is an inevitable consequence of human activity, and its management has received increased attention in the past decade as society attempts to manage this waste in a manner that is both economical and protective of the environment. The number of communities that offer curbside programs for the separate collection of recyclables and yard waste has increased, thus decreasing the mass of waste that must be buried in landfills or burned in combustion facilities, with consequent management of the resultant ash. In addition, consideration of the environmental implications of waste disposal is becoming a factor in the development and packaging of consumer products.[2]

IMPLICATIONS

Life-cycle analysis provides an analytical framework for comparing the environmental emissions associated with alternate waste management strategies. This paper presents a methodology for the development of a life-cycle inventory of MSW combustion as a function of both waste quantity and composition. In combination with data on other solid waste management processes, these results can be used to evaluate the environmental emissions associated with alternate integrated solid waste management strategies. These combustion life-cycle inventory results quantify the benefits of recovering electrical energy from MSW, which will also be useful in comparing alternate solid waste management strategies.

The objectives of solid waste management (SWM) programs that include composting, recycling, and, in some cases, combustion with energy recovery are to decrease societal dependence on landfills and to conserve natural resources through material and energy recovery. Given the geographical variation in the availability of recycling markets and numerous other location-specific considerations, the design of SWM strategies that are efficient with respect to material and energy conservation requires a site-specific evaluation of multiple SWM alternatives. For example, energy recovery in a waste-to-energy (WTE) facility may represent an efficient way to recover the energy value of many recyclables while displacing some fossil fuel utilization. Thus, the benefits of WTE facilities should be compared to the benefits of converting recyclables to new products.

To evaluate the environmental burdens of SWM strategies, models are required that can calculate the energy consumption and environmental emissions for each unit process that may be used in the solid waste system, including collection, separation, recycling, treatment, and landfill processes. These unit process models then can be integrated into a larger model to compare energy use and environmental emissions

across a large number of technically feasible alternate SWM strategies.[3,4]

The objective of this paper is to present a methodology to calculate the life-cycle inventory (LCI) for MSW combustion. This methodology has also been followed to calculate the LCI of other solid waste unit processes for use in an SWM-LCI decision support tool that is under development.[4] This tool has the capability to identify integrated SWM strategies that are optimal with respect to cost, energy consumption, or one of eight environmental emissions.[4] General information on LCI analysis is presented in the next section, followed by a description of the system boundaries and design basis for the combustion LCI analysis. The methodology used to calculate each emission and energy recovery is then described. Finally, typical results are presented, along with the sensitivity of these results to the fuel mix which are assumed to be offset due to electrical energy recovery from MSW combustion.

BACKGROUND ON LIFE-CYCLE INVENTORY ANALYSIS

An LCI represents a compilation of a specific set of inputs and outputs associated with a product or process. LCI analysis may be used to evaluate the environmental impacts of a process, to evaluate areas where the process can be improved to minimize environmental emissions, and to compare a process with an equivalent process, such as a comparison of waste-to-energy and landfills for MSW management. In this manuscript, the LCI concept is applied to MSW combustion. In the MSW combustion LCI, a set of environmental emissions plus energy recovery associated with waste combustion are quantified. The essential feature of LCI methodology is an attempt to thoroughly consider all aspects of a process. In the context of MSW combustion, LCI methodology requires that in addition to an inventory of the direct emissions from a combustion facility that recovers energy, an inventory of the avoided emissions at a power plant (including associated steps for fuel extraction and transportation) should also be included. General information on LCI methodology as it can be applied to MSW management[5] and to product life cycles[6] has been presented previously.

SYSTEM BOUNDARIES AND DESIGN BASIS

The combustion LCI modeling includes all activities associated with operating a combustion facility once waste is received. The LCIs of waste collection and ash management and disposal were considered in separate models that were integrated into the overall decision support tool. It was assumed that emissions associated with construction of the combustion plant were not significant; these emissions were not considered in the LCI. Energy recovered from waste combustion was assumed to be in the form of electrical energy. The emissions avoided because of reduced electricity generation by a utility were subtracted from the combustion facility emissions to calculate the overall combustion LCI.

The combustion LCI is a function of waste quantity and composition. The assumed waste composition and waste properties are presented in Table 1, and results are presented for a 500-metric-ton-per-day (mTpd) facility. Although a mass burn combustion facility is assumed for this model, the actual detailed design of the facility is not critical. As described in the following section, the major factors controlling energy production and environmental emissions are the heat rate, the waste composition and quantity, and the efficiency of the air pollution control (APC) equipment. The APC equipment assumed to be present includes a spray dryer for acid gas control, injection of activated carbon for mercury control, injection of ammonia (or urea) for NO_x control by conventional selective non-catalytic reduction, and a fabric filter for PM control. After APC, the flue gas is released to the atmosphere. The default values used in this paper are based on a modern combustion facility in compliance with MSW combustion facility regulations.[8] The major input parameters that characterize the combustion system are summarized in Table 2. Alternate values may be used to represent other scenarios.

The combustion LCI should include the LCI of all consumable materials associated with facility operation, including the materials used for APC: lime, ammonia (or urea), and activated carbon. However, while we were able to acquire LCI data for lime and ammonia, LCI data for activated carbon were unavailable.

The total quantity of ash generated is calculated from the ash content of the MSW plus a fraction of the combustible fraction of each component that does not burn because of inadequate mixing (Table 2). In addition, the lime and activated carbon added for APC are included in the total quantity of ash produced. No differentiation is made between bottom ash and fly ash. The LCI associated with ash transportation, management, and disposal is considered separately.[12] Many combustion facilities recover ferrous metal from bottom ash with a magnet. The combustion LCI accounts for the mass of ferrous metal recovered, which reduces total ash generation. The LCI of ferrous metal recovery is addressed in separate process models, which consider its transportation to a manufacturing facility and account for the difference between the production of ferrous metal from virgin and scrap materials.[4,13]

The LCI parameters considered include gaseous and liquid releases as well as solid waste and energy consumption. Although it is assumed that there are no water releases or solid waste production other than ash at the

Table 1. Waste composition and physical properties.

MSW Component	Composition[a] (% by wet weight)	Moisture Content[b] (% by wet weight)	Heating Value[b] (Btu/wet kg)	Ash Content[b] (% of dry weight)
Leaves	5.6	60.0	5722	6.3
Grass	9.3	60.0	5722	6.3
Branches	3.7	60.0	14,608	6.3
Old newsprint	6.7	6.0	16,590	1.5
Old corrugated cardboard	2.1	5.0	15,168	5.0
Office paper	1.3	6.0	13,888	6.0
Old magazines	1.7	6.0	11,850	23.3
3rd class mail	2.2	6.0	13,367	6.0
Other paper	18.2	6.0	14,220	6.0
HDPE - translucent	0.4	2.0	41,111	0.4
HDPE - pigmented	0.5	2.0	41,111	0.4
PET	0.4	2.0	41,111	0.4
Other plastic	9.9	2.0	31,022	10.0
Ferrous cans	1.5	3.0	662[c]	97.0
Other ferrous	3.2	3.0	0	100.0
Aluminum cans	0.9	2.0	0	100.0
Other aluminum	0.5	2.0	0	100.0
Glass - clear	3.9	2.0	185[c]	98.9
Glass - brown	1.6	2.0	185[c]	98.9
Glass - green	1.0	2.0	185[c]	98.9
Other glass	0.7	2.0	0	100.0
Food waste	4.9	70.0	3953	5.0
Miscellaneous - combustible	7.5	20.0	8072	6.0
Miscellaneous - non-combustible	12.3	20.0	0	100.0

[a]Adapted from reference 1; [b]Adapted from reference 7; [c]Energy value attributable to labels.

actual combustion facility modeled, these parameters are included because such releases are associated with the electrical energy offset and APC material production. All values represent the mass of material released to the environment after treatment.

The LCI of waste combustion is calculated from the sum of the calculated emissions associated with the combustion of each MSW component listed in Table 1. The allocation of the LCI on a component-specific basis is critical so that the integrated SWM-LCI model can be used to compare waste management scenarios in which specific waste components are either buried in a landfill, burned for energy recovery, composted, or recycled. The methodology used to calculate and allocate emissions from each part of the combustion LCI is described in the following section.

CALCULATION OF COMBUSTION LCI

The combustion LCI considers the offsets associated with energy recovery, combustor stack emissions, and the LCI of the lime and ammonia consumed during stack gas treatment. The combustor stack emissions calculated include CO_2-biomass, CO_2-fossil, SO_x, HCl, NO_x, dioxins/furans (PCDD/F), PM, CO, and 11 metals. Fossil and biomass CO_2 emissions are calculated separately to facilitate use of the results for an impact assessment in which these CO_2 sources may be treated differently. The methodology used to calculate and allocate energy recovery and each emission is described in this section.

Table 2. Summary of major default parameters characterizing combustion facility operation.

Parameter	Value	Units	Reference
Facility capacity factor[a]	1.0	no units	
Heat rate	18,000	Btu/kWh	
Lime input	7.1	kg lime/mT MSW	9
Ammonia input	1.5	kg ammonia/mT MSW	10
Activated carbon input	0.4	kg carbon/mT MSW	11
Ferrous recovery rate	90%	no units	
Unburned waste	5	% of combustible waste not burned because of incomplete combustion	

[a]For this exercise, it was assumed that the combustion facility was operating at the design capacity of 500 mTpd 100% of the time. In practice, a 500-mTpd facility would handle less than 500 mTpd on an annual average because of downtime for maintenance.

Energy Recovery

The efficiency of energy recovery is defined by a heat rate (Btu/kWh) that relates the energy of the combusted MSW (Btu) to the production of 1 kWh electrical energy exported from a WTE facility to the electrical grid (after the house load has been met). The export of electrical energy from a WTE facility results in a decrease in the amount of electricity generated by a utility and a corresponding decrease in emissions from the utility's electrical generating plants. These avoided utility emissions are subtracted from the emissions associated with waste combustion to calculate the overall combustion LCI. The energy that is recovered is calculated as the sum of the energy attributable to each waste component based on its energy content and the facility heat rate (Tables 1 and 2). Thus, where emissions are avoided, the avoided emissions are allocated only to those waste components with energy content.

The mix of fuels used to generate electricity at a utility and the mix of fuels for which generation is avoided when energy is recovered from MSW can be specified by the user. Default values are provided for the national electrical energy grid and for the nine North American Electric Reliability Council (NERC) electrical energy grids.[14] Table 3 presents the default fuel mixes for four NERC grids. For this paper, the fuel mix of the Southeastern Electric Reliability Council (SERC) is used, and it is assumed that the combustion of coal and natural gas are avoided in proportion to their use when energy is recovered from MSW. This emission avoidance scheme is based on the assumption that new electrical energy generation of the type usually produced (coal and natural gas) would not occur in response to new electricity generation from MSW. Based on these assumptions, the emissions that are avoided as a result of energy recovery from MSW combustion are presented in Table 4. The energy and emissions associated with the extraction and transportation of fuels for energy generation are accounted for in the values presented in Table 4. The sensitivity of overall combustion LCI results to the NERC grid selected is explored later in the paper.

Table 3. Fuel mix used for electrical energy generation and energy offset calculation.

Energy Source	Use for Electrical Energy Generation[a]				Fuels Used to Calculate Energy Emission Offsets[b]
	SERC[c]	ECAR[c]	ERCOT[c]	NPCC[c]	
Coal	56.8	90.91	46.87	19.55	95.1
Distillate oil	0.27	0.24	0.05	0.41	0
Residual oil	5.26	0.12	0.09	13.58	0
Natural gas	2.94	0.34	38.62	11.83	4.9
Nuclear	28.7	7.72	14.03	37.86	0
Hydroelectric	6.03	0.68	0.34	16.73	0
Wood	0	0	0	0.04	0

[a]The fuel mixture used for electrical energy generation.[14] Units are percent of total generation within region; [b]The hypothetical composition of the mixture of fuels not used when electrical energy is recovered from MSW in the SERC region; [c]SERC, East Central Area Coordination Agreement, Electric Reliability Council of Texas, Northeast Power Coordinating Council (NPCC).

Table 4. Emissions offsets due to electricity generation in the SERC region.[14,a]

LCI Parameter	kg/kWh
Gaseous emissions	
Biomass CO_2	1.3E-04
Fossil CO_2	9.5E-01
SO_x	6.3E-03
HCl	7.7E-05
NO_x	3.6E-03
PCDD/F	no data
CO	2.7E-04
PM	1.2E-03
CH_4	2.1E-03
NH_3	7.6E-07
Hydrocarbons	1.8E-04
As	no data
B	no data
Cd	no data
Cr	no data
Cu	no data
Hg	no data
Ni	no data
Pb	4.1E-08
Sb	no data
Se	no data
Zn	no data
Liquid emissions	
Dissolved solids	8.1E-04
Suspended solids	6.7E-04
BOD[b]	7.9E-07
COD[c]	1.1E-05
Fe	5.1E-05
NH_3	2.1E-08
Cd	3.6E-08
Hg	2.9E-12
P_5O_2	4.7E-06
Cr	3.6E-08
Pb	2.7E-12
Zn	1.3E-08
Solid waste	1.8E-01
Energy (Btu)	10.6

[a]Data are mathematically derived from a series of calculations, and the number of significant figures likely exceeds the precision of the data; [b]BOD = biochemical oxygen demand; [c]COD = chemical oxygen demand.

Carbon Dioxide Emission Factor

Emissions of CO_2 (fossil and biomass derived) are calculated based on a stoichiometric equation for waste combustion

$$C_cH_hN_nS_sO_oCl_l + \alpha(O_2 + 3.78N_2) + wH_2O \rightarrow cCO_2 + \left(\frac{h}{2} + w - \frac{l}{2}\right)H_2O + sSO_2 + \left(3.78\alpha + \frac{n}{2}\right)N_2 + \left(\frac{o}{2} + \alpha + \frac{w}{2} - c - \frac{h}{4} - \frac{w}{2} + \frac{l}{4} - s\right)O_2 + lHCl \quad (1)$$

where α is the number of moles of air supplied; w is the number of moles of water entrained in the fuel; and c, h, n, s, o, and l are the number of moles of each element in one mole of the combustible fraction of each waste component.

There are several assumptions implicit in the use of eq 1 for calculating both CO_2 emission factors and, as described below, for calculating the total stack gas flow rate. In using eq 1, it is assumed that all fuel-bound N is converted to N_2, that all fuel-bound S is converted to SO_2, that ash is inert, and that the volume of CO and NO_x is negligible in calculating the total flue gas volume. Elemental analysis data were adopted from several sources, including published values,[15] measured values for C and N on some components (Barlaz, unpublished data), and chemical formulas for specific plastics. The use of eq 1 is illustrated for old corrugated cardboard (OCC).

The elemental analysis of OCC on a dry and ash-free basis is 46.9% C, 6.6% H, 46% O, 0.0009% N, 0.2% Cl, and 0.3% S. The stoichiometric formula for OCC, as calculated from this analysis, is $C_{3.91}H_{6.605}O_{2.88}N_{0.0000643}Cl_{0.00439}S_{0.009345}$, which has a molecular weight of 100. Based on eq 1, the CO_2 emission factor for the combustion of one mole of dry, ash-free OCC is 172.04 g/mole. To express this emission factor based on the manner in which OCC is typically received at a combustion facility, it must be corrected for its moisture content, its ash content, and the amount of OCC that does not burn because of incomplete combustion. As presented in Tables 1 and 2, the default ash and moisture contents for OCC are both 5%, and it is assumed that 5% of the combustible material does not burn because of incomplete combustion. Thus, 85.74 g of dry, ash-free OCC will burn per 100 g of wet OCC entering a combustion facility, and the emission factor can be expressed as 147.5 g CO_2 emitted per 100 g wet OCC that enters the combustion facility. As OCC originates from plant-derived carbon, this OCC is classified as CO_2-biomass. CO_2 emission factors for each waste component are summarized in Table 5.

Table 5. Flue gas production and emission factors for CO_2, SO_2, HCl, NO_x, PCDD/F, CO, and PM (kg pollutant/mT waste component as received).[a]

MSW Component	Flue Gas Volume (dscm at 7% O_2/mT as received)	Controlled Emissions (kg pollutant/mT waste component as received) Biomass CO_2	Fossil CO_2	SO_2	HCl	NO_x (as NO)	PCDD/F	CO	PM
Leaves	2569	6.4E + 2	0	2.2E-1	1.0E-1	5.2E-1	3.3E-8	3.2E-1	6.2E-2
Grass	2388	5.9E + 2	0	2.0E-1	9.7E-2	4.8E-1	3.1E-8	3.0E-1	5.7E-2
Branches	2569	6.4E + 2	0	2.2E-1	1.0E-1	5.2E-1	3.3E-8	3.2E-1	6.2E-2
Old newsprint	6082	1.6E + 3	0	5.2E-1	2.5E-1	1.2E + 0	7.9E-8	7.6E-1	1.5E-1
OCC	5637	1.5E + 3	0	4.8E-1	2.3E-1	1.1E + 0	7.3E-8	7.0E-1	1.4E-1
Office paper	4899	1.2E + 3	0	4.2E-1	2.0E-1	9.8E-1	6.4E-8	6.1E-1	1.2E-1
Old magazines	3365	8.6E + 2	0	2.9E-1	1.4E-1	6.8E-1	4.4E-8	4.2E-1	8.1E-2
3rd class mail	4261	1.1E + 3	0	3.7E-1	1.7E-1	8.6E-1	5.5E-8	5.3E-1	1.0E-1
Other paper	4900	1.2E + 3	0	4.2E-1	2.0E-1	9.8E-1	6.4E-8	6.1E-1	1.2E-1
HDPE - translucent	14,871	0	2.9E + 3	1.3E + 0	6.1E-1	3.0E + 0	1.9E-7	1.9E + 0	3.6E-1
HDPE - pigmented	14,871	0	2.9E + 3	1.3E + 0	6.1E-1	3.0E + 0	1.9E-7	1.9E + 0	3.6E-1
PET	7771	0	2.1E + 3	6.7E-1	3.2E-1	1.6E + 0	1.0E-7	9.7E-1	1.9E-1
Other plastic	12,932	0	2.7E + 3	1.1E + 0	5.3E-1	2.6E + 0	1.7E-7	1.6E + 0	3.1E-1
Ferrous cans	182	4.8E+1	0	1.6E-2	7.4E-3	3.7E-2	2.4E-9	2.3E-2	4.4E-3
Other ferrous	0	0	0	0.0E + 0	0.0E + 0	0.0E + 0	0.0E + 0	0.0E + 0	0.0E + 0
Aluminum cans	0	0	0	0.0E + 0	0.0E + 0	0.0E + 0	0.0E + 0	0.0E + 0	0.0E + 0
Other aluminum	0	0	0	0.0E + 0	0.0E + 0	0.0E + 0	0.0E + 0	0.0E + 0	0.0E + 0
Glass - clear	78	1.7E + 1	0	6.7E-3	3.2E-3	1.6E-2	1.0E-9	9.8E-3	1.9E-3
Glass - brown	78	1.7E + 1	0	6.7E-3	3.2E-3	1.6E-2	1.0E-9	9.8E-3	1.9E-3
Glass - green	78	1.7E + 1	0	6.7E-3	3.2E-3	1.6E-2	1.0E-9	9.8E-3	1.9E-3
Other glass	0	0	0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0
Food waste	2,089	5.0E + 2	0	1.8E-1	8.5E-2	4.2E-1	2.7E-8	2.6E-1	5.0E-2
Miscellaneous -combustible	5,457	1.3E + 3	0	4.7E-1	2.2E-1	1.1E+0	7.1E-8	6.8E-1	1.3E-1
Miscellaneous - non-combustible	0	0	0	0	0	0	0	0	0

[a]Data are mathematically derived from a series of calculations, and the number of significant figures likely exceeds the precision of the data.

Emission Factors for SO_2, HCl, NO_x, Dioxins/Furans, CO, and PM

The emissions of SO_2, HCl, NO_x, dioxins/furans (PCDD/F), CO and PM are assumed to occur at the regulated values presented in Table 6. These values may overestimate actual emissions, based on the data for some modern WTE facilities also presented in Table 6. The model user may specify stack gas concentrations to reflect an alternate scenario, with emissions either higher or lower than the regulated values. Because the regulated pollutant emission values are in units of mass per volume of flue gas at 7% O_2, the volume of flue gas produced during the combustion of each MSW component is required.

The moles of dry flue gas (G) may be calculated by summing the terms on the right side of eq 1 (excluding H_2O), as shown in eq 2

$$G = \frac{o}{2} + 4.78\alpha - \frac{h}{4} + \frac{5l}{4} + \frac{n}{2} \quad (2)$$

The moles of air added (α) are calculated by solving for the value of α that results in 7% oxygen in the flue gas

$$\frac{G_O}{G} = 7\% \quad (3)$$

where G_0 is the moles of oxygen in the dry flue gas based on the stoichiometric coefficient for oxygen in eq 1

$$G_O = \frac{o}{2} + \alpha - c - \frac{h}{4} + \frac{l}{4} - s \quad (4)$$

Solving eqs 3 and 4 simultaneously results in eq 5 for α

$$\alpha = -0.699o + 1.50c + 0.35h - 0.244l + 1.50s + 0.053n \quad (5)$$

Thus, for an MSW component with a known elemental analysis, α and then *G* may be calculated. For OCC, this results in 29.35 moles of flue gas per 100 g of dry ash-free OCC, or 5637 dscm per mT OCC at standard temperature and pressure. Component-specific flue gas flow rates were calculated using this methodology, and the results are presented in Table 5.

The component-specific flue gas flow rates (Table 5) and the assumed emission factors (Table 6) were then used to calculate emission factors for SO_2, HCl, NO_x, PCDD/F, CO, and PM. These results are summarized in Table 5. Thus, emissions of these pollutants are effectively allocated based on the volume of flue gas attributed to a waste component.

Table 6. Regulated and actual emissions for combustion facilities.

Pollutant	Standard[a]	Actual Performance[b]	Units[c]
CO	100	26	ppmv
PCDD/F	13	4.5	ng/dscm
PM	24	4.0	mg/dscm
SO_2	30[d]	8.0	ppmv
HCl	25[d]	8.9	ppmv
NO_x	150	136	ppmv

[a]Reference 8; [b]Performance data for combustion facilities with a spray dryer, fabric filter, selective non-catalytic reduction, and carbon injection;[16] [c]All concentration levels reported in the table are corrected to 7% O_2, dry basis; [d]The regulations allow a combustion facility to either control emissions by a specified percentage (80% for SO_2, 95% for HCl) or to meet a specific concentration standard. The combustion LCI model is based on the concentration standard.

Metals Emissions Factors

Emission factors were developed for 11 metals, including As, B, Cd, Cr, Cu, Hg, Ni, Pb, Sb, Se, and Zn. The amount of a metal that volatilizes and escapes through APC equipment is a complex function of how the metal is incorporated in a material, the temperatures attained during combustion, and other physical and chemical factors. Unfortunately, because of our limited understanding of these factors, a mechanistic model of component-specific metal release could not be developed with sufficient accuracy. There is one study in which an attempt was made to correlate metals emissions to inlet waste composition.[17] However, relationships between metals emissions and the input waste composition were not statistically significant, due in part to insufficient variation in waste composition during the study period. Thus, the approach adopted for this model was selected in consideration of insufficient statistical and mechanistic information and the desire to do more than assume that metals emissions vary with mass input rate only.

The methodology presented here is based on the assumption that the uncontrolled mass emission rate of a metal is directly proportional to its input to a combustion facility. First, uncontrolled emission factors are developed based on published emissions data.[17] These metals emissions are then reduced by treatment efficiencies to calculate metals emissions to the environment. The methodology is illustrated for Pb in office paper and then generalized to all metals and all waste components using metal and component-specific information.

In the emissions tests reported by Chandler,[17] office paper was reported to make up 2.69% of the waste input to the combustor on a wet-weight or as-received basis and to contain 4.5 mg Pb/wet kg. Thus, office paper was responsible for the input of 0.121g of Pb per mT of waste, and the total waste stream was calculated to contain 188 g Pb/mT. The uncontrolled emissions flow rate for Pb was then calculated as the product of the Pb concentration at the inlet to the APC equipment and the combustion offgas flow rate at this point. The average uncontrolled emission flow rate was 4.8 g Pb/min, which corresponds to a

Pb emission of 9.86 g/mT of waste burned at a waste input of 0.487 mT/min over the 5-day test.

As described above, the Pb input was 188 g Pb/metric ton of waste, which means that 0.052 g Pb were released from the waste to the APC equipment per g Pb initially present in the waste. As calculated above, the office paper contributed 0.121 g of Pb/mT of waste burned, which results in a Pb emission factor of 6.34 mg Pb/mT of waste, or, since a mT of waste contained 26.9 kg of office paper, a Pb release rate of 234 μg/kg of office paper. This value represents the release rate of Pb from office paper to the APC equipment. The remaining Pb partitions to the bottom ash. This procedure was applied to each modeled MSW component for 11 metals, and the results are summarized in Table 7.

In those cases where there was not a one-to-one correspondence between the waste components reported by Chandler[17] and those used for this model, some judgment was used. For example, there is only one category for old newsprint (ONP) in this study, while ONP was presented in three categories by Chandler: (1) glued, (2) black and white unglued, and (3) colored unglued. One uncontrolled emission factor for ONP was calculated from the weighted average of Chandler's three categories. Finally, a removal efficiency (user input) was applied to the release rate for each metal to calculate the metal release to the environment that could be attributed to individual waste components (Table 8).

In the United States, emissions of Cd, Hg, and Pb are regulated, and the maximum limits are 0.02, 0.2, and 0.08 mg/dscm at 7% O_2.[8] The methodology described here has the potential to predict emissions in excess of these values. To evaluate the potential for this to occur, the combustion LCI was calculated with a number of plausible waste mixtures, and in no case were emissions standards violated. However, the potential for a modeled emission in excess of a regulated value must be considered if the regulatory limit changes or if additional metals are regulated.

Consumption of Materials for APC

Lime, ammonia (or urea), and activated carbon are all used for APC, and their default consumption rates are all quite

Table 7. Uncontrolled metal emission factors (kg pollutant/mT waste component as received).[a]

MSW Component	As	B	Cd	Cr	Cu	Hg	Ni	Pb	Sb	Se	Zn
Leaves	1.3E-5	6.4E-3	7.3E-4	5.5E-4	1.5E-4	6.9E-4	4.0E-4	8.1E-3	2.3E-4	1.3E-7	8.5E-3
Grass	1.3E-5	6.4E-3	7.3E-4	5.5E-4	1.5E-4	6.9E-4	4.0E-4	8.1E-3	2.3E-4	1.3E-7	8.5E-3
Branches	1.6E-6	2.7E-4	1.3E-4	1.3E-4	9.6E-6	2.0E-4	1.8E-4	3.3E-3	3.4E-5	7.5E-8	2.9E-3
Old newsprint	1.2E-6	1.1E-4	1.2E-5	2.9E-4	3.9E-6	1.0E-3	5.0E-4	3.4E-4	9.9E-6	1.9E-7	4.8E-4
Old corrugated cardboard	1.1E-6	3.8E-5	1.2E-5	9.7E-6	6.4E-7	4.9E-5	6.4E-5	2.0E-4	6.6E-6	7.5E-8	2.3E-4
Office paper	2.3E-6	2.7E-5	1.2E-5	1.8E-5	1.7E-6	1.5E-4	1.3E-4	2.4E-4	1.0E-5	4.7E-7	4.8E-3
Old magazines	1.4E-6	7.4E-5	1.2E-5	7.0E-6	2.1E-6	1.5E-4	7.3E-5	1.3E-4	5.3E-6	2.1E-7	1.9E-4
3rd class mail	7.1E-7	4.6E-4	4.9E-5	4.7E-5	8.6E-6	9.8E-5	2.4E-5	2.6E-7	1.3E-7	2.4E-7	2.0E-3
Other paper	1.6E-6	1.2E-4	4.6E-5	8.7E-5	4.1E-6	2.6E-4	1.6E-4	1.9E-3	3.8E-5	2.0E-7	1.5E-3
HDPE - translucent	2.5E-6	6.0E-5	1.8E-5	6.2E-5	6.7E-6	1.5E-4	2.2E-4	1.6E-4	2.1E-4	1.9E-7	6.4E-4
HDPE - pigmented	2.1E-6	8.0E-5	2.1E-4	1.8E-4	5.1E-6	2.0E-4	1.3E-4	1.2E-2	2.2E-5	5.6E-8	1.9E-3
PET	6.0E-5	2.5E-4	4.9E-6	3.1E-4	9.9E-6	2.0E-4	1.4E-5	1.7E-2	2.2E-6	1.9E-8	4.8E-3
Other plastic	8.8E-7	3.6E-4	3.5E-4	8.1E-5	5.1E-6	9.8E-5	1.2E-4	3.2E-3	2.3E-4	9.4E-8	3.3E-3
Ferrous cans	1.6E-6	1.2E-4	4.6E-5	8.7E-5	4.1E-6	2.6E-4	1.6E-4	1.9E-3	3.8E-5	2.0E-7	1.5E-3
Other ferrous	1.4E-6	2.3E-3	6.5E-4	9.0E-5	6.6E-6	9.8E-5	1.4E-4	3.2E-3	7.7E-4	9.4E-8	2.2E-3
Aluminum cans	1.6E-6	1.2E-4	4.6E-5	8.7E-5	4.1E-6	2.6E-4	1.6E-4	1.9E-3	3.8E-5	2.0E-7	1.5E-3
Other aluminum	1.1E-6	1.0E-3	4.5E-4	8.4E-5	5.6E-6	9.8E-5	1.3E-4	3.2E-3	4.1E-4	9.4E-8	2.9E-3
Glass - clear	1.6E-6	1.2E-4	4.6E-5	8.7E-5	4.1E-6	2.6E-4	1.6E-4	1.9E-3	3.8E-5	2.0E-7	1.5E-3
Glass - brown	1.6E-6	1.2E-4	4.6E-5	8.7E-5	4.1E-6	2.6E-4	1.6E-4	1.9E-3	3.8E-5	2.0E-7	1.5E-3
Glass - green	1.6E-6	1.2E-4	4.6E-5	8.7E-5	4.1E-6	2.6E-4	1.6E-4	1.9E-3	3.8E-5	2.0E-7	1.5E-3
Other glass	1.1E-6	1.0E-3	4.5E-4	8.4E-5	5.6E-6	9.8E-5	1.3E-4	3.2E-3	4.1E-4	9.4E-8	2.9E-3
Food waste	1.6E-6	1.2E-4	4.6E-5	8.7E-5	4.1E-6	2.6E-4	1.6E-4	1.9E-3	3.8E-5	2.0E-7	1.5E-3
Miscellaneous - combustible	8.8E-7	3.6E-4	3.5E-4	8.1E-5	5.1E-6	9.8E-5	1.2E-4	3.2E-3	2.3E-4	9.4E-8	3.3E-3
Miscellaneous - non-combustible	1.1E-6	1.0E-3	4.5E-4	8.4E-5	5.6E-6	9.8E-5	1.3E-4	3.2E-3	4.1E-4	9.4E-8	2.9E-3

[a]Data are mathematically derived from a series of calculations, and the number of significant figures likely exceeds the precision of the data.

Table 8. Metals removal efficiencies in air pollution control equipment.

Pollutant	Removal Efficiency (%)	Reference
As	99.9	18
B	76.5	17
Cd	99.7	18
Cr	99.3	18
Cu	99.6	18
Hg	92.7	16
Ni	96.6	18
Pb	99.8	18
Sb	96.7	17
Se	92.9	17
Zn	99.7	17

small (Table 2). Nevertheless, their manufacture should be considered in the LCI for completeness. At the time of this work, LCI data were available for lime and ammonia but not for activated carbon. The LCI for lime and ammonia production is summarized in Table 9. This LCI includes both the production process and emissions associated with the production and consumption of fuel for lime and ammonia manufacturing. All LCI parameters associated with lime and ammonia consumption were allocated evenly by mass across all MSW components. Given the small amount of activated carbon consumed, the absence of LCI data on activated carbon is not expected to have a significant impact on the results. The effect of lime and ammonia on the overall combustion LCI is evaluated with the model results.

MODEL RESULTS AND SENSITIVITY ANALYSIS

The LCI of a WTE combustion facility that can process 500 mTpd is presented in Table 10. Model results are based on the waste composition and default parameters presented throughout this paper. The results in Table 10 are divided into three components: (1) waste combustion, (2) electrical energy offsets, and (3) APC material consumption. Where no data were available for any one component, the sum was not reported, to emphasize that the absence of data does not necessarily mean that the correct value is zero. Energy offsets are included in Table 10 as negative numbers to indicate that the energy offsets represent avoided emissions. As a result of these offsets, the total LCI is negative for several parameters. For air emissions, the contribution of lime and ammonia to the overall LCI was generally minimal, with the exception of airborne ammonia due to emissions during the ammonia production process. For most wastewater emissions, the contributions of lime and ammonia proved more significant.

By changing user inputs through the spreadsheet-like interface, the user of the integrated SWM-LCI model has sufficient flexibility to represent a range of scenarios. For example, if a facility does not inject activated carbon for Hg control, then the Hg removal efficiency (Table 8) could be decreased. Similarly, if the facility to be represented does not recover energy, then the heat rate could be set to a very high number to trivialize the energy output. To illustrate the sensitivity of the model to the electrical energy

Table 9. LCI for lime and ammonia production.[a,b]

Pollutant	kg/mT Lime Manufactured	kg/mT Ammonia
Gaseous emissions		
Biomass CO_2	4.8E-02	2.1E + 00
Fossil CO_2	1.3E + 03	5.6E + 03
SO_x	3.7E + 00	8.6E + 01
HCl	1.2E-06	2.5E-02
NO_x	1.3E + 00	9.1E + 00
PCDD/F	no data	no data
CO	3.5E-01	2.8E + 01
PM	2.7E + 00	5.6E-01
CH_4	9.5E-01	1.7E + 01
NH_3	2.0E-04	4.6E + 00
Hydrocarbons	3.0E-01	3.3E + 01
As	1.5E-04	no data
B	no data	no data
Cd	5.0E-05	no data
Cr	3.1E-04	no data
Cu	no data	no data
Hg	4.3E-06	no data
Ni	2.1E-04	no data
Pb	1.9E-05	2.5E-05
Sb	7.3E-07	no data
Se	8.0E-07	no data
Zn	no data	no data
Liquid emissions		
Dissolved solids	1.1E + 00	1.3E + 02
Suspended solids	4.3E-02	4.2E-01
BOD	1.2E-03	2.8E + 00
COD	1.6E-02	9.0E + 00
Oil	1.9E-02	2.3E + 00
H_2SO_4	3.9E-03	3.4E-03
Fe	2.1E-02	1.9E-02
NH_3	5.9E-05	8.8E-02
Cd	5.2E-05	6.0E-03
Hg	4.0E-09	4.7E-07
P_5O_2	1.9E-03	1.7E-03
Cr	5.0E-05	6.0E-03
Pb	1.5E-08	5.4E-08
Zn	1.7E-05	2.1E-03
Solid waste	8.3E + 01	3.0E + 02
Energy (Btu)	5.1E + 06	5.1E + 07

[a]LCI data for lime and ammonia were provided by Franklin Associates and Ecobalance Inc., respectively; [b]Data are mathematically derived from a series of calculations, and the number of significant figures likely exceeds the precision of the data.

generation fuel mix, the combustion LCI was calculated for three additional electrical energy grids—ECAR, ERCOT, and the Northeast Power Coordinating Council (NPCC)—as described in Table 3. These regions were selected because they vary widely in the ratio of coal to natural gas used for electrical energy generation, which in turn impacts the fuels used for energy offsets. The LCI results for PM, CO_2-fossil, and Pb based on the different electrical energy generating regions are compared in Figure 1.

To interpret Figure 1, recall that for the scenarios modeled here, electric generation offsets will occur in proportion to the relative contribution of coal and natural gas to electricity generation in a specified generating region. For example, the NPCC regional generation comprises 19.6% coal and 11.8% natural gas. While this represents only 31.4% of total NPCC electricity generation, combustion offsets are attributed only to these two fuel types. Therefore, the offset for 1 kWh of MSW combustion generation eliminates emissions associated with 0.62 kWh generated from coal combustion and 0.38 kWh generated from natural gas combustion.

PM offsets are negative for all regions shown in Figure 1, since combustor PM emissions per kWh are quite low compared to those from coal generation. In the SERC and ECAR regions, PM offsets are similar (Figure 1), even though their use of coal is quite different, at 56.8 and 90.9%, respectively. This is because the use of natural gas for electricity generation is quite low in both regions (2.9% SERC and 0.3% ECAR). Thus, when normalized to coal and natural gas only, the offset fractions are nearly 100% coal for both regions. In addition, PM offsets are strongly governed by the coal offset since the total PM emission (precombustion and combustion) is 1.3 kg/kWh for coal and only 0.002 kg/kWh for natural gas.

The CO_2 offsets for the four electrical generation regions are more nearly equal than the PM offsets (Figure 1). This is due to the one order of magnitude difference in CO_2 emissions associated with 1 kWh of generation from coal (982 kg/kWh) and natural gas (62.3 kg/kWh) versus the four orders of magnitude difference in PM emissions for the two fuel types. The CO_2 offsets for the four regions are all negative, although there are large CO_2 emissions associated with 1 kWh of generation from MSW combustion. The emissions reported in Figure 1 represent CO_2-fossil; however, a significant part of the CO_2 emitted from MSW combustion is from the oxidation of carbon in paper products, which is considered CO_2-biomass and is not included in the fossil CO_2 offset calculations depicted in Figure 1.

For Pb air emissions, the trend for the ERCOT and NPCC regions differs from the trend for the SERC and ECAR regions (Figure 1). The gaseous Pb emission from coal generation (4.3×10^{-5} kg/kWh) is two orders of magnitude higher than that for natural gas generation ($2.7 \times$

Table 10. Combustion LCI for SERC region.[a,b]

	Annual Emissions (kg/year)			
	WTE Facility	Energy Offsets	APC LCI	Total
Gaseous emissions				
Biomass CO_2	1.2E + 8	-1.4E + 4	6.5E + 2	1.2E + 8
Fossil CO_2	5.6E + 7	-1.0E + 8	3.2E + 6	-4.2E + 7
SO_x	6.3E + 4	-6.7E + 5	2.8E + 4	-5.8E + 5
HCl	3.0E + 4	-8.2E + 3	6.8E + 0	2.2E + 4
NO_x	1.5E + 5	-3.8E + 5	4.2E + 3	-2.3E + 5
PCDD/F	9.6E-3	no data	0.0E + 0	
CO	9.3E + 4	-2.9E + 4	8.1E + 3	7.2E + 4
PM	1.8E + 4	-1.3E + 5	3.6E + 3	-1.1E + 5
CH_4	2.7E + 2	-2.2E + 5	5.8E + 3	-2.2E + 5
NH_3	0	-8.1E + 1	1.3E + 3	1.2E + 3
Hydrocarbons	0	-2.0E + 4	9.4E + 3	-1.0E + 4
As	1.1E-1	no data	1.9E-1	
B	7.2E + 1	no data	0.0E + 0	
Cd	7.6E-1	no data	6.4E-2	
Cr	8.2E-1	no data	4.0E-1	
Cu	3.9E + 0	no data	0.0E + 0	
Hg	7.4E + 0	no data	5.5E-3	
Ni	2.4E + 0	no data	2.7E-1	
Pb	4.0E + 0	-4.3E + 0	3.1E-2	-2.9E-1
Sb	1.7E + 0	no data	9.4E-4	
Se	3.5E-1	no data	1.0E-3	
Zn	2.0E + 1	no data	0.0E + 0	
Liquid emissions				
Dissolved solids	0	-8.6E + 4	3.7E + 4	-4.9E + 4
Suspended solids	0	-7.1E + 4	1.7E + 2	-7.1E + 4
BOD	0	-8.5E + 1	7.7E + 2	6.9E + 2
COD	0	-1.2E + 3	2.5E + 3	1.3E + 3
Oil	0	-1.5E + 3	6.6E + 2	-8.5E + 2
Sulfuric acid	0	-1.0E + 3	5.9E + 0	-1.0E + 3
Iron	0	-5.4E + 3	3.2E + 1	-5.4E + 3
Ammonia	0	-2.2E + 0	2.4E + 1	2.2E + 1
Cadmium	0	-3.9E + 0	1.7E + 0	-2.2E + 0
Mercury	0	-3.1E-4	1.3E-4	-1.7E-4
Phosphate	0	-5.0E + 2	3.0E + 0	-5.0E + 2
Chromium	0	-3.9E + 0	1.7E + 0	-2.2E + 0
Lead	0	-2.9E-4	3.5E-5	-2.5E-4
Zinc	0	-1.3E + 0	5.8E-1	-7.5E-1
Solid waste	0	-1.9E + 7	1.9E + 5	-1.9E + 7
Energy (Btu)	0	-1.1E + 12	3.8E + 10	-1.1E + 12

[a]Results are based on a 500 mT/day facility; [b]Data are mathematically derived from a series of calculations, and the number of significant figures likely exceeds the precision of the data.

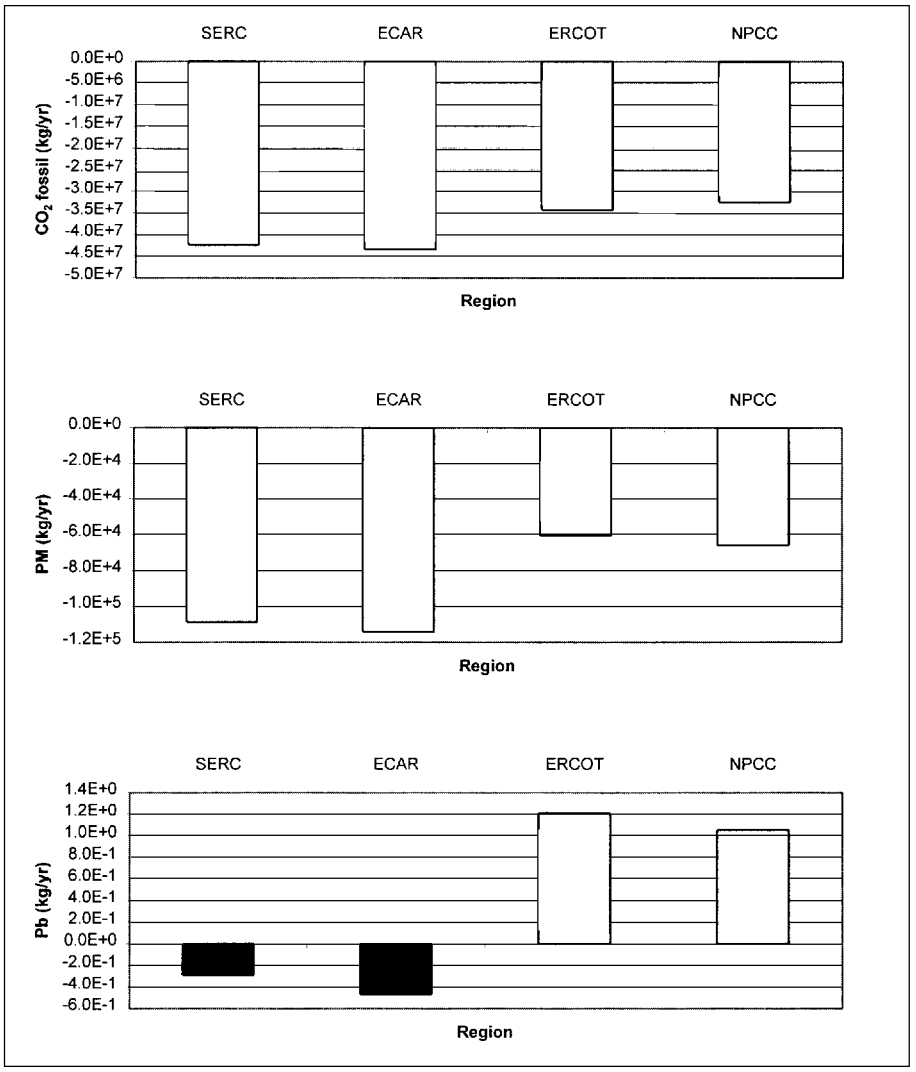

Figure 1. Sensitivity analysis using different regional electrical grids. Data represent annual emissions based on the combustion of 500 mTpd.

10^{-7} kg/kWh). In contrast to the lower PM emissions from MSW combustors relative to coal on a per kWh basis, Pb emissions from MSW combustion are relatively high such that the two regions that have nearly 100% coal generation in the offset fuel definition (SERC and ECAR) have negative offsets, while the two regions that have approximately 60% coal generation in the offset fuel definition (ERCOT and NPCC) have positive offsets.

DISCUSSION

The methodology presented here for calculation of the LCI of a combustion facility is a useful first step in comparing alternate SWM strategies. In combination with process models of other parts of the SWM system (collection, separation, materials recycling, composting, and disposal), the combustion model can be used in an overall SWM-LCI model to identify waste management alternatives that are optimal with respect to specific environmental emissions.[3] However, it is important to understand the limitations associated with this application of LCI to waste management. This paper has described several assumptions related to the combustion process and electrical energy generation associated with the combustion methodology. In addition, where uniform data for a specific parameter are not available across all SWM alternatives (e.g., PCDD/F emissions from a landfill flare), management alternatives cannot be compared on the basis of that parameter.

It must also be noted that the overall LCI does not address the location of specific emissions that will impact local air quality. As presented in Table 10, the operation of a WTE facility results in a net decrease in the emissions of a number of pollutants. However, in many cases, the negative values presented in Table 10 represent the sum of positive values associated with the combustion facility and larger negative values associated with electrical energy offsets. Where the locations of the WTE facility and the avoided electrical energy generation are not in the same airshed, the global benefit of overall reduced emissions is in contrast to increased emissions in the airshed encompassing the WTE facility. The relationship between global and airshed-specific emissions has been examined for a series of SWM strategies, and it has been shown that SWM strategies representing global optimum solutions may actually decrease air quality in the local SWM region/airshed of interest.[19]

Despite limitations associated with use of LCIs, the LCI methodology represents a framework for the evaluation of alternate SWM strategies in which a number of emissions can be considered. The methodology described here will be useful for quantification of the emissions attributable to combustion and for understanding how they compare to alternate processes such as recycling and landfills for the management of solid waste.

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