

# Greenhouse Gas Dynamics of Municipal Solid Waste Alternatives

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## ABSTRACT

Previous greenhouse gas studies comparing landfilling with combustion of municipal solid waste (MSW) are limited to examinations of the emissions weighted by their relative radiative activity. This paper adds another dimension by analyzing the atmospheric response to these emissions. The heart of the analysis is a time-dependent model using a perturbation analysis of the IS92a results of the Intergovernmental Panel on Climate Change (IPCC). Using as inputs the emissions from the two technologies, the model calculates atmospheric concentration histories. Scenarios for a landfill and a combustor envision each accepting 1000 Mg refuse/day for a 30-year operating period followed by a 70-year postclosure period. The baseline scenario examines the basic greenhouse impact of each technology. The other scenario adds active gas collection at the landfill and energy offset credits for avoided power plant carbon emissions. For both scenarios, CH<sub>4</sub> and trace gases from the landfill persist in the atmosphere, and they are relatively potent at forcing IR heating. The combination of these features place the landfill much higher than previously expected on the greenhouse impact scale. For the baseline scenario, the time-integrated radiative forcing from landfilling is 115 times that of combustion, and this ratio is 45 for the second scenario.

## IMPLICATIONS

Replacement of landfills with municipal waste combustors significantly reduces greenhouse gas impacts. Conventional comparisons between these alternatives consider a fixed time horizon, whereas this analysis traces the integrated time history of the emissions over the periods of operation and postclosure years. As greenhouse emissions trading markets mature, communities that switch to the combustor alternative may accrue financial credits that could offset higher amortization and operational charges. Thus, consideration of greenhouse gas reduction benefits adds a new dimension to the economics of solid waste management.

## INTRODUCTION

Researchers intensively debate the role of anthropogenic (manmade) emissions<sup>1</sup> in explaining observed secular warming trends<sup>2</sup> in the earth's atmosphere. Without entering the debate, this paper compares the warming effects of emissions from two methods of municipal solid waste (MSW) disposal: landfilling and combustion. Initial steps have already been taken<sup>3</sup> in this comparison; they suggest that for a given quantity of MSW, landfilling has about a 10-fold greater greenhouse effect than combustion. This conclusion relies only upon radiation-weighted emissions. Later work<sup>4,5</sup> addresses these issues in further detail, but its focus is still limited to emissions.

The present work extends the analysis to include the atmospheric responses to the emissions. Atmospheric response, in this context, considers both the persistence and the effects of each greenhouse gas over time. The analysis begins with emissions calculations and ends with the atmospheric assessments. Emissions calculations rely on measured data, and the atmospheric assessments use a perturbation analysis using the model data (IS92a)<sup>6</sup> developed by the Intergovernmental Panel on Climate Change (IPCC) as the unperturbed solution. The atmospheric concentration histories supply input to the impact assessment that forms the conclusion of this paper.

Successive sections describe the steps in the analysis. Emissions calculations for both the landfill and the combustor form the inputs to the baseline scenario. Chemical kinetic estimates determine the chlorofluorocarbon (CFC) destruction in the combustor. Both facilities present the possibility of producing electrical energy; therefore, in the second scenario, fossil fuel plant offset credits are appropriately applied. Next, we derive the dynamic atmospheric species budgets for each of the greenhouse gases emitted by each facility. The product of a pollutant's radiative forcing factor times its concentration is its index of impact. The analysis is then extended to a landfill gas recovery scenario with fossil fuel-based electrical energy offset credits applied to both technologies.

## LANDFILL EMISSIONS CALCULATIONS

### Baseline Case

The landfill air emissions estimation model<sup>7</sup> suggested in the AP-42 guidance<sup>8</sup> from the U.S. Environmental Protection Agency (EPA) provides the annual gas generation for

a scenario of 1000 Mg/day refuse disposed over a 30-year period followed by a 70-year closure. The model run uses the Clean Air Act Amendments default option for gas generation quantity and rate. Following the guidance, the gas consists of 50% CH<sub>4</sub> and 50% CO<sub>2</sub> as its major components. Table 4-1 on p 4-14 of AP-42<sup>7</sup> gives the minor contaminant composition from which their emissions are derived. Only those components for which radiative forcing factors are available entered the calculation. They are mainly CFCs, which have relatively large radiative forcing factors and relatively long lifetimes.

Since emission factors for N<sub>2</sub>O from landfills cannot be found in the literature, it is necessary to devise an approximate calculation. It is assumed that 1% of the nitrogen in refuse is converted to N<sub>2</sub>O by the same bioreaction mechanism postulated for the soil. The remainder goes to form NO<sub>3</sub> and ammoniacal nitrogen observed in the leachate. This is likely to be a conservative estimate because it neglects the nitrogen in the pore air of the refuse mass during the initial aerobic decay phase. Using measured assay values of nitrogen in refuse from p 33 of the EMCON handbook<sup>9</sup> and the gas generation calculation, we calculate an N<sub>2</sub>O concentration of 166 parts per million by volume (ppmv) in the landfill gas.

#### Gas Recovery and Energy-Emissions Offset Case

Modern landfills collect and treat much of the gas generated by the refuse in place. An EPA background information document<sup>10</sup> estimates (on p 4-9) collection efficiencies to be from 50 to 60%; however, a recent EPA life-cycle study<sup>11</sup> assumes that 90% is collected. The present work follows Licata and Minott<sup>12</sup> by using 75% and assumes further that internal combustion engines burn the gas to produce electrical energy. CO<sub>2</sub> is the only greenhouse gas emission attributed to the engines. Thus, the fugitive 25% gas emission that is not collected has the same composition as the gas described in the previous section.

#### COMBUSTION EMISSIONS CALCULATIONS

The fundamental premise here is that all of the carbon in the refuse (30% by mass is assumed here<sup>8</sup>) is burned to CO<sub>2</sub> in the combustor. This is clearly conservative because up to 10% of the carbon fired may be sequestered in the ash that is landfilled. The inorganic substrate and the alkalinity of ash monofills minimize or eliminate any gas generation; therefore, this carbon is, under normal circumstances, unavailable. In addition to the CO<sub>2</sub>, there are emissions of N<sub>2</sub>O. The measurements reported by Spoelstra<sup>13</sup> provided the emission factor for this gas; namely, 20 g/Mg refuse burned. Estimates for this emission factor ranging from 4 g/Mg<sup>5</sup> to 160 g/Mg<sup>4</sup> bracket the actual measured value used in this analysis.

Chemical kinetic analyses are needed to assess CFC destruction or removal emissions from combustors. Based on preliminary pathway analysis, the OH abstraction reaction is energetically favored by far over straight thermal cracking for CFC destruction. The activation energy barrier for the abstraction reaction<sup>14</sup> is about an order of magnitude less than the bond strengths of either the hydrogen or the halogen to the carbon, and flame zones contain measurable levels of the OH. Since the activation energy appears in the exponential, there is no contest. Kinetic data for this rate-controlling step permit the scaling of data for CFC destruction from an experimental combustion tunnel<sup>15</sup> to a resource recovery combustor for which the temperatures and residence times are known.<sup>16</sup> The combustion tunnel results establish the pre-exponential factor and ref 14 supplies the exponential factor; thus, in the resource recovery case, the destruction or removal efficiency can be calculated directly. This calculation shows essentially complete decomposition of these compounds, a finding that is consistent with the opinions of an EPA expert panel<sup>17</sup> whose 1989 report stated, "Thermal incineration is the only technology for CFC or halon destruction that was found to be currently available at commercial scale...." Based on this analysis, our greenhouse gas emission inventory for the combustor does not include CFCs. The 1000-Mg firing rate establishes the emission rates through mass balance in the case of CO<sub>2</sub> and emission factor in the case of N<sub>2</sub>O, both of which are constant over 30 years and then zero for the next 70 years.

#### EMISSIONS OFFSET CALCULATIONS

For the second scenario, the collected landfill gas fuels engines that generate electrical power. The supply of this power to the grid avoids some amounts of CO<sub>2</sub> emissions from a fossil fuel (coal in this case) utility boiler. Likewise, the MSW combustor produces electrical power, which in turn leads to offset emissions credits for the same reason as for the landfill. To translate the common denominator of electrical energy into emissions, one must postulate some thermodynamic performance parameters both for the waste disposal facility and for the utility unit in both cases. Emissions from transport trucks and on-site materials-handling equipment are neglected in all cases.

Let us consider the landfill engines first. As a benchmark, we use a spark ignition engine with a brake-specific fuel consumption (bsfc) of 0.5 lb gasoline per brake horsepower hour (0.3 kg/kWh). Indeed, this is not the best achievable efficiency, but this analysis models engines burning low heating value landfill gas with wide variations in both quantity and quality. This bsfc gives an energy equivalent of ~1.1 kWh/m<sup>3</sup> of landfill gas under the assumptions of 500 Btu/ft<sup>3</sup> heating value and 90% generator efficiency. The major components of landfill gas

are 50% CO<sub>2</sub> and 50% CH<sub>4</sub>, which burns to CO<sub>2</sub> on a one-to-one mole basis. On the power station side, the value was  $1.7 \times 10^{-4}$  t of carbon equivalent per kWh<sub>e</sub> as used in the greenhouse emission study cited earlier.<sup>4</sup> It is not possible to quote a single figure for annual offsets for the landfill, because the amount of gas available is different for each year of the operation; consequently, the spreadsheet recalculates energy offsets on a year-by-year basis over the one-century study period.

The SEMASS facility performance<sup>18</sup> record is the source of data for energy production from the waste combustor. It is 823 kWh<sub>e</sub>/t of refuse fired. This value, combined with the fossil-fueled power station performance, results in an offset of ~50,000 t of carbon equivalent annually for each of the 30 years of operation.

### ATMOSPHERIC MODELS

In the IPCC modeling hierarchy, basically two methods are used—one for CO<sub>2</sub> and another for the remainder of the greenhouse gases. CO<sub>2</sub> experiences many production and removal processes, whereas the other greenhouse gas levels balance emissions (largely anthropogenic) with gas-phase chemical removal mechanisms. Half-life (0.693/first-order rate constant) characterizes these gas-phase removal mechanisms. For CO<sub>2</sub>, however, half-life (of the order of a century) is only part of the picture. This distinction grows from the recognition that the environmental phenomenology of the CO<sub>2</sub> budget is more complicated than that of the other gases. The carbon budget due to CO<sub>2</sub> is expressed as<sup>19</sup>

$$2.123\Delta C = (I + D - W - X)\Delta t \quad (1)$$

where  $\Delta C$  is the annual concentration change in ppmv. The factor 2.123 converts the concentration change into GtC (1 GtC =  $10^{15}$  g C) in the atmosphere. All other terms are in units of GtC. The symbol  $I$  denotes industrial sources;  $D$ , land-use changes;  $W$ , ocean flux; and  $X$ , other sinks.

Our puff model assumes that small annual perturbations about the solution of eq 1 are approximated by a lumped-parameter first-order process. Thus, the following equation represents changes in the  $j$ th species concentration,  $C_j$ , during the  $i$ th year:

$$\left(\frac{dC_j}{dt}\right)_i = S_{ij} - k_j C_j \quad (2)$$

where  $S_{ij}$  is a puff emission over the duration of the  $i$ th year of the  $j$ th species, and  $k_j$  is the lumped parameter perturbation rate constant in units of year<sup>-1</sup>. It should be noted that  $k_j$  is valid only for small excursions from the natural system; specifically, it is a lumped proxy for the entire suite of removal processes. The solution of eq 2 at the end of the first time interval ( $\Delta t = 1$  year in all further analysis below) is

$$C_j(1st - yr) = \left(\frac{S_{ij}}{k_j}\right) [1 - \exp(-k_j \Delta t)] = \left(\frac{S_{ij}}{k_j}\right) [1 - \exp(-k_j)] \quad (3)$$

Equation 3 tells us that with no initial perturbation concentration, the buildup during the first year fits a  $[1 - \exp(-k)]$  growth law approaching an asymptotic value of  $S_{ij}/k_j$ . That limiting value would prevail over the time step only if  $k_j$  were so large that the factor in brackets equaled 1 for most of the year.

After the first year, there is a different formula that determines the end-of-year concentration perturbation. For the end of the  $i$ th year, it is

$$C_j(i\text{th}/\text{year}) = C_j[(i-1)\text{st}/\text{year}] \exp(-k_j) + \left(\frac{S_{ij}}{k_j}\right) [1 - \exp(-k_j)] \quad (4)$$

Equation 4 can be used recursively in spreadsheet cells to calculate perturbed concentrations. It begins with the perturbation at the end of the previous interval and follows its exponential decay. At the same time, it treats the buildup due to current year emissions the same way as in eq 3 for the first year.

The solution method developed above is a hybrid analytical and finite-difference approach. The finite-difference aspect is that emissions are assumed constant over any given year. This stair-step emission profile is an approximation consistent with the accuracy of the emissions models. Within each 1-year time step, however, the first-order rate equation solutions over the interval are exact mathematical solutions. (A conventional forward finite-difference approach would calculate  $\Delta C_{ij}$  using a truncated series expansion of  $S_{ij} - k_j C_j$ .) Reasonably good integration accuracy should be expected of the system set up by eqs 3 and 4 considering the ratio of interval size to total integration time.

Using the schedules of  $S_{\text{CO}_2}$  and  $C_{\text{CO}_2}$  plotted on p 83 of ref 6 for the IS92a modeling run in the IPCC studies, we can determine  $k_{\text{CO}_2}$  from inverting the solution of eq 4. The best-fit value of  $k_{\text{CO}_2}$  emerges from a least-square optimization using trial solutions. This technique implies that anthropogenic emissions are small perturbations of the natural systems. To a root-mean-square fractional error of 0.005 over the period 1990–2100, the perturbation rate constant for CO<sub>2</sub> is 1.8 year<sup>-1</sup>. Thus, first-order kinetics describes adequately the perturbation response of the CO<sub>2</sub> model system employed by the IPCC.

Equation 2 is used directly in the IPCC literature to represent species other than CO<sub>2</sub>; therefore, values of  $k$  are directly related to half-life because of a single dominant first-order removal mechanism (unlike that of CO<sub>2</sub>). Values given there for  $k$  in units of year<sup>-1</sup> are as follows: CH<sub>4</sub>—0.082, N<sub>2</sub>O—0.0083, CFC11—0.02, CFC12—0.0098, and HCFC22—0.083. A spreadsheet tool implements the model using these values for rate constants and the

results of calculations described in the section "Combustion Emissions Calculations" for emission rates. Equations 3 and 4 express the end of step concentrations for each year. Another pass through the spreadsheet averages the end-of-year and the beginning-of-year concentrations of each greenhouse gas to get the value appropriate for that year.

**CONCLUSIONS ABOUT RADIATIVE IMPACTS OF EMISSIONS**

Each year's concentration for each species multiplied by the radiative forcing coefficient for that species gives its IR trapping potential in kilowatts per square kilometer. The operation can be expressed by

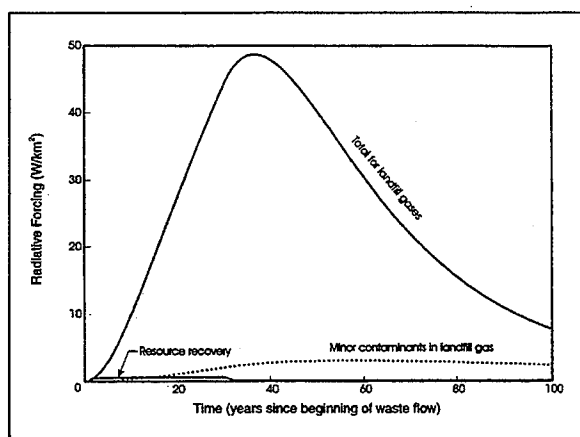
$$R_i = \sum_{j=1}^s F_j C_{ij} \tag{5}$$

where  $R_i$  is the radiative forcing of greenhouse gases during the  $i$ th year,  $F_j$  is the radiative forcing coefficient for the  $j$ th species, and  $s$  is the total number of species under consideration. The cumulative radiative forcing over the study century is expressed as

$$R = \sum_{i=1}^{100} R_i \tag{6}$$

Equation 5 might be thought of as the subchronic measure of warming impact, and eq 6 as the chronic warming effect.

Figure 1 shows plots of  $R_i$  for the emissions scenario with no control over landfill emissions and with no energy-emissions offset credits for either facility. The ordinate on the graph is broken down for the landfill as the total greenhouse gas impact and the trace gas contribution (greenhouse gases other than  $CO_2$  and  $CH_4$ ). The rising and falling characteristic of the landfill impacts reflects the combined buildup and decline of emissions over time and the persistent potency of the radiative forcing potential of relatively small concentrations of trace gases. This



**Figure 1.** Greenhouse comparison—landfill vs. resource recovery with no landfill gas collection; no energy-emission offset credits.

graph shows the relatively small greenhouse contribution of the resource recovery technology. Table 1 supplements the graph by giving values on 10-year intervals. The impacts integrated over the century show that the landfill impacts are ~115 times greater than those of resource recovery; that is, they are dramatically larger than the 25-fold estimate based solely upon emissions.

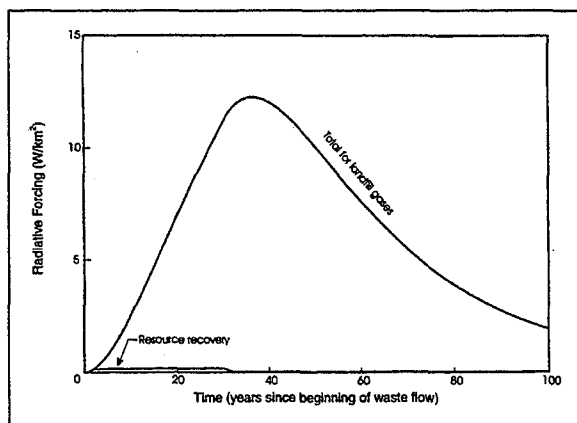
Figure 2 plots the impacts for the case of landfill gas recovery and energy-emission credits from avoided use

**Table 1.** Annual radiative forcing comparison; 1000 Mg/year for first 30 years; closure for 70 years.

Year	No Energy-Emissions Offset Credits	
	Annual Radiative Forcing (W/km <sup>2</sup> )	
	Landfill (LF) No Gas Collection	Resource Recovery (RR)
0	0	0
10	9.91	0.55
20	27.61	0.58
30	44.39	0.61
40	47.85	0.09
50	40.03	0.08
60	30.30	0.07
70	21.87	0.07
80	15.46	0.06
90	10.88	0.06
100	7.72	0.05
One century cumulative forcing (W-yrs/km <sup>2</sup> ):		
	LF = 2528	RR = 22
	Cumulative ratio LF/RR = 115	

**Table 2.** Annual radiative forcing comparison; 1000 Mg/year for first 30 years; closure for 70 years.

Year	With Energy-Emissions Offset Credits	
	Annual Radiative Forcing (W/km <sup>2</sup> )	
	Landfill (LF) with Gas Collection	Resource Recovery (RR)
0	0	0
10	2.51	0.27
20	6.97	0.30
30	11.18	0.33
40	12.02	0.09
50	10.04	0.08
60	7.59	0.07
70	5.48	0.07
80	3.87	0.06
90	2.72	0.06
100	1.93	0.05
One century cumulative forcing (W-yrs/km <sup>2</sup> ):		
	LF = 635	RR = 14
	Cumulative ratio LF/RR = 45	



**Figure 2.** Greenhouse comparison—landfill vs. resource recovery with landfill gas collection; with energy-emission offset credits.

of fossil-fueled power plants. Table 2 supplements the graph in Figure 2 by giving values on 10-year intervals. This scenario reduces the cumulative landfill impact by almost 4-fold and the resource recovery impact by ~36%. Under these conditions, the landfill impact is still 45 times that of the resource recovery facility. These results demonstrate that the greenhouse impact advantage of resource recovery is even larger than estimated before because of the influences of atmospheric fate processes.

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