Greenhouse Gas Emission Factors for Municipal Waste Combustion and Other Practices

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Abstract

Waste management practices can impact greenhouse gas (GHG) emissions by affecting energy consumption, methane generation, carbon sequestration, and non-energy-related manufacturing emissions. This paper examines GHG emissions and sinks, from a life-cycle perspective, for selected paper, glass, metal, and plastic materials comprising about one-third of municipal solid waste (MSW) generated in the US; it also provides information on mixed MSW. Some key methodologic considerations for estimating GHG emissions associated with combustion are briefly described. Manufacturers, solid waste decision-makers, and others interested in the GHG implications of MSW management may use this information for voluntary reporting of GHG emission reductions associated with waste management practices and to develop strategies to reduce GHG emissions. Each of the waste management options provides opportunities for GHG reductions for one or more materials. The relative advantages of combustion versus landfilling depend on several factors, chiefly the extent to which landfill methane releases are controlled, the extent of long-term carbon storage in landfills, and the magnitude of utility fossil fuels displaced by electricity generation at the combustion facility.

Introduction

In 1993, the U.S. issued its Climate Change Action Plan (CCAP), which outlines over 50 voluntary initiatives to reduce national GHG emissions. Initiative 16 of the Plan calls for accelerated source reduction and recycling of municipal solid waste[1] through combined efforts by the US Environmental Protection Agency (EPA), the Department of Energy, and the Department of Agriculture. To support EPA's efforts on this initiative, a research project was launched to develop material-specific emission factors for MSW management practices, including waste combustion.[2] This paper briefly describes the research effort's approach, results, and applications, emphasizing issues associated with characterizing GHG emissions from combustion.

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[1] Source reduction is defined as making less of a product, and may be the result of (1) "lightweighting" (e.g., producing less glass or plastic because bottles are made thinner and lighter), (2) more efficient use of a material (e.g., double-sided photocopying), (3) extending the life of a product, or (4) material substitution (e.g., substituting cans for bottles, or vice versa). Recycling is defined as remanufacturing a material to make more of the same material, or a different material (e.g., office paper can be recycled to make office paper or tissue paper).

[2] A complete description of the research results is available on the internet at http://www.epa.gov/ epaoswer/non-hw/muncpl/ghg.htm

Approach

Method for Analyzing GHG Emissions From Municipal Waste Management
We selected ten materials for analysis, based on an initial screen for the quantity of waste generated, the potential to increase source reduction or recycling of the material, and the difference in energy used to manufacture the product from virgin inputs rather than recycled inputs. The ten materials are newspaper; office paper; corrugated cardboard; mixed paper; aluminum cans; steel cans; glass containers; high density polyethylene (HDE) plastic; low density polyethylene (LDPE) plastic; and polyethylene terephthalate (PET) plastic. These materials constitute 31 percent of municipal solid waste in the US, as shown in Table 1.[3] In addition to the individual materials, mixed MSW was also analyzed as disposed in landfills and through combustion in waste-to-energy (WTE) facilities.

We examined those stages of the life cycle that have the potential to affect GHG emissions as materials are converted from their raw states to products, and then disposed as waste. Figure 1 shows the steps in the life cycle in which GHGs are emitted, carbon sequestration is affected, and electric utility energy is displaced (reducing utility GHG emissions).[4] At each of these points, we also considered transportation-related energy emissions. We did not analyze the GHG emissions associated with consumer use of products, but believe them to be negligible for the selected materials.

The reference case for characterizing raw material acquisition and manufacturing GHG emissions is a baseline where industry uses the current mix of virgin and recycled inputs. Similarly, the projected stock of carbon in forests and harvested forest products, under existing recycling policies and projected market conditions, was the reference case against which changes in forest carbon were estimated. Table 2 summarizes the GHG sources and sinks for each MSW management option. Throughout the analysis, we used methods consistent with guidance from the Intergovernmental Panel on Climate Change (IPCC) on accounting and estimating techniques for GHG emissions and sinks (IPCC 1997).

GHG Emissions From Raw Materials Acquisition and Manufacturing.
For this first stage of the lifecycle, we estimated the GHG emissions from fossil fuel combustion for both (1) raw materials acquisition and manufacturing, or "process energy," and (2) transportation. Transportation energy includes CO_2 emissions from transportation of raw materials, and of intermediate products to the final manufacturing or fabrication facility. For transportation of recycled inputs, we considered transportation (1) from the curbside to the materials recovery facility (MRF), (2) from the MRF to a broker, and (3) from a broker to the plant or mill.

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[3] Mixed paper is a term used in the recycling industry; it does not correspond directly to paper grades as generated, and thus does not appear in Table 1.

[4] EPA's Office of Research and Development (ORD) is performing a more extensive application of life cycle assessment for various waste management options for MSW. ORD's analysis will inventory a broader set of emissions (air, water, and waste) associated with these options. For more information on this effort, go to their project web-site at http://www.epa.gov/docs/crb/apb/apb.htm.

We developed separate estimates for process and transportation energy GHG emissions for virgin inputs and recycled inputs, based on two sets of estimates: (1) the amount of each type of fuel used to make a given quantity of the material, and (2) an emission factor for each fuel.

Forest Carbon Sequestration

When paper products are source reduced or recycled, trees that would otherwise be harvested are left standing. In the short term, this results in a larger amount of carbon remaining sequestered – in effect, resulting in "negative emissions" – because the standing trees continue to store carbon, whereas paper production and use tends to release carbon. In the long term, some of the short-term benefits disappear as market forces result in less planting of new managed forests than there would otherwise be, so that there is comparatively less forest acreage in trees that are growing rapidly (and thus sequestering carbon rapidly). Working with US Forest Service staff, who generated outputs from Forest Service models, we estimated that recovering one metric ton of paper results in incremental forest carbon sequestration of 0.81 metric tons of carbon equivalent (MTCE). This estimate includes changes in carbon storage in trees and understory, and excludes changes in the forest floor and soil.

Source Reduction and Recycling

Source reduction avoids energy use, and GHG emissions, in the raw materials acquisition and manufacturing stage. For paper products, source reduction also results in forest carbon sequestration.

For recycling, manufacturing from recycled inputs generally requires less energy than manufacturing from virgin inputs. Consequently, manufacturing from recycled inputs generally results in lower GHG emissions than manufacturing from virgin inputs (although changes in the fuel mix can result in higher emissions in the case of some paper products). As with source reduction of paper products, recycling of paper products also results in forest carbon sequestration.

Combustion

Combustion, like landfilling, is a management practice used for the full spectrum of materials in the solid wastestream. There are several important methodologic issues associated with estimating GHGs from combustion. First, although combustion of MSW results in relatively high total emissions of CO_2, in the US the application of the IPCC emission inventory guidelines results in only counting the CO_2 emitted from burning organics from *nonbiogenic sources*. In other words, the CO_2 emissions from burning paper, yard trimmings, wood, and other materials of recent biological origin is not counted as a GHG emission. Thus, the primary sources of emissions from combustion are plastics and other synthetic organics, and the overall emission estimate is sensitive to the proportion of the wastestream comprised by these materials.

CO_2 Emissions from Sustainably Harvested Biogenic Sources

One of the elements of the IPCC guidance that deserves special mention is the approach used to address CO_2 emissions from biogenic sources. For many countries, the treatment of CO_2 releases from biogenic sources is most important when addressing releases from deforestation or energy derived from biomass (e.g., burning wood). But this issue is also important when evaluating waste management emissions (for example, the decomposition or combustion of paper or yard trimmings). The carbon in paper and yard trimmings was originally removed from the atmosphere by photosynthesis, and under natural conditions, it would eventually cycle back to the atmosphere as CO_2 due to degradation processes. The quantity of carbon that these natural processes cycle through the earth's atmosphere, waters, soils, and biota is much greater than the quantity added by anthropogenic GHG sources. But the focus of the Framework Convention on Climate Change is on anthropogenic emissions - emissions resulting from human activities and subject to human control - because it is these emissions that have the potential to alter the climate by disrupting the natural balances in carbon's biogeochemical cycle, and altering the atmosphere's heat-trapping ability.

Thus, for processes with CO_2 emissions, if (a) the emissions are from biogenic materials and (b) the materials are grown on a sustainable basis, then those emissions are considered to simply close the loop in the natural carbon cycle -- that is, they return to the atmosphere CO_2 which was originally removed by photosynthesis. In this case, the CO_2 emissions *are not* counted On the other hand, CO_2 emissions from burning fossil fuels *are* counted because these emissions would not enter the cycle were it not for human activity. Likewise, CH_4 emissions from landfills *are* counted - even though the source of carbon is primarily biogenic, CH_4 would not be emitted were it not for the human activity of landfilling the waste, which creates anaerobic conditions conducive to CH_4 formation.

The life cycle emissions framework used in the analysis also incorporates the transportation CO_2 emissions associated with collecting MSW; this is a relatively small factor in terms of net emissions.

Another minor component of GHG emissions from waste combustion is N_2O. The method used here relies on a default emission factor provided by the IPCC, which is highly uncertain.

The CO_2 and N_2O emissions are offset by GHG emission reductions from electricity generation[5] and, to a much smaller extent, by ferrous recovery (which saves energy in iron manufacture). We assumed that when electricity is generated, it displaces fossil fuels in the current ratio of use in the US (84% coal, 13% gas, 3% oil). We regarded fossil fuels to be the marginal fuels for utility generation because other sources (nuclear, hydropower, renewables) tend to have low variable costs, and are relatively insensitive to changes in demand. We obtained data on overall combustion system efficiency (in terms of net electricity produced per ton of solid waste input) for both mass burn and refuse-derived fuel (RDF) systems. The limited data available indicated that net efficiency is slightly higher for mass burn systems, and thus the potential to offset utility emissions is slightly higher for these systems.

In the US, most WTE plants magnetically separate ferrous metals from bottom ash, and route the recovered metal to recycling. Using the methods to evaluate life-cycle energy savings for steel recycling (described earlier), we credit the GHG emission reductions from ferrous recycling to the combustion process.

For mixed MSW, the magnitude of the avoided utility emissions exceeds the emissions from non-biogenic CO_2; thus, combustion has slightly net negative GHG emissions. In terms of individual materials, combustion of paper results in negative net emissions (the avoided fossil fuel emissions produce net benefits), whereas there are positive emissions for plastics (the CO_2 from combustion exceeds the avoided utility emissions).

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[5] In the US, virtually all combustors are waste-to-energy facilities, i.e., they use the heat of combustion to produce steam and generate electricity (thus avoiding generation from fossil fuel sources).

Landfilling
Steel and aluminum cans, glass containers, and HDPE, LDPE, and PET plastic are essentially inert in landfills. The IPCC accounting convention for carbon in plastics that are landfilled does not "count" that carbon — in essence, landfilling returns the (modified) fossil fuel back to the earth.[6] Consequently, the net GHG emissions from landfilling of metals, glass, and plastics is zero (other than small transportation CO_2 emissions). For paper and mixed MSW, however, both methane emissions and carbon sequestration must be considered.

To estimate methane emissions and carbon sequestration from landfilling of paper and mixed MSW, we used data from laboratory experiments conducted by North Carolina State University (Eleazer et al. 1997; Barlaz 1998). The experiments provided data on (1) the amount of methane generated by paper, when digested by bacteria in anaerobic conditions simulating those in a landfill, and (2) the amount of carbon remaining undecomposed (i.e., sequestered) at the end of the experiment. The long-term carbon storage for some materials (e.g., newspaper) is sufficient to counterbalance the methane emissions so that landfilling can represent a net sink; for other materials (e.g., office paper) methane emissions far exceed carbon storage, so landfilling is a net source.

For all paper types and mixed MSW, the net emissions vary widely depending on whether landfill gas (LFG, which is about 50 percent CH_4) systems are in place. An increasing number of landfills are collecting LFG, and some of the larger LFG projects are using the gas to generate electricity.[7] As with combustion, the avoided electric utility emissions (assumed to be CO_2 from fossil fuels) can have a significant effect on total emissions.

Results and Applications

Use of Emission Factors.
The primary application of the GHG emission factors in this report is to support climate change mitigation analysis and accounting for waste management practices. Organizations interested in quantifying and voluntarily reporting GHG emission reductions associated with waste management practices may use these emission factors for that purpose. In conjunction with the US Department of Energy, EPA has used these emission factors to develop guidance for voluntary reporting of GHG reductions, as authorized by the US Congress in Section 1605 (b) of the Energy Policy Act of 1992. WTE facilities have been active in reporting GHG emission reductions through this program, with 65 of 103 US plants, representing 87 percent of US combustion capcity, covered by a report submitted by IWSA in 1998[8]. Other countries may be

[6] The fossil source (oil or gas) is not counted as an emission in the national GHG inventory because it is not combusted.

[7] The Landfill Methane Outreach Program, a voluntary partnership between the USEPA, state agencies, landfill gas-to-energy developers and energy users, aims to reduce landfill methane emissions by facilitating the development of landfill gas utilization projects. The program has an Internet home page (http://www.epa.gov/landfill.html), and can be reached via a toll-free hotline number (1-800-782-7937).

[8] Personal Communication, Maria Zannes, President of Integrated Waste Services Association. IWSA uses somewhat different approaches from those described in this paper.

able to adapt the methodology presented in this report to develop GHG emission estimates for their solid wastestreams.[9]

Table 3 presents the range of GHG emissions associated with landfilling and combustion of mixed MSW. Emission factors are expressed in units of metric tonnes of carbon equivalent per wet tonne of material; they represent the cumulative emissions summed across all GHGs (after weighting each gas by its 100-year global warming potential). The variation in GHG emissions for the four categories of landfills (i.e., landfills without LFG recovery, landfills with LFG recovery and flaring, landfills with LFG recovery and electricity generation, and the U.S. national average landfill) illustrates the effect of landfill gas recovery practices on net GHG emissions. As the table indicates, net GHG emissions associated with disposal of mixed MSW at landfills are positive for landfills without LFG recovery and the US national average landfill, and negative for landfills with either flaring or energy recovery. Therefore, LFG recovery practices must be considered when comparing the GHG impacts of landfilling to combustion or other waste management practices. As this table indicates, net GHG emissions from combustion at mass burn and RDF plants are negative, and are bracketed by the range of GHG emissions estimated for landfills with LFG recovery and flaring and landfills with LFG recovery and electricity generation. It is important to note that the relative GHG impacts of combustion as compared to landfilling are highly dependent on the assumptions that 1) marginal fuels being displaced by electricity generation are fossil fuels, and 2) most of the CO_2 emissions are derived from sustainable biogenic sources.

In order to apply the emission factors to a waste management strategy, one must first establish a baseline scenario and an alternative scenario. Once emissions for the two scenarios have been determined, one calculates the difference between the alternative scenario and the baseline scenario. The result represents the GHG emission reductions or increases attributable to the alternative waste management practice.

Example Calculation

Given a baseline scenario of landfilling 1,000 metric tons of mixed MSW and an alternative scenario of combusting the same amount at a mass burn plant, one could estimate the change in net emissions as follows. For combustion:

1,000 MT x -0.05 MTCE/MT = -50 MTCE

The net emissions of landfilling 1,000 MT, in the "US average" landfill, is

1,000 MT x 0.05 MTCE/MT = 50 MTCE.

The change in GHG emissions for the alternate scenario, with respect to the baseline, is

–50 MTCE –50 MTCE = -100 MTCE,

so GHG emissions would be reduced by 100 MTCE.

The life cycle GHG emissions for source reduction, recycling, and combustion are compared to the GHG emissions from landfilling in Table 4. The values in the table indicate the effect of changing management of one ton of each material from landfilling (often viewed as the baseline waste management strategy) to one of the other waste management options, based on average US conditions. GHG emissions are sensitive to some factors that vary on a local basis, and thus site-specific emissions differ from those summarized here. The WAste Reduction Model (WARM) provides the emission factors, along with the capability of incorporating key site-specific parameters to improve the accuracy of the emission factors for specific conditions.[10]

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[9] Note that waste composition and product life cycles vary significantly among countries, but the basic methodologic framework would still apply.

Major Limitations of the Analysis
When conducting this analysis, we used a number of analytical approaches and numerous data sources, each with its own limitations. In addition, we employed major assumptions throughout the analysis. Some of the major limitations follow:

- The manufacturing GHG analysis is based on estimated industry averages for energy usage, and in some cases the estimates are based on limited data and average values for electricity generation.
- The forest carbon sequestration analysis uses a point estimate for forest carbon sequestration, whereas the system of models predicts changing net sequestration over time.
- The combustion analysis uses US national average values for a number of parameters (e.g., ferrous recovery, marginal utility fuel mix) that may not be representative of a given combustor facility.
- The landfill analysis is based on laboratory data from a single research effort.

Many of the emissions are likely to vary considerably among sites; applying the values in this paper to specific circumstances at the site is an exercise involving considerable uncertainty. Also, many different emission estimation methodologies are being employed to measure the impact of climate change mitigation activities. While the methods and results reported here are appropriate for evaluating voluntary measures, they are not sufficiently accurate for purposes that go beyond evaluation of GHG emissions from waste management options in a voluntary setting. For a more thorough description of the limitations and assumptions that underlie the results in this paper, please see our full report, *Greenhouse Gas Emissions from Management of Selected Materials in Municipal Solid Waste* (US EPA 1998).

Conclusions

Management of MSW presents many opportunities for GHG emission reductions. On a material by material basis, management practices such as source reduction and recycling offer the greatest potential for GHG emission reductions. However, when the wastestream is considered as a whole (i.e., mixed MSW as disposed), the comparison between waste management practices is driven by site-specific factors at landfills and WTE plants. Landfill GHG emissions are highly variable, depending primarily on whether a LFG collection system is in place, and the results of a comparison between landfilling and combustion will be driven largely by whether the landfill has a LFG system in place or not. GHG emissions from WTE plants vary as well, depending in part on the proportion of plastics in the wastestream. Other factors that affect GHG accounting for both WTE facilities and landfills include the marginal utility fuel mix (which drives the extent of the offset for avoided utility emissions), and whether the sources of biogenic carbon are sustainable (if not, net emissions from both sources would be considerably higher).

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[10] WARM is available on the Internet at http://www.epa.gov/mswclimate/ .

Given the uncertainty in our estimates and the site-specific variability in several key factors, our findings do not indicate that there is a clear distinction between mass burn and RDF WTE plants in terms of net GHG emissions.

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References

1. Barlaz, Morton A.; "Carbon storage during biodegradation of municipal solid waste components in laboratory-scale landfills"; *Global Biogeochemical Cycles*, Vol. 12, No. 2, pp. 373-380; June 1998.

2. Eleazer, William E., William S. Odle, Yu-Shen Wang, and Morton A. Barlaz; "Biodegradability of Municipal Solid Waste Components in Laboratory-Scale Landfills"; *Environmental Science and Technology*, Vol. 31, No. 3, pp. 911-917; March 1997.

3. Intergovernmental Panel on Climate Change (IPCC); *Guidelines for National Greenhouse Gas Inventories* (three volumes); IPCC, Hadley Centre Meteorological Office, Bracknell, England; 1997.

4. US Environmental Protection Agency (EPA); *Greenhouse Gas Emissions from Management of Selected Materials in Municipal Solid Waste; Final Report*; EPA 530-R-98-013; Published on the Internet at http://www.epa.gov/ epaoswer/non-hw/muncpl/ghg.htm; Sept 1998.

Tables and Figures

Table 1. Percentage of 1996 US Generation of MSW

Material	Percentage of MSW Generation
Newspaper	5.9%
Office paper	3.2%
Corrugated cardboard	13.8%
Aluminum cans	0.8%
Steel cans	1.3%
Glass containers	5.3%
HDPE plastic*	0.6%
LDPE plastic*	0.01%
PET plastic*	0.5%
Total	**31%**

*Based on blow-molded containers.

Source: USEPA, *Characterization of Municipal Solid Waste in the United States: 1997 Update*, **May 1998.** EPA 530-R-98-007.

Table 2. Components of Net Emissions for Various Municipal Solid Waste Management Strategies

	Greenhouse Gas Sources and Sinks		
Municipal Solid Waste Management Strategy	**Raw Materials Acquisition and Manufacturing**	**Change in Forest or Soil Carbon Storage**	**Waste Management**
Source Reduction	Decrease in GHG emissions, relative to the baseline of manufacturing	Increase in forest carbon storage (paper only)	No emissions/ sinks
Recycling	Decrease in GHG emissions due to lower energy requirements (compared to manufacture from virgin inputs) and avoided process non-energy GHGs	Increase in forest carbon storage (paper only)	Process and transportation emissions associated with recycling are counted in the manufacturing stage
Combustion	No change	No change	Nonbiogenic CO_2, N_2O emissions, avoided utility emissions, and transportation emissions
Landfilling	No change	No change	Methane emissions, long-term carbon storage, avoided utility emissions, and transportation emissions

Table 3
Net GHG Emissions from Waste Management Options MTCE/Wet Tonne)

Material	Landfilling				Combustion	
	Landfills Without Recovery	Landfills With LFG Recovery and Flaring	Landfills With LFG Recovery Electric Generation	Projected US National Average	Mass Burn	RDF
Mixed MSW	0.19	-0.03	-0.07	0.05	-0.05	-0.03

Table 4
Greenhouse Gas Emissions of MSW Management Options Compared to Landfilling (MTCE/Metric Ton)

Material	Source Reduction Net Emissions Minus Landfilling Net Emissions	Recycling Net Emissions Minus Landfilling Net Emissions	Combustion Net Emissions Minus Landfilling Net Emissions
Newspaper	-0.75	-0.70	0.01
Office Paper	-1.72	-1.49	-0.79
Corrugated Cardboard	-0.90	-0.81	-0.25
Mixed Paper			
Broad Definition	NA	-0.80	-0.28
Residential Definition	NA	-0.77	-0.24
Office Paper Definition	NA	-1.05	-0.31
Aluminum Cans	-3.30	-4.29	0.02
Steel Cans	-0.93	-0.64	-0.54
Glass	-0.17	-0.10	0.01
HDPE	-0.68	-0.41	0.22
LDPE	-1.00	-0.56	0.22
PET	-1.09	-0.70	0.25
Mixed MSW	NA	NA	-0.10

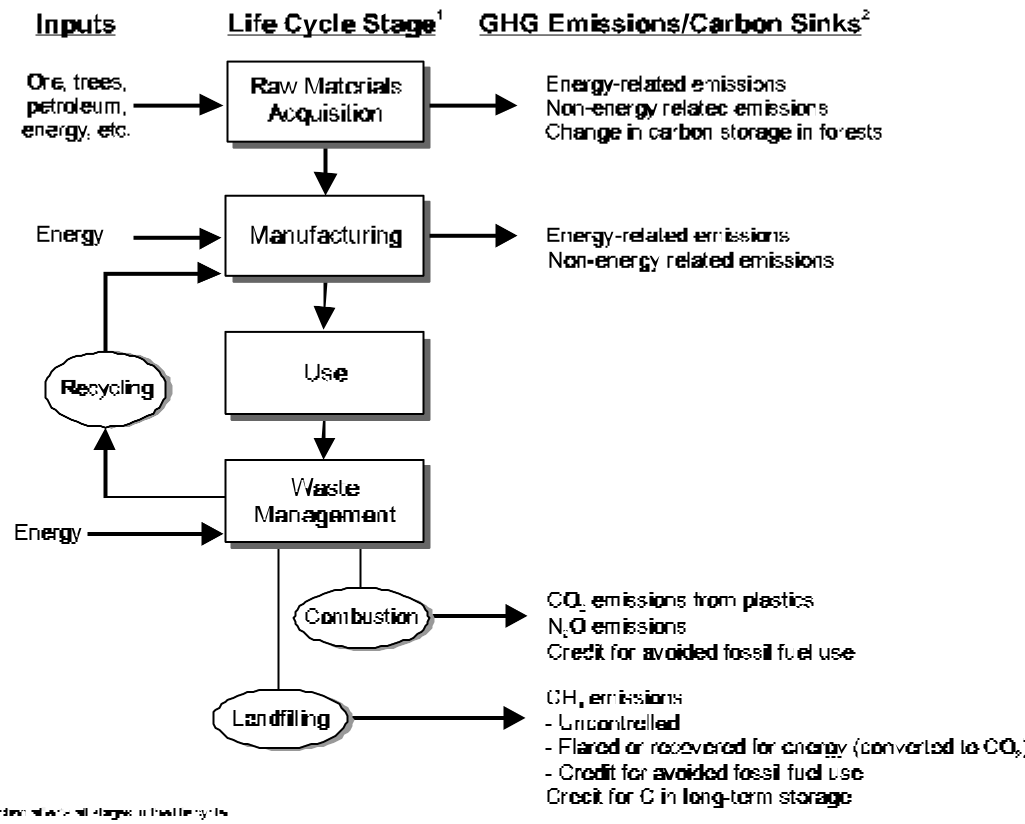
Note that values reflect US national averages, and more digits may be displayed than are significant.

[1]Values for landfilling reflect projected US national average methane recovery in year 2000.

[2]Source reduction assumes initial production using the current mix of virgin and recycled inputs.

[3]Values are for mass burn facilities with national average rate of ferrous recovery.

Figure 1
GHG Sources and Sinks Associated with Materials in the MSW Stream



[1] Note that [illegible] at all stages in the life cycle.
[2] All life-cycle stages include transportation energy-related emissions (except that emissions from transporting products from manufacturers to consumers were not counted in the analysis).