Life Cycle Assessment of the Environmental Emissions of Waste-to-Energy Facilities

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INTRODUCTION

Over the past ten years, environmental issues have become an increasing priority for both government and industry alike. In the U.S. as well as in Europe, the emphasis has gradually shifted from a site specific focus to a product specific focus. For this reason, tools are needed to scientifically assess the overall environmental performance of products and/or industrial systems. **Life Cycle Assessment (LCA)** belongs to that category of tools, and is used to perform this study.

In numerous industrial countries, LCA is now recognized, and is rapidly becoming the tool of preference, to successfully provide quantitative and scientific analyses of the environmental impacts of industrial systems. By providing an unbiased analysis of entire systems, LCA has shown that the reality behind widely held beliefs regarding "green" issues, such as reusable vs. one way products, and "natural" vs. synthetic products, were far more complex than expected, and sometimes not as "green" as assumed.

This paper describes the modeling and assumptions of an LCA, commissioned by the Integrated Waste Services Association (IWSA), that summarizes the environmental emissions of waste-to-energy facilities, and compares them to the environmental emissions generated by major combustible energy sources of the northeast part of the United States (NE). The geographical boundary for this study is, therefore, the NE US.

General Principle of Life Cycle Assessment

LCA is an analytical tool used to comprehensively quantify (with further option to interpret) the material and energy flows (flows to and from the environment, including air emissions, water effluents, solid waste, and the consumption/depletion of energy and other resources), over the entire life cycle of a product or process. The life cycle is meant to be studied comprehensively, including production and extraction of raw materials, intermediate products manufacturing, transportation, distribution, use, and final disposal. The general principle for extending system boundaries is illustrated in Figure 1.

All flows within the system are normalized to a unit summarizing the *function* of the system. This allows for the comparison of different industrial systems performing the same function. Once this shared function is defined, a unit has to be chosen in order to compare the systems on the same quantitative basis. The concept of the *function* is presented in the example of comparing milk bottles of different packaging materials (glass, plastic, etc.). The *function* of the comparison would be: *packaging of milk*. The *functional unit* would be: *the packaging of one gallon of milk.*

APPLICATION TO THIS STUDY: FUNCTIONAL UNIT AND SYSTEM BOUNDARIES

The Life Cycle Starting Point for MSW

In the Life Cycle approach, it is necessary to study the environmental and resource consequences of a product or process comprehensively. In the case of waste-to-energy, the commonly accepted starting is the generation of waste at the point of collection[1].

Functional Analysis

WTE is a process that performs two functions: MSW is being disposed of, and it is being reused in a beneficial way as a fuel source to generate electricity. In an LCA, when an additional function is introduced, it must be meaningfully compared in all of the options. Although the disposal of MSW is considered a meaningful function, it will not be studied in this LCA: following LCA reasoning, the function of disposing MSW in the WTE option would also have to be presented for all of the comparisons. However, the study of an alternate means of disposal on the other electricity options would entail the analysis of processes of landfilling, recycling, etc., and studying these large and complex processes would go beyond the scope of this study.

As a result, the remaining main function considered in this study is the production of electricity, comparing each electricity option on a per unit of electricity generated.

Figure 2 presents the three electricity comparisons in this study: the production of electricity from a waste-to-energy facility vs. the production of electricity from the major combustible sources electricity: coal, fuel oil, and natural gas.

Figures 2 shows each comparison as having only one function **(F1)**: producing electricity. Producing electricity, however, is not the only function that is associated with WTE. An additional function of WTE is recycling steel scraps. The WTE process recovers ferrous material from MSW and sends it off site to be recycled into usable steel (secondary steel), which displaces the production and use of steel from natural resources (primary steel).

Since none of the combustible electricity sources perform this same function, the production of primary steel must be subtracted out of only the WTE system. Figure 3 presents the two systems which contain the processes of each option and their respective functions. Note: only coal combustion is shown here, although WTE is compared to fuel oil and natural gas in the same way.

The Functional Unit Precisely Defined

The functional unit that will meaningfully compare the function of energy is a defined quantity of electricity produced, and has been chosen as 1 kilowatt-hour (kWh).

MODELING

This section describes all of the components modeled in the LCA. The entire waste-to-energy system and a general overview of the NE electricity grid contributors are discussed. Due to limited space in this paper, the detailed descriptions for modeling NE electricity grid components are not included. All data are modeled in Ecobalance's LCA software, TEAM^{TM2}.

Waste-To-Energy System

The waste-to-energy system includes the transportation of MSW to the waste-to-energy facility, combustion of MSW, including air emissions and water effluent control, disposal of the waste-to-energy ash residue, and production of steel with recovered ferrous materials.

Transportation of MSW to Waste-to-Energy Facility. Municipal solid waste is processed from the surrounding residential, commercial, and industrial facilities. The service area is assumed to be 50 miles in diameter with the average hauling distance of 25 miles. Approximately two-thirds of the waste stream is delivered by transfer trailer and one-third by roll-off containers and packer trucks. They return empty from the facility.

Residential MSW is typically collected with a 20- to 30- cubic yard packer truck. Since packer truck utilization is normally about 80 percent with a packing density of 750 pounds per cubic yard, a packer truck collects approximately 7.5 short tons of MSW per load. The average consumption of diesel oil per load is 13 gal/load which implies a fuel consumption of 1.8 gal per short ton of MSW[3]. Transfer trailers and roll-off containers will be modeled from Ecobalance's database, DEAM™[4], on standard heavy-duty diesel-powered trucks.

Air emissions generated from the collection vehicles are based on measured air emissions of a diesel oil heavy-duty truck[5], however, actual air emissions may be higher than considered, due to the high stop-start frequency.

Waste-to-Energy Facility. In order to use a representative waste-to-energy facility as a fair comparison to other NE electricity grid contributors, a typical facility was defined to produce average facility parameters. Figure 4 presents the five different areas of the waste-to-energy process for which typical data were obtained.

General Characteristics of the Waste-to-Energy Facility. The size of the waste-to-energy facility is assumed to be a 1500 ton-per-day (TPD), 5000 Btu/lb. refuse throughput. The facility has an annualized capacity factor of 92%, so it combusts an average of 1380 TPD of MSW. The facility consists of two 750 TPD mass burn waterwall furnaces, multi-pass boilers. Superheated steam is generated and used to drive a condensing steam turbine and generator set to produce electricity.

The facility includes an enclosed tipping hall for waste deliveries and a refuse storage bunker which holds up to 5000 short tons of MSW. Each boiler generates steam at 850 psig, 850°F, and operates continuously 24 hours per day, seven days per week, with the exception of power outages. The steam system includes a turbine generator, a water-cooled condenser, a wet cooling tower, condensate pumps, a low pressure heater, a deaerator, feedwater pumps, a boiler with an economizer, generating banks and superheater sections, and all ancillary equipment required to generate steam at the specified condition. Net power produced is 37.5 Megawatts (MW). 600 kilowatt-hours of electricity are produced per short ton of MSW combusted[6].

Auxiliary Burners. Auxiliary burners are provided for startup, shutdowns and any upset conditions. No auxiliary fuel is combusted other than for these conditions. The auxiliary fuel is assumed to be fuel oil, and on average 0.6 gallons per short ton of MSW fired is used for combustion (less than 1% of total heat release).

Water Systems. City water is demineralized in the water treatment system, and sulfuric acid (35% solution H_2SO_4) and caustic soda (50% solution NaOH) are used to regenerate the treatment system. In addition, small quantities of other chemicals are used for water treatment. The demineralized water is used for boiler makeup, and it is assumed that all process waste water is reused in the facility.

MSW Handling On-Site. Trucks carrying MSW enter the site, proceed to the weigh scales and remote scalehouse and continue on to the tipping floor. On the floor they back into bays to discharge their load into the refuse bunker. The trucks leave the tipping area and proceed to the facility scales to be weighed out before exiting the facility grounds.

Ancillary Materials. Besides MSW and the fuel oil used periodically in the auxiliary burners, there are additional materials that are consumed during the waste-to-energy process. The materials added to emissions control operations include powdered activated carbon (1.0 pounds per short ton of MSW), pebble lime (25 pounds per short ton of MSW), and aqueous ammonia (0.5 gallons per short ton of MSW). Materials used to regenerate the water treatment system are caustic soda (0.006 pounds per short ton of MSW), and sulfuric acid (0.004 pounds per short ton of MSW).

Air Emissions. The waste-to-energy facility contains emissions control equipment that complies with EPA's emissions guidelines. These include a selective non-catalytic reduction (SNCR) NOx control system, an activated dry carbon injection system, a lime-based spray dryer absorber system, and a fabric filter.

This facility uses technology that meets the Maximum Achievable Control Technology (MACT), as defined by the U.S. Environmental Protection Agency (EPA) for waste-to-energy facilities[7] for electricity production in the NE US. Table 1 presents average values for actual WTE emissions as reported by the U.S. EPA[8], per short ton of MSW combusted.

A fraction of the 2080 pounds of CO_2 emitted per short ton of MSW combusted comes from burning biomass. Paper and paperboard make up 25% of total MSW directed to WTE plants, yard trimmings make up 18%, and wood makes up 4%[9]. Organic carbon content by weight of biomass is assumed to be 41%[10]

Ash and Ferrous Scrap Management. After combustion of MSW, bottom ash falls off the grate into a quench basin and is combined with grate siftings. The bottom ash is conveyed to a ferrous recovery system. Fly ash and spent salts of reaction are conditioned with water and combined with the bottom ash for disposal. All ash handling occurs in buildings and enclosures so that no significant fugitive emissions occur. Ash and ferrous materials are stored separately in a grade level storage building, and then are sent to be disposed of or recycled in the ash residue monofill and the scrap metal recycling facility, respectively.

Ash Residue Monofill. The amount of combined fly ash residue and bottom ash that is generated at the facility is assumed to be 500 pounds per short ton of MSW. Ash is transported 50 miles to a double-lined monofill in payloads of 22.5 short tons. The typical truck used to transport ash residue is a tandem truck, filled based on weight of the material. Besides the emissions due to truck and transport of the material, it is assumed that no significant fugitive emissions come from the ash due to ash wetting, indoor loading, and covered transport.

The ash residue monofill is double-lined, consisting of a 24-inch clay layer and a 60-mils geosynthetic layer. Leachate from the landfill (40 pounds per short ton of MSW) is collected and discharged to a treatment works plant.

Scrap Metal Recycling Facility. Forty pounds of clean ferrous scrap metal per short ton of MSW are hauled fifty miles to a scrap metal recycling facility. Ferrous material is transported 50 miles to a scrap recycler in payloads of 22.5 short tons.

From an LCA modeling perspective,

- the burdens of the recycling of 40 pounds of ferrous scrap (secondary steel from an electric arc furnace) are added to the waste-to-energy system; and

- the burdens of producing that quantity of steel from primary means are subtracted out of the waste-to-energy system. This is because, since steel is being recycled and used for secondary steel production, the same quantity of steel that would have been produced by primary means is offset.

Electricity from Combustible Sources of Electricity

The combustible sources of electricity that are compared to waste-to-energy electricity production are coal, fuel oil, and natural gas.

Electricity from coal. The coal important to this study is eastern bituminous, since the vast majority of coal burned in the northeast is eastern bituminous coal. Modeling electricity production from coal includes materials, energy consumed, and emissions due to bituminous coal mining, preparation, transportation to facilities, combustion, emissions control technology such as flue gas desulfurization, and management of coal combustion byproducts at a landfill or storage pond.

Emissions due to coal combustion are figured for each type of firing configuration since firing configurations have different combustion requirements (coal burning temperatures, firing methods, and emissions control equipment, etc.) and emit varying amounts of pollutants.

Electricity from fuel oil

Heavy fuel oil, or residual oil, is the fuel oil used in power utilities. This type of oil is produced from the residue remaining after the lighter fractions of oils, such as gasoline, kerosene, and distillate oils have been removed from the crude oil. In general, the combustion of residual oils generates large quantities of ash, NOx, and SOx.

Modeled in this report includes energy, raw materials consumed, and emissions due to mining crude oil (including onshore production, offshore production, and thermal enhanced recovery methods), refining crude oil, and transportation from the mining site to the power generation plant.

Petroleum Administration for Defense Districts[11] (PADD's) were originally defined during WWII for purposes of administering oil allocation. The PADD region in the NE US that contains MACC and NPCC is PADD region I. Over 97% of the crude oil in PADD Region I comes from foreign crude oil sources. Therefore, transportation will take into account foreign oil brought into the US. It is assumed that foreign oil precombustion processes require the same energy and have the same environmental impacts as domestic oil processes, so figures for domestic oil precombustion processes are used in the model.

Electricity from natural gas. Raw natural gas is a mixture of hydrocarbons, N_2, CO_2, sulfur compounds, and water. It may have any range of compounds from mostly methane to inert gases, such as nitrogen, carbon dioxide, and helium, and smaller amounts of ethane, propane, and butane. Natural gas may be mined onshore, offshore, and in conjunction with petroleum processes.

Modeling natural gas includes taking into account the energy, raw materials, and emissions due to mining and cleaning natural gas, pipeline transportation, and combustion.

Modeling Software: TEAM™

All of the modeling for this LCA is performed on TEAM™, the LCA modeling tool developed and used by Ecobalance for the last 5 years. This tool, developed in C^{++}, efficiently performs complex Life Cycle Assessments, and models material and chemical flows through extended industrial process networks. This model contains an extensive database called DEAM™ of the basic Life Cycle Inventory of commodity materials, transportation means, energy sources and disposal options. This model strictly follows the LCA methodological framework developed by Society of Environmental Toxicology and Chemistry and adopted by the U.S. EPA. It also follows the recommendations developed in the ISO 14000 forum.

DISCUSSION ON WATER EFFLUENTS

Water effluents are not being taken into account for any of the electricity options for the following reasons:

Pre-electricity production: Water effluents coming from pre-electricity production processes are considered negligible for this study since the only effluents coming from precombustion are those from mining the fuels that are used to transport materials and refinery processes. Over the entire life cycle, these quantities are considered negligible.

Electricity Production: Water used during combustion of MSW includes demineralized water used for boiler makeup, for treatment of fumes, and for slag cooling. It is assumed that most of the water is recycled in the facility, so water effluents generated as a result of MSW combustion are negligible. The same applies for other combustible fuels.

Post-combustion waste management: The monofill that holds MSW ash residue is lined, and leachate is collected and transported to an offsite waste water treatment plant (WWTP). This collection of leachate is considered standard practice for typical waste-to-energy facilities in the U.S. Water discharged from the WWTP is considered safe enough to be released into the environment.

Leachate from coal combustion byproduct (CCB) monofills in the U.S. is generally not collected and taken off-site, so it is very difficult to quantify its actual amount per specified quantity of coal combusted. In terms of environmental impacts, leachate generated from coal ash at a monofill depends upon local conditions, such as precipitation, the leachability of the fly ash, and origin of the coal.

RESULTS

The results of this study will be presented at the conference. The comparisons between the electricity options are made to comparatively assess different impacts each option makes on the environment. Following is a brief overview of what the results will show.

Direct Comparison: Waste-to-Energy vs. Coal, Fuel Oil and Natural Gas

A direct comparison will be made between electricity produced from waste-to-energy and electricity produced by each of the combustible fuels. Actual quantities for each flow are directly compared. Examples of flows are as follows:

- **Raw materials** extracted from the earth and consumed: coal, natural gas, oil, uranium, and limestone;
- **Air pollutants** emitted: particulate matter, CO_2, NOx, SOx, and CO;
- **Energy** consumed: total renewable and non-renewable and feedstock and fuel energy.

Impact Analyses

Acidification potential, global warming potential, and natural resource depletion for each electricity option will be presented at the conference.

Acidification Potential. Potential acidic deposition (onto soil, vegetation, and water) can be expressed as potential H^+ equivalents. Potentially acidifying emissions of SO_2, NO_x and NH_x can be aggregated on the basis of their potential to form H^+, and the resulting value is the acidification potential.

Global Warming Potential. The "greenhouse effect" refers to the ability of some atmospheric gases to retain heat which is radiating from the earth. Global Warming Potentials (GWPs) have been calculated to compare the emission of different greenhouse gases. The emissions accounted for in this assessment are CO_2, N_2O, and CH_4., the pollutants recognized to potentially contribute to global warming.

Natural Resources Depletion Index. Resource depletion can be defined as the decreasing availability of natural resources. Resources considered in this impact are fossil and mineral resources, excluding biotic resources and associated impacts such as species extinction and loss of biodiversity. The fossil and mineral resources taken into account for this study are: coal, iron, natural gas, oil, and uranium. It is important to recognize that what is addressed in this index is the fact that some resources are depleted, not the fact that their extraction from the environment will generate impacts (e.g., methane emissions from coal mining).

TABLES

Table 1. MACT emissions limits and Waste-to-Energy facility emissions per short ton of MSW.

Pollutant$^{\text{note 1}}$	MACT Rule (per dry std. m^3)	WTE Facility Emissions (lb./short ton MSW)
SOx	7.9 ppm	0.19
NOx	136 ppm$^{\text{note 2}}$	2.4
CO	40 ppmv$^{\text{note 3}}$	0.42
Particulate Matter	4.8 mg	0.099
HCl	9.7 ppm	0.13
Pb	0.006 mg	$5.4*10^{-5}$
Hg	0.022 mg	$1.9*10^{-4}$
Cd	0.00098 mg	$8.8*10^{-6}$
PCDD/PCDF	3.3 ng	$3.0*10^{-8}$
$CO_2$$^{\text{note 4}}$	Unregulated	2080
CH_4	Unregulated	0.003
N_20	Unregulated	0.008

1 All pollutants are assumed to have O_2 at 7%.

2 Emissions from Mass Burn/Water Wall Furnace type of boiler, 200 ppm NOx.

3 Emissions from Mass Burn Waterwall, 100 ppmv CO.

4 The emissions values chosen for unregulated emissions such as CO2 (2080 lb./short ton of MSW), methane (0.003 lb./short ton of MSW) and N20 (0.008 lb./short ton of MSW), were supplied by IWSA engineers.

FIGURES

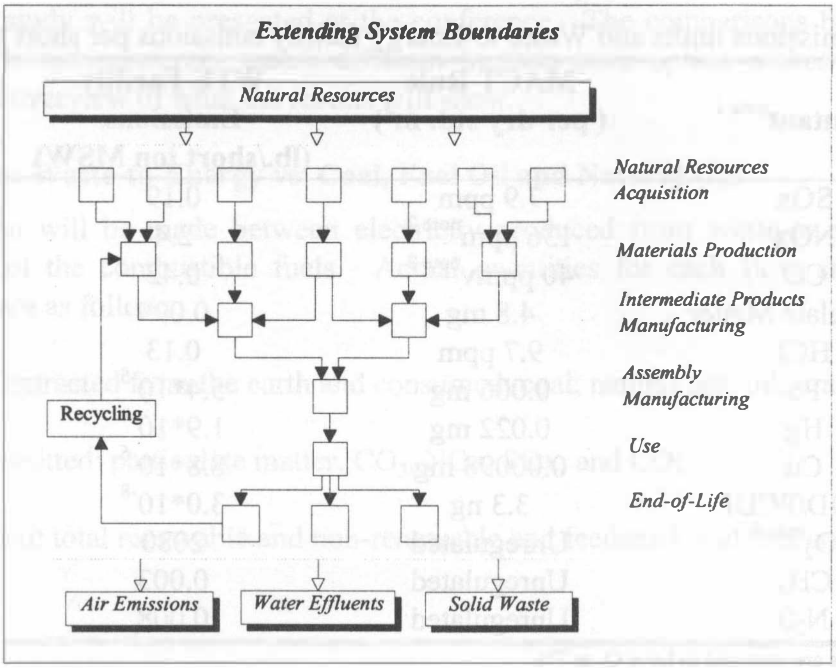

Figure 1 Extending system boundaries.

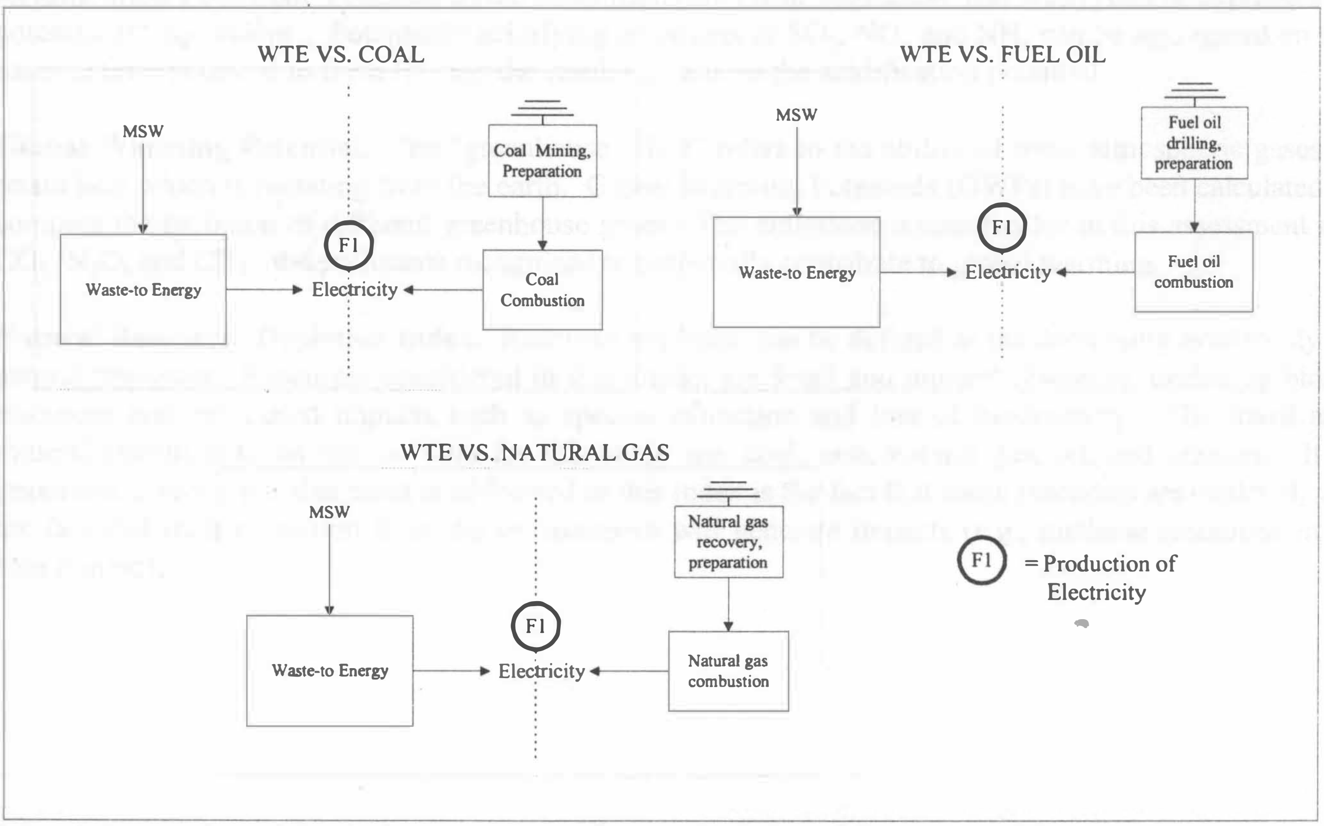

Figure 2 Production of electricity by a waste-to-energy facility and the combustible electricity sources.

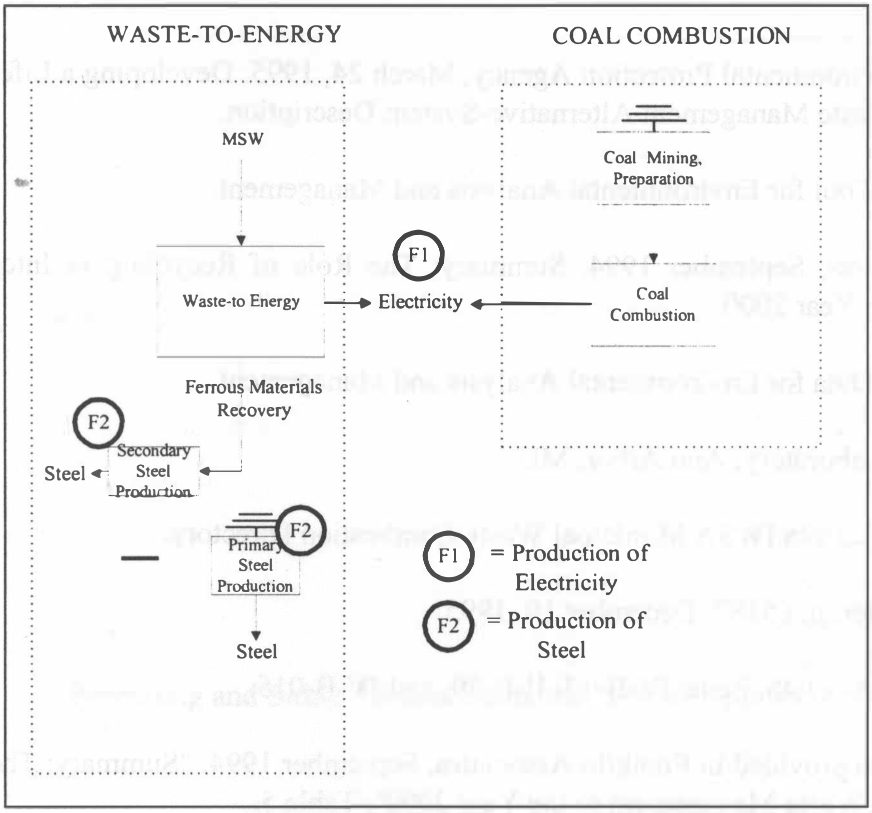

Figure 3 System boundaries for WTE vs. the combustible source of electricity.

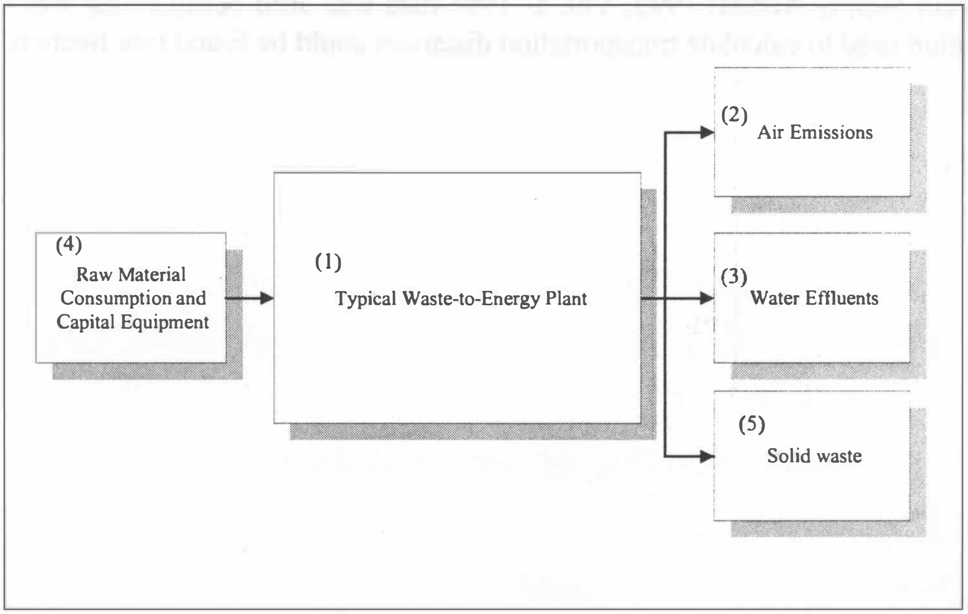

Figure 4 Schematic of the waste-to-energy facility.

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[5] EPA Emissions Laboratory, Ann Arbor, MI.

[6] IWSA, May 1996. 1996 IWSA Municipal Waste Combustion Directory.

[7] 60 Federal Register, p. 65387, December 19, 1995.

[8] US EPA Docket A-90-45, items IV-B-13, II-B-39, and IV-B-015.

[9] Derived from data provided in Franklin Associates, September 1994. "Summary: The Role of Recycling in Integrated Solid Waste Management to the Year 2000", Table 5.

[10] Carbon content percentage for paper and paperboard products from an unpublished LCA report by Ecobalance for American Forest and Paper Association on unbleached paper products, 1995.

[11] EIA Petroleum Supply Annual 1993, Vol. 1. 1993 data was used because that was the latest year for which information used to calculate transportation distances could be found (see Section 3.3.2).