ABSTRACT

LI, MINSHENG LIFE-CYCLE INVENTORY (LCI) DEVELOPMENT FOR A SOLID WASTE/COAL BLEND GASIFICATION SYSTEM FOR PRODUCTION OF POWER AND CHEMICALS (Under the Direction of Drs. Morton A. Barlaz and H. Chris Frey)

To make good estimates of pollution prevention, performance, and cost of potentially promising new technologies, it is important to develop new assessment methodologies for managing technological development and for evaluating technologies. The research presented in this study is part of a larger effort to develop novel assessment methodologies for evaluation of the risks and potential pay-offs of new technologies that minimize or avoid pollutant production. The assessment methodology was demonstrated via a detailed case study of one promising pollution prevention technology – gasification of municipal solid waste (MSW), which was evaluated using a tiered approach including process simulation and life-cycle analysis (LCA).

In this study, an overall life-cycle inventory (LCI) model was developed for calculation of the LCI of the MSW/coal blend gasification system by combining the IGCC based polygeneration model, the refuse derived fuel (RDF) process model, the landfill process model, the conventional methanol process model, and the remanufacturing model. Specially, the development of the RDF process model was part of this research. Also, an existing LCI model was used for calculation of the LCI of the conventional mass burn waste to energy (WTE) system based on the WTE process model.

The gasification system was evaluated in two cases: a landfill with energy recovery and a landfill without energy recovery. Compared to a landfill without energy recovery, there is an environmental performance improvement for landfill with energy recovery. However, this improvement is negligible to the total LCI of the gasification system.

For both the gasification system and the WTE system, the emissions of most pollutants are negative due to the avoided emissions associated with electricity production, aluminum and ferrous recovery, and methanol production (gasification system only).

Compared to the WTE system, the gasification system has a better LCI for all the pollutants including atmospheric emissions, waterborne emissions, and solid waste emissions partly because more electricity was produced in the gasification system than the WTE system. Another reason is due to the production of methanol in the gasification system. The only exception is the BOD emissions, for which emissions associated with the MSW residual disposal in the landfill has a large contribution to its total emissions.

As the methanol plant size increases, the total emissions of the gasification system keep decreasing. Therefore, it is favorable for the gasification system to increase methanol production.

In this study, the avoided emissions associated with the sulfur recovery in the gasification were not included due to lack of data. Therefore, the total emissions of the gasification system were overestimated. Also, the effect of ammonia production on the LCI of the gasification system could not be evaluated in this study because the ammonia process model was not combined with the MSW/coal gasification system.

LIFE-CYCLE INVENTORY (LCI) DEVELOPMENT FOR A SOLID WASTE/COAL BLEND GASIFICATION SYSTEM FOR PRODUCTION OF POWER AND CHEMICALS

By

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PERSONAL BIOGRAPHY

Minsheng Li was born on January 13, 1977 in Jilin Province, P.R.China. Mr. Minsheng Li graduated from Quanlin High School in Jilin Province, China in 1995. He attended Tsinghua University, earning a Bachelor of Science degree in Environmental in July 2000. In August 2000, he entered the Civil Engineering graduate program at North Carolina State University. His graduate focus was in environmental engineering and his research areas were in process modeling and Life-Cycle Inventory development. His graduate advisors were Drs. Morton A. Barlaz and H. Christopher Frey. Mr. Li received a Master of Science degree in August 2002.

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1.0 INTRODUCTION

Technology development is an iterative process involving decisions regarding which research paths to pursue based upon current results and assessment of competing technologies and market needs (Frey and Barlaz, 2001). Due to limited data during research, development, and demonstration (RD&D), there is significant variability and uncertainty that may result in misleading estimates of pollution prevention, performance, and the cost of potentially promising new technologies. With a limited pool of funds available to support RD&D, it is important to develop new methods for managing technological development and for evaluating technologies. The research presented in this study is part of a larger effort to develop novel assessment methodologies for evaluation of the risks and potential pay-offs of new technologies that minimize or avoid pollutant production. The assessment methodology was demonstrated via a detailed case study of one promising pollution prevention technology – gasification of municipal solid waste (MSW), which was evaluated using a tiered approach including process simulation and life-cycle analysis (LCA).

Two alternatives for the thermal processing of MSW are incineration and gasification. Due to recently demonstrated benefits of gasification over incineration, gasification technology is receiving significant attention (Simbeck *et al.*, 1983; Stiegel, 2000). However, at present, MSW gasification is a relatively new concept. There are several research projects investigating the process. The only commercially demonstrated IGCC system firing solid waste is the Lurgi Schwarze/Pumpe plant in Germany (Pickett, 2000). To evaluate the risks and potential pay-offs of MSW gasification, a systematic approach for assessment must be explored. Models must be developed to characterize its performance and environmental emissions, so that it can be compared to other MSW treatment alternatives including the most common thermal treatment alternative, mass burn combustion with energy recovery or waste-to-energy (WTE).

The objective of this study is to develop a model to calculate the life-cycle inventory (LCI) of a process in which gasification is utilized to treat MSW with the production of energy and chemical feedstocks and then to compare the LCI for gasification technology to a MSW treatment alternative based on a conventional WTE facility.

Specific objectives are:

1) To develop a process model for a refuse derived fuel (RDF) plant to calculate energy requirements and environmental emissions.

2) To combine the RDF process model with a previously developed model for an integrated gasification combined cycle (IGCC) system, a landfill process model, electrical energy production, and recyclables remanufacturing into an overall model for calculation of the LCI of the MSW gasification process.

3) To perform sensitivity analyses on the LCI model to identify the key parameters affecting the LCI of the MSW gasification process.

4) To compare the LCI of a process utilizing MSW gasification to that of a process in which MSW is burned in a WTE.

Chapter 2 provides an overview of each component of the overall LCI model. In addition, the RDF process model that was developed as part of the research is documented in detail. Chapter 3 describes the results of a case study of MSW gasification and the results of sensitivity analyses on the overall LCI model. The LCI calculation for the conventional MSW combustion process, and a comparison between the LCI of the MSW gasification process and that of the conventional MSW combustion process are presented in Chapter 4. Finally, conclusions and recommendations for future work are presented in Chapter 5.

2.0 OVERVIEW OF THE MSW GASIFICATION PROCESS AND THE LCI MODEL OF THE MSW/COAL BLENDS GASIFICATION SYSTEM

The objective of this chapter is to describe the various sub-models that were used to conduct a complete LCI of MSW gasification, including models that were developed in previous research as well as models developed in the research described in this thesis. To evaluate the environmental performance of the MSW gasification process, the MSW/coal blends gasification system is defined to incorporate all aspects of the treatment process, including the production of RDF required for gasification, the IGCC process, the liquid phase methanol (LPMEOH) process, landfill burial of residuals from both RDF production and MSW/coal gasification, and the beneficial reuse of recyclables recovered during RDF production, henceforth referred to as remanufacturing. A simplified schematic of the overall system as modeled in this study is presented in Figure 2-1. Initially, MSW must be processed to separate it into high and low heating value streams. This step occurs in what is referred to as a RDF plant. The high heating value stream, referred to as RDF, is used to feed the IGCC system as a fuel; the low heating value stream is assumed to be disposed of in a landfill. Recyclable ferrous and aluminum are recovered at a RDF plant and recycled in the remanufacturing plants. The RDF is mixed with coal and the blend is fed into the IGCC system. In the IGCC based polygeneration system, the RDF/coal blend is converted into synthesis gas (syngas) which is then used to produce energy, methanol, and ammonia. For a detailed description of the IGCC system model, methanol production from syngas and ammonia production the user is referred to Pickett (2000), Vaswani (2000), and Xie (2001), respectively.

The following section presents an introduction to LCA methodology, followed by an overview of the LCI model.

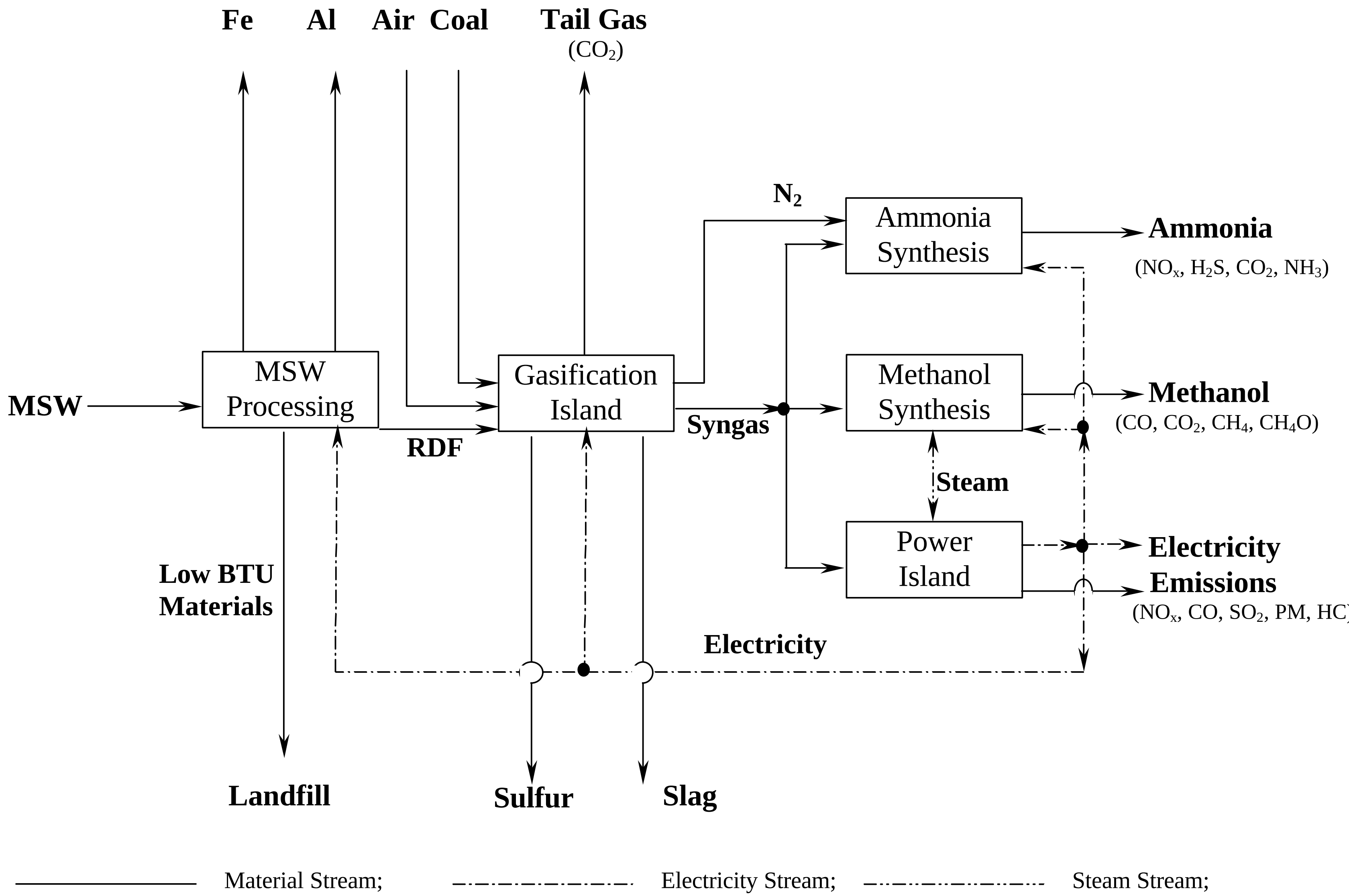


Figure 2-1 Simplified Process Flow Diagram of the MSW Gasification Process

2.1 Introduction to Life-Cycle Analysis

LCA is an objective process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and materials use and wastes released to the environment, and to evaluate and implement opportunities to effect environmental improvements (SETAC Code of Practice, 1991). A LCI represents a compilation of a specific set of inputs and outputs associated with a product or process. A complete life-cycle study consists of three complementary components: (1) inventory analysis, which is a compilation of all material and energy requirements associated with each stage of product manufacture, use and disposal; (2) impact analysis, a process in which the effects of the inventory on the environment are assessed; and (3) improvement analysis, which is aimed at reducing the impact of a product or process on the environment (Pistikopulos *et al.*, 1994).

2.2 Overview of Overall LCI Model of the MSW/Coal Blends System

As illustrated in Figure 2-2, the overall LCI model is comprised of multiple sub-models, including the RDF process model, the IGCC system model, the landfill model, and the remanufacturing model. An ammonia process model was developed by Xie, 2000. However, it has not been integrated with the entire system. Therefore, the effect of the ammonia production on the LCI of the gasification system can not be estimated in this study.

The essential feature of LCI methodology is an attempt to thoroughly consider all aspects of a process. In the context of gasification of MSW, the LCI methodology requires that in addition to an inventory of the direct emissions associated with the RDF plant, the transportation from the RDF to the remanufacturing plant, the IGCC system, the traditional landfill, and the ash landfill, an inventory of the avoided emissions is also included. This accounts for the avoided emissions associated with the recovery of recyclable materials (ferrous and aluminum), and the production of methanol, electricity, ammonia and sulfur from syngas. An offset analysis was used to capture the benefit of recyclables recovery, and energy and chemical production. In an offset analysis, the emissions associated with producing a product by a conventional process are subtracted from the emissions generated in an alternative process. For example, when recycled

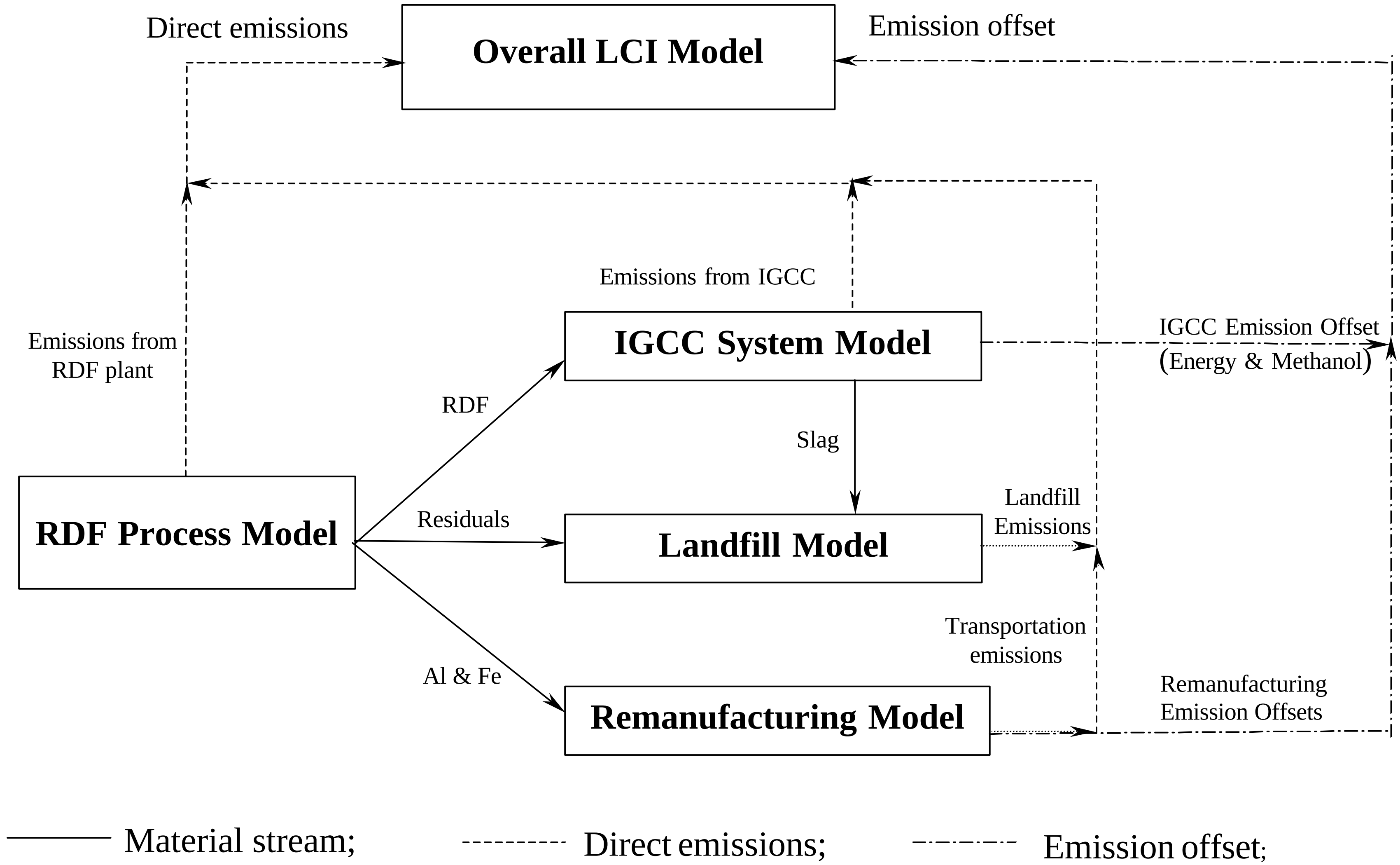


Figure 2-2 Simplified Structure of the Overall LCI Model

aluminum is converted to a new product, there are emissions associated with the manufacturing process. There are also emissions that are avoided because the aluminum product is not produced from virgin materials. In an offset analysis, the emissions from the virgin process are subtracted from the emissions from the recycle process and the net value is added to the overall system LCI. This net value is a negative number if the recovery process is beneficial. The overall LCI model integrates all the sub models and calculates the LCI of the direct emissions and the avoided emissions for the entire MSW/coal blends gasification process.

2.2.1 Overview of the IGCC Based Polygeneration System Model

Gasification is a technology that has been widely used in commercial applications for over 40 years in the production of fuels and chemicals. Current trends in the chemical manufacturing and petroleum refinery industries indicate that use of gasification facilities to produce syngas will continue to increase (Orr, et. al, 2000). Attractive features of the technology include: 1) the ability to produce a consistent, high quality syngas product composed primarily of carbon monoxide and hydrogen, which can be used as a fuel to generate electricity, steam and/or used as a basic chemical building block in the petrochemical and refining industries; and 2) the ability to accommodate a wide variety of gaseous, liquid, and solid feedstocks. Gasification regained attention in 1970's due to the energy crisis in the US at that time.

An IGCC system is one system that utilizes gasification technology to produce power. It replaces the traditional coal combustor with a gasifier and gas turbine. Exhaust heat from the gas turbine is used to produce steam for a conventional steam turbine, thus the gas turbine and steam turbine operate in a combined cycle. The IGCC configuration provides high system efficiencies and ultra-low pollution levels compared to conventional power generation systems (Orr *et. al*, 2000). In addition to electricity, the syngas produced in a gasification plant can also be used to produce industrial feedstocks including methanol, hydrogen, ammonia, sulfuric acid, formaldehyde, and other chemicals (Simbeck *et al.*, 1983).

In early 2001, there are 163 active commercial scale gasification projects with a total of 468 gasifiers (real and planned) rated at 67,800 MW syngas or about 37,375 MW

IGCC equivalent. (Simbeck, 2001). In Table 2-1, the top 10 commercial gasification projects are presented.

Table 2-1 Top 10 Commercial Gasification Projects (Simbeck, 2001)

Plants	**Location**	**Gasifiers**	**MW syngas**	**Year**	**Feedstock/Products**
Sasol-Π	S. Africa	Lurgi	5,090	1977	Coal/F-T liquids
Sasol-Ø	S. Africa	Lurgi	5,090	1982	Coal/F-T liquids
Confidential*	USA	Texaco	2,761	2006	Coal/Electric
Port Authur*	USA	E-Gas	2,029	2005	Coal/Electric
Dakota	USA	Lurgi	1,900	1984	Lignite/SNG
Repsol*	Spain	Texaco	1,654	2005	Residue/Electric
Lake Charles*	USA	Texaco	1,407	2005	Coke/Electric
Deer Park*	USA	Texaco	1,400	2006	Coke/Electric
Eagle Energy*	USA	Texaco	1,367	2005	Coke/Electric
SARLUX	Italy	Texaco	1,217	2001	Residue/Electric

* Planned

2.2.1.1 Introduction to ASPEN PLUS Software

In this study, the gasification process is simulated as an IGCC system model by using a chemical software, ASPEN (Advanced Systems for Process Engineering) PLUS. ASPEN PLUS is a chemical process simulation software that enables users to design and simulate a process. ASPEN PLUS can estimate material and energy balances, phase and equilibrium, physical properties of chemical compounds and even the capital cost of equipment. With users' inputs, reliable thermodynamic data, realistic operating conditions, and rigorous equipment models, it can model, control, optimize and manage a steady-state chemical process (ASPEN Tech 2000). ASPEN PLUS 10.1-0, which runs on Windows 98 platform and incorporates a Graphic User Interface (GUI), was employed to develop and implement the IGCC model.

2.2.1.2 Overview of the IGCC System Model

The IGCC system model, which calculates mass and energy balances for the entire IGCC system, was developed by Pickett (2000) and Vaswani (2000). In this study, this model was calibrated to the MSW/coal blends as described in Appendix C. The model consists of sub-modules including the gasification island and the power island. The auxiliary power requirements for each process area and for supporting facilities are also modeled.

The gasification island consists of the gasification area, the gas cooling/cleaning and liquor separation area, and the sulfur recovery area. In the gasification island, clean syngas is produced and then used as the feedstock to produce energy in the power island or to produce chemicals such as methanol and ammonia. A simplified schematic of the gasification island is illustrated in Figure 2-3.

The gasification area is based on a British Gas/Lurgi (BGL) slagging gasifier. As modeled, the fuel in the gasification area is first converted to a form that can be processed by ASPEN PLUS. Then the hydrocarbons that enter the combustion zone are generated from the carbon, hydrogen, and oxygen. In this process, some carbon and sulfur are taken out of the fuel and are added to the slag. In the combustion zone, carbon and oxygen are partially combusted and the resulting products enter the gasifier for gasification. The crude syngas generated in the gasifier is then separated from ash and CaO and enter the gas cooling area.

To simulate the gasification of solid materials such as MSW in ASPEN PLUS, an ultimate analysis, a proximate analysis, and the sulfur content must be specified. For RDF, these values were calculated in the RDF process model which is described in section 2.2.3. For coal, these values were obtained from the literature (Pechtl *et al.*, 1992).

Crude syngas is then cooled before it enters the gas cleaning area. The gas cooling section is highly integrated with the rest of the IGCC system. Water used to cool the syngas is from the fuel gas saturation area and steam cycle.

The gas cleaning section utilizes the Rectisol® cleaning process to remove sulfur and other contaminants from the syngas. The Rectisol® cleaning unit separates the cooled syngas into a clean gas, an acid gas, a naphtha rich gas, a condensate and a CO_2 rich gas.

The gas liquor separation area separates the combustible hydrocarbons from water in the liquor stream from the gas cleaning area. The tar, oil, naphtha and phenol contained

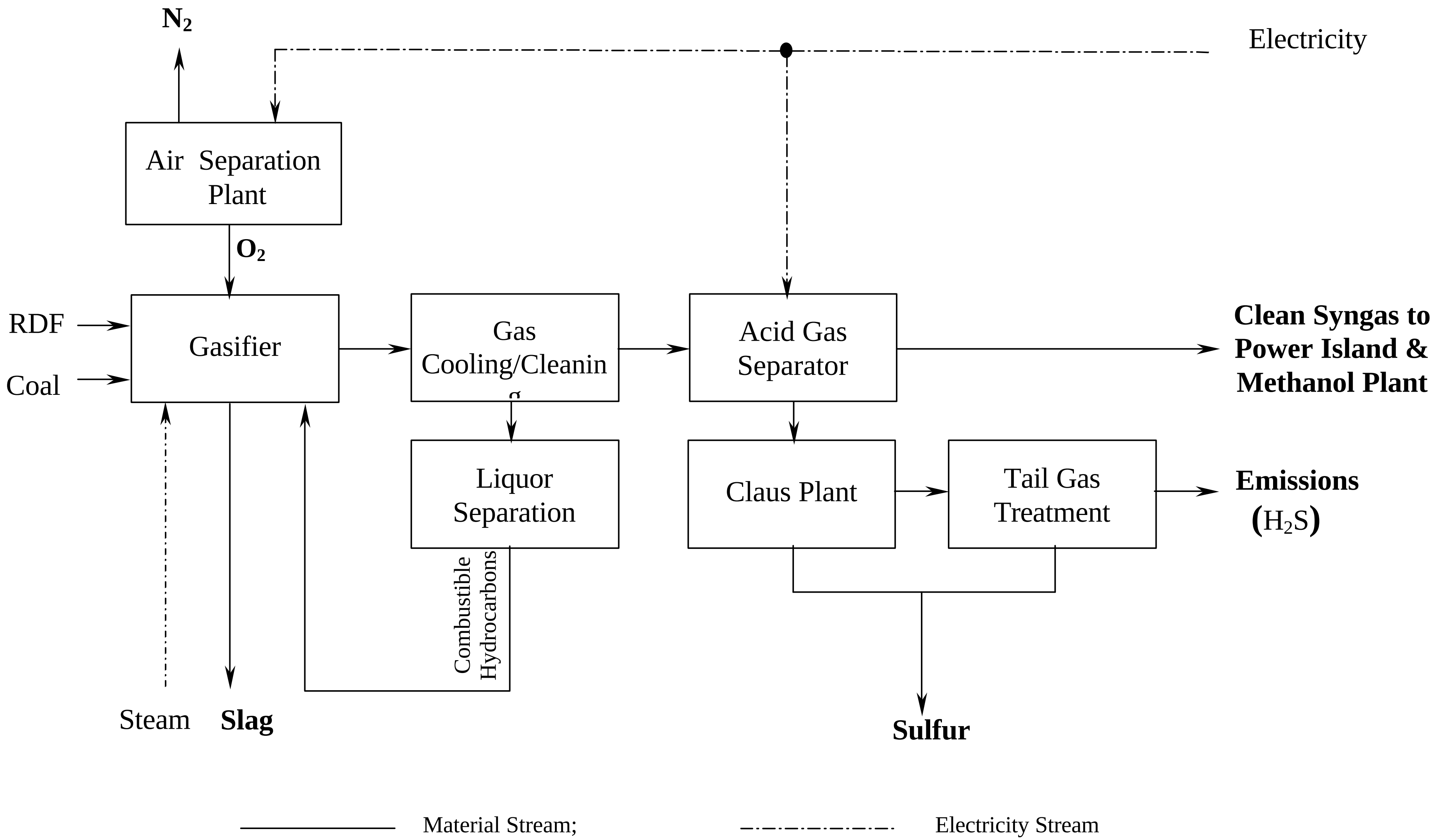


Figure 2-3 Simplified Schematic of Gasification Island of IGCC System

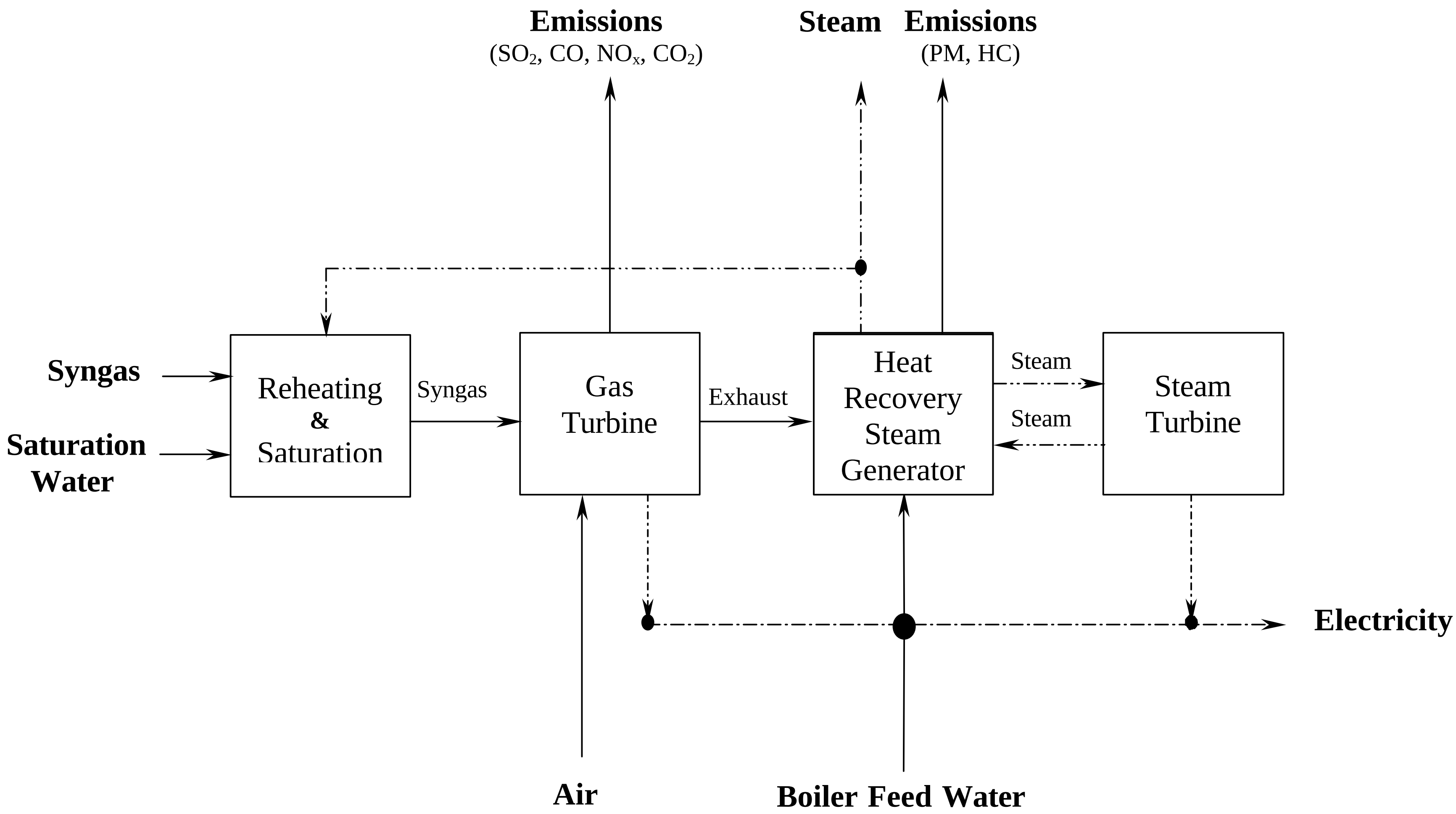
in the process condensate are separated and recycled to the gasifier. While the other stream containing the gases dissolved in the liquor proceeds to the Beavon-Stretford tail-gas treatment process. The remaining liquid is split for use in the quench units in the gasification area and gas cooling section.

The sulfur recovery section consists of a Claus plant and a Beavon-Stretford tail gas treatment plant. In the Claus plant, sulfur is recovered from H_2S while a tail gas of SO_2 is also generated. The tail gas is further treated in the Beavon-Stretford tail gas treatment plant to recover sulfur from SO_2.

After the removal of impurities and sulfur containing compounds, the syngas enters the saturation area. In the power island, the clean syngas is saturated with water to reduce NO_x emissions and increase power output from the gas turbine. After saturation in the fuel gas saturation area, the outlet stream is advanced to gas turbine. The heat of the exit gas from the gas turbines is recovered as steam. A simplified schematic of power island is illustrated in Figure 2-4.

The gas turbines modeled for the IGCC system represent a heavy-duty "F" class system, similar to a General Electric MS7001F. The default assumed IGCC plant size includes two gas turbines in parallel (Pickett, 2000). The gas turbine consists of three sections; compression, combustion and expansion. The compression section pressurizes and heats air. Cooling air is extracted from the compression section to cool the expander blades and rotors with air, thereby prolonging the life of the expanders. The fuel, along with compressed air, is introduced to the combustion section. After combustion, the hot, compressed exhaust gas expands to generate electrical energy.

The steam cycle consists of two sections: the heat recovery steam generator (HRSG) and the steam turbine. The HRSG cools the exit gas from the gas turbine and recovers the sensible heat in steam production. Liquid water enters the steam cycle process area to generate high-pressure, intermediate-pressure, and low-pressure steam. There are four HEATER blocks in HRSG to cool the exhaust gas of the gas turbine and to provide heat to four "trains" of heat requirements: (1) high-pressure steam generation, (2) intermediate-pressure steam generation, (3) low-pressure steam generation, and (4) deaeration.



Material Stream; Electricity Stream; Steam Stream;

Figure 2-4 Simplified Schematic of Power Island of IGCC System

There are three stages in the steam turbine. The super-heated, high-pressure steam enters the first stage of the steam turbine. Its pressure is reduced in the first stage and then it mixes with the intermediate-pressure steam. The mixture advances to the second stage of the steam turbine. The outlet stream is mixed with low-pressure steam and the mixture enters the final stage of the steam turbine.

2.2.1.3 Overview of Liquid Phase Methanol Process and Conventional Methanol Production Model

A Liquid Phase Methanol Process (LPMEOH^{TM}) model was developed and integrated with the IGCC model (Vaswami 2000, Pickett, 2000). The LPMEOH^{TM} model simulates the production of methanol from syngas produced by the MSW/coal blends gasification. In addition to syngas, the steam produced during gasification is used in methanol production. The process model consists of twenty-six unit operation blocks, four FORTRAN blocks and four design-specs (Vaswani 2000).

To calculate the offset LCI of the methanol produced by the gasification system, a model for calculation of the LCI of the methanol produced using conventional technology was required. This model was also developed by Vaswani (2000). It was modeled based on conventional feedstock (natural gas). Coefficients were calculated from mass and energy balance as well as consideration of overall energy requirements. The offset LCI coefficients for the conventional methanol process are presented in Table B-1.

2.2.2 Overview of Waste to Energy Model

The objective of the waste-to-energy process model is to calculate the cost and LCI for a MSW WTE facility. A detailed description of the WTE-LCI model has been presented previously (Harrison et al. 2000). In this study, the LCI portion of the waste-to-energy model was used to calculate the LCI associated with MSW combustion.

LCI parameters are calculated on the basis of both user input and default design information. Model results are based on both the quantity and composition of the waste input to a WTE facility.

The WTE process model calculates the direct emissions associated with a WTE facility. For CO_2, emissions were calculated based on the stoichiometry of waste combustion. For SO_x, NO_x, CO and particulate matter, emissions were calculated from information on regulatory requirements for MSW combustion. In addition, the direct emissions associated with the transportation from the WTE facility to the remanufacturing plant were calculated. The WTE-LCI model also computes the avoided emissions due to energy recovered by MSW combustion. Avoided emissions were calculated by assuming that any energy recovered offsets the use of natural gas and coal (Harrison et al., 2000). In this study, the fuel mix of the Southeastern Electric Reliability Council (SERC) was used.

2.2.3 Overview of RDF Process Model

The objective of the RDF process model is to calculate the energy consumption and LCI parameters for converting MSW into a fuel that is used to produce syngas by gasification. The conceptual design of the RDF model is illustrated in Figure 2-5. A detailed description of the RDF process model with all equations is presented in Appendix A and an overview of the model is presented below. All input default values are also presented in Appendix A.

In the modeled RDF facility, refuse that is received either loose or in bags is loaded onto a conveyor and fed to a flail mill. The flail mill opens any unopened bags and reduces the size of some of the refuse. From the flail mill, the refused passes under a magnet that recovers ferrous metal. The remaining refuse then continues to a trommel for removal of material less than 2 inches in diameter. The trommel removes materials like broken glass, dirt, and some food waste, all of which have a low energy value. From the trommel, refuse is shredded and then routed to an air classifier that separates the “lights”, considered to have the high BTU content, from the “heavies”, which have a relatively low BTU content. The “lights” then flow to an eddy current separator for aluminum removal. The material remaining after aluminum removal is fed to the IGCC system as a fuel.

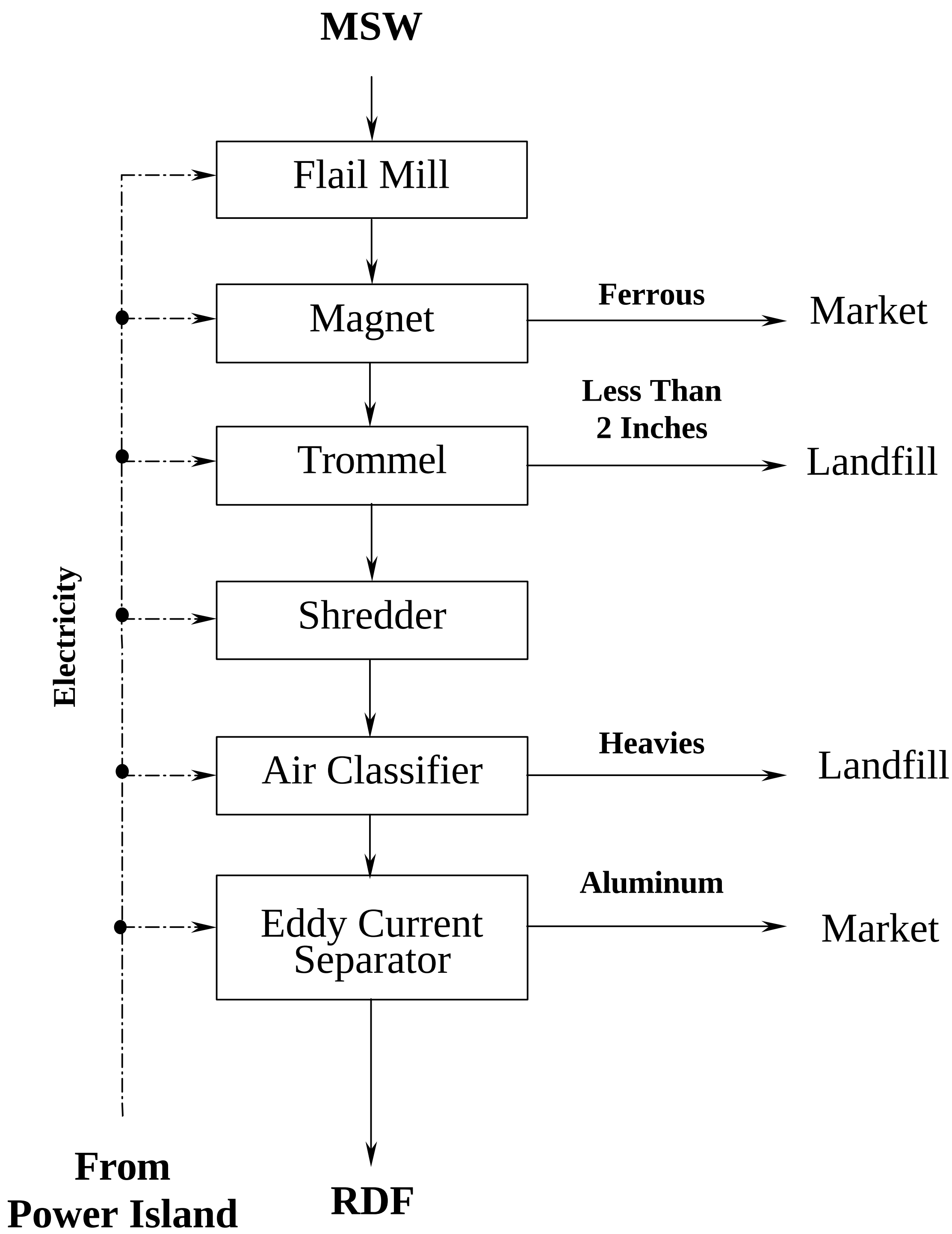


Figure 2-5 Process Flow Diagram for Refuse Derived Fuel Production

The calculation sequence for the RDF process model is illustrated in Figure 2-6. The quantity and composition of materials flowing through the RDF plant, including the RDF stream, the residual stream, and the recovered ferrous and aluminum, are calculated through mass balance equations based on assumed separation efficiencies at each step. Energy is consumed in the production of RDF both by processing equipment such as the shredder and by rolling stock. Thus, both diesel fuel and electrical energy are consumed. For each type of energy, both combustion energy and precombusiton energy is considered. Combustion energy is the energy consumed directly (diesel or electricity), while precombustion energy is the energy that is required to produce the combustion energy. The ultimate analysis of RDF is a required input to the IGCC model and is calculated based on the ultimate analysis of each MSW component and a mass balance through the RDF plant. The LCI associated with the RDF process contains three parts: diesel combustion in rolling stock; pre-combustion emissions associated with diesel production; and emissions associated with electrical consumption. The benefits associated with the recovered aluminum and ferrous are calculated in the remanufacturing process model.

The LCI coefficients for the RDF process model are presented in Table B-2.

2.2.4 Overview of the Landfill Model

The objective of the landfill process model is to calculate the cost and LCI for a landfill. The landfill process model is a sub-model of the ISWM model. Only the LCI results were used for this study.

In the RDF production process, the low heating value materials that are referred to as residuals are managed in a traditional landfill. The landfill process model was used to evaluate two scenarios, a landfill with or without energy recovery. For the landfill with energy recovery, energy was recovered by the conversion of methane to electrical energy in a turbine. Avoided emissions associated with electrical energy production were handled as for the WTE-LCI model. In this study, the fuel mix of the SERC was used, which is the same as used in the WTE model. In the IGCC system, slag is generated and

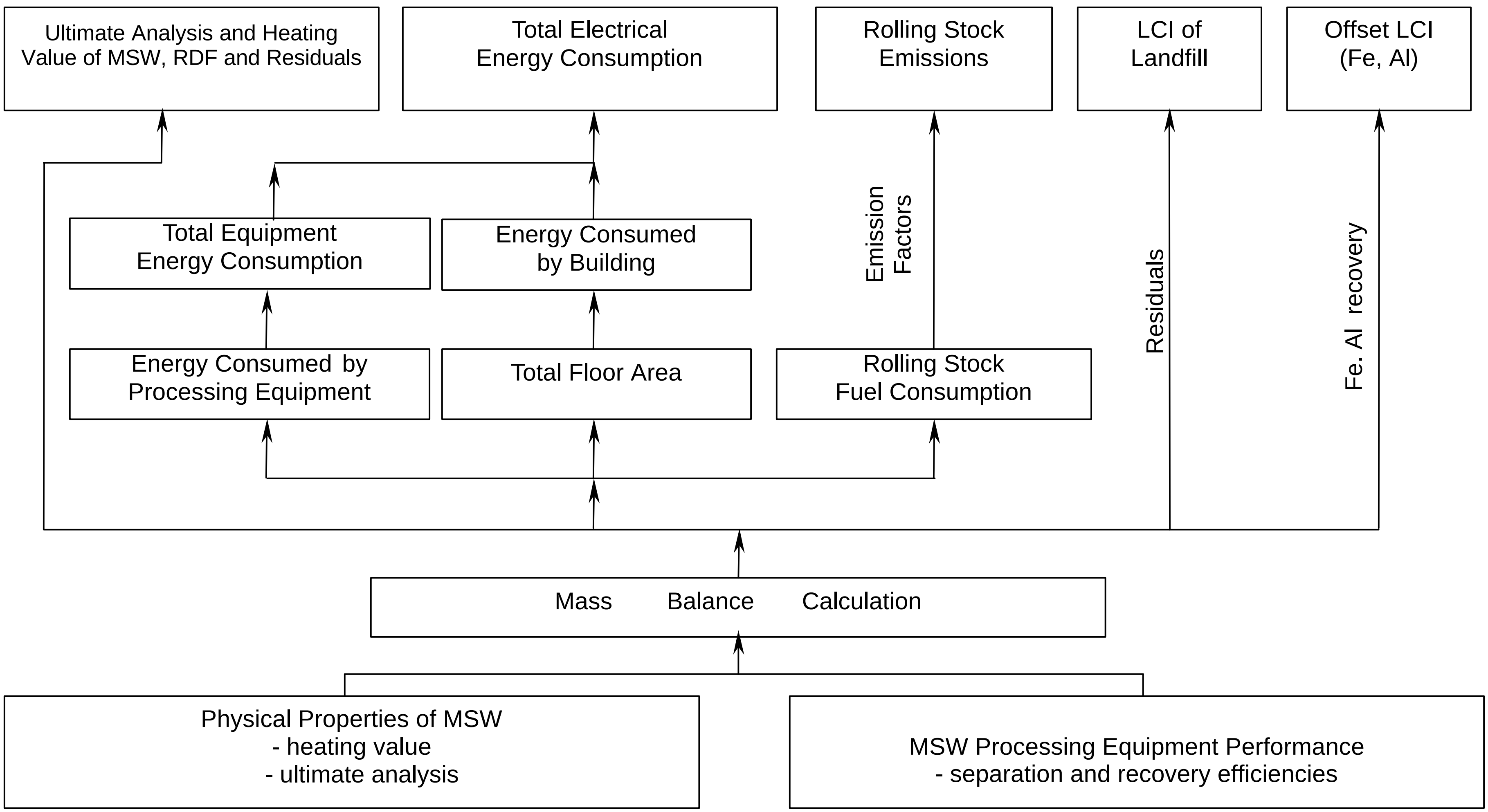


Figure 2-6 RDF Process Model Calculation Sequence

it is managed in an ash landfill. There are environmental emissions associated with the landfill treatment of the residuals and slag.

The landfill process model simulates landfill operation based on default design information and user inputs. In this study, the LCI coefficients of the traditional and ash landfill are used to compute the environmental burdens for the disposal of the MSW residuals and the slag from the IGCC system. A detailed description of the landfill process model is presented in Sich (1999). The LCI coefficients for the traditional landfill with/without energy and the coefficients for the ash landfill are presented in Table B-3, B-4 and B-5, respectively.

2.2.5 Overview of Transportation Model

The objective of the transportation model is to calculate the LCI coefficients for transporting the recovered ferrous and aluminum from the recovery units such as the RDF plant to the remanufacturing plants. The transportation model is a sub-model of the ISWM model. In this study, it was used to calculate the recovered ferrous and aluminum transportation associated emissions from both the RDF plant and the WTE plant to the remanufacturing plant. The assumed distances to the remanufacturing plant and the transportation associated LCI coefficients for the RDF plant and the WTE plant are presented in Table B-6, and Table B-7, respectively.

2.2.6 Overview of Remanufacturing Model

The objective of the remanufacturing model is to calculate emission offsets associated with the recovery of recycled aluminum and ferrous. The remanufacturing model is a sub-model of the ISWM model. One ton ferrous or aluminum can be produced either by virgin material or by recycled material. If virgin material is used to produce one ton ferrous or aluminum, there are energy consumption and environmental emissions associated with the processes of mining, combustion, and transportation, which will be avoided if recycled materials are used. Therefore, there exist offset LCIs when ferrous and aluminum are recovered for remanufacturing. The offset is calculated as the difference in emissions between the manufacturing processes based on virgin and recycled materials. The values used for this study, as obtained from the ISWM model, are presented in Table B-8.

3.0 CASE STUDIES ON THE APPLICATION OF GASIFICATION TECHNOLOGY TO MSW

This chapter presents the results of case studies on the application of gasification technology to MSW. Three scenarios were defined to analyze the gasification system. In addition to the results for these scenarios, sensitivity analyses were conducted on the LCI model based on the base case.

3.1 Scenario Definition

Three scenarios were designed to evaluate the LCI of MSW gasification. The IGCC plant size was varied in each scenario by varying methanol production. The size of the methanol production plant was set at 10,000, 20,000 and 40,000 lb/hr in scenarios A, B and C, respectively. In each scenario, the size of the two gas turbines modeled in the IGCC system model is constant.

For each scenario, a series of model runs was made to determine (1) material usage, material production, energy production, and the emissions associated with the RDF/coal blends, (2) the material usage, the material production, the energy production and the emissions that could be attributed to RDF production and (3) the environmental burdens associated with the application of gasification technology to MSW. For each of the three scenarios, two cases are considered. In case 1, the MSW residual is disposed in a traditional landfill with no energy recovery. In case 2, the MSW residual is disposed in a traditional landfill with electrical energy recovery. The landfill gas (LFG) is treated differently in these two cases, as listed in Table 3-1.

As developed, the IGCC model allows for calculation of the LCI for the MSW/coal blend. However, it was necessary to separate out the fraction of the LCI that was attributable to MSW. This is because in Chapter 4, the LCI of MSW gasification is compared to that of WTE that processes MSW without coal. The allocation technique is described in section 3.2.3.

Table 3-1 LFG Treatment in the First, Second, Third Treatment Periods in Case 1 & 2

Landfill Gas Treatment Methods		**Case 1 (%)**	**Case 2 (%)**
Year 1 - 5	Vent	100	100
Year 6 - 40	Flare	100	0
	Turbine	0	100
Year 41 - 80	Flare	100	0
	Turbine	0	100

3.2 Input Assumptions and Results of the Base Case

The calculation sequence for the LCI model is as follows.

1. Use the RDF process model to compute the proximate analysis, ultimate analysis and the heating value of the RDF based on the user specified MSW composition and physical properties.
2. Use the IGCC system model to compute the material usage, material production, and energy production with a specified RDF/coal blend and methanol plant size.
3. Use the RDF process model, the IGCC model, the landfill model, the electricity model, the remanufacturing model and the conventional methanol production model to compute the total LCI of the MSW/coal blends system.

In the base case, the RDF/coal blend is specified on the weight average with 25% Pittsburgh #8 coal and 75% RDF. The methanol plant size is set to produce 10,000 lb methanol /hr.

3.2.1 MSW Waste Composition

The MSW waste stream used in the base case is characterized by 39 waste components. Table 3-2 lists the weight fraction and heating value of each waste item.

Table 3-2 Waste Composition and Heating Value of Each MSW Component [a]

WASTE ITEM	Composition (%, wet basis)	Moisture content (%, wet basis)	Heating Value (Btu/lb, wet basis)
Leaves	5.6	60.0	2,601
Grass	9.3	60.0	2,601
Branches	3.7	60.0	6,640
Old Newsprint	6.7	6.0	7,541
Old Corr. Cardboard	2.1	5.0	6,895
Office Paper	1.3	6.0	6,313
Phone Books	0.2	6.0	6,248
Books	0.9	6.0	6,248
Old Magazines	1.7	6.0	5,386
3rd Class Mail	2.2	6.0	6,076
Paper Other	17.1	6.0	6,464
CCCR Other	0.0	6.0	6,464
Mixed Paper	0.0	6.0	6,799
HDPE - Translucent	0.4	2.0	18,687
HDPE - Pigmented	0.5	2.0	18,687
PET	0.4	2.0	18,687
Plastic - Other	9.9	2.0	14,101
Mixed Plastic	0.0	2.0	14,101
CCNR Other	0.0	2.0	14,101
Ferrous Cans	1.5	3.0	301
Ferrous Metal - Other	3.2	3.0	0
Aluminum Cans	0.9	2.0	0
Aluminum - Other	0.5	2.0	0
Glass - Clear	3.9	2.0	84
Glass - Brown	1.6	2.0	84
Glass - Green	1.0	2.0	84
Mixed Glass	0.0	2.0	84
CNNR Other	0.0	2.0	0
Paper - Non-recyclable	0.0	6.0	6,464
Food Waste	4.9	70.0	1,797
CCCN Other	0.0	70.0	6,799
Plastic - Non-Recyclable	0.0	2.0	14,101
Misc.	7.5	20.0	3,669
CCNN Other	0.0	20.0	10,000
Ferrous - Non-recyclable	0.0	3.0	0
Al - Non-recyclable	0.0	2.0	0
Glass - Non-recyclable	0.7	2.0	0
Misc.	12.3	20.0	0
CNNN Other	0.0	20.0	10

[a] As presented in Harrison et al. 2000

3.2.2 Input Assumptions for the Base Case

Table 3-3 provides the proximate analysis, ultimate analysis, and the higher heating value of the RDF/coal blend that will be fed into the IGCC system. They are the weighted average of 25% Pittsburgh #8 coal and 75% RDF. The data for RDF was computed in the RDF process model based on the MSW specified in Table 3-2. The heating value for the RDF/coal blends used in this study was calculated by Dulong correlation equation instead of by the RDF process model to account for the uncertainty and variability in the RDF process model inputs and parameters.

Table 3-3. Proximate and Ultimate Analysis of Pittsburgh No. 8 Coal, RDF, and RDF/coal blend

Proximate Analysis, dry wt%	Pittsburgh No. 8[a]	RDF	RDF/coal blend[b]
Moisture (wt %)	6.00	14.42	13.32
FC & VM[c]	87.77	86.54	86.87
Ash	12.23	13.46	13.13
Ultimate Analysis, dry wt%			
Carbon	73.21	46.96	53.99
Hydrogen	4.94	6.39	6.00
Nitrogen	1.38	0.58	0.79
Chlorine	0.00	1.19	0.87
Sulfur	3.39	0.41	1.21
Oxygen	4.85	31.01	24.00
Ash	12.23	13.46	13.13
HHV – Dry Basis (BTU/lb)	13,138	9,658[d]	9,738[d]

[a] Pechtl *et al.*, 1992
[b] The RDF/coal blend is comprised of 25% of Pittsburgh #8 coal and 75% of RDF
[c] FC – Fixed Carbon and VM – Volatile Matter
[d] HHV calculated from the ultimate analysis using the Dulong correlation

The input assumptions for the IGCC system firing the MSW/coal blends are presented in Table 3-4. The input assumptions were developed based on a review of design and performance parameters obtained from the literatures (Pickett, 2000). A detailed description of these parameters has been presented by Pickett (2000).

Table 3-4. Input Assumptions for the IGCC System Firing the RDF/coal blend[a]

Gasification Island	
Combustion Zone Temperature, °F	3,600
Gasification Zone Temperature, °F	1,107
Heat Loss from Gasifier, %	0.3
Approach Temperature, °F	
$C + H_2O \leftrightarrow CO + H_2$ (Endothermic)	540
$C + CO_2 \leftrightarrow CO$ (Endothermic)	485
$C + 2\ H_2 \leftrightarrow CH_4$ (Exothermic)	400
$CO + H_2O \leftrightarrow CO_2 + H_2$ (Exothermic)	-170
Steam-to-oxygen Molar Ratio	1.087
Fuel Gas Saturation Process Area	
Saturation Level, %	45.8
Exit Syngas Temperature, °F	572

a – The input assumptions for the IGCC system firing RDF/coal blends were calibrated in Appendix C.

3.2.3 The LCI Model Results for the Base Case

3.2.3.1 The Results of the IGCC Based Polygeneration System Model

After specifying the input RDF/coal blend and the input assumptions for the IGCC system, the IGCC model is used to compute data for the LCI calculation of the MSW/coal gasification system, including total material usage, total material production, total power production, and total emissions from IGCC system when firing RDF/coal blends and producing 10,000 lb/hr methanol. The contribution of the RDF to the total material flows, energy flows, and emissions is also computed. The contribution of the RDF was calculated based on the contribution of the RDF to the total energy input, except two cases: 1) The contribution of the RDF to the fuel, which is calculated based on the weight percentage of RDF and coal; 2) The contribution of the RDF to the ash and sulfur, which is calculated based on the ratio of the ash and sulfur content in the RDF to the ash and sulfur content in the RDF/coal blends. The calculation is given by Equation 3-1. The basis for this calculation is that material production, energy production, and emissions are related to the energy input.

$$M_{RDF} = M_{Total} \times \frac{E\_input_{RDF}}{E\_input_{Total}} \qquad \text{(Eqn 3-1)}$$

Where:

M_{RDF} -- Contribution factor for RDF for material usage, material production, energy production, and emissions (Lb/hr or kWh/hr)

M_{Total} -- Total material usage, material production, energy production, and emissions (Lb/hr or kWh/hr)

E_input_{RDF} -- Contribution of RDF to the total energy input.

E_input_{RDF} = 75% x Fuel_Input x HHV^{wet} of RDF

E_input_{Total} -- Total energy input

E_input_{Total} = Fuel_Input x (75% x HHV^{wet} of RDF + 25% x HHV^{wet} of coal)

HHV^{wet} – Higher heating value on wet basis

For the LCI, CO_2 is categorized into fossil CO_2 and biomass CO_2. However, the IGCC system model only calculates the sum of these two types of CO_2. Therefore, the CO_2 emission must be categorized. This was done based on Table 3-5.

Table 3-5 Categorization of Waste Items with Respect to CO_2 Emission Source

Waste Item	**Biomass CO_2**	**Fossil CO_2**
Leaves	X	
Grass	X	
Branches	X	
Old Newsprint	X	
Old Corr. Cardboard	X	
Office Paper	X	
Phone Books	X	
Books	X	
Old Magazines	X	
3rd Class Mail	X	
Paper Other	X	
CCCR Other	X	
Mixed Paper	X	
HDPE - Translucent		X
HDPE - Pigmented		X
PET		X
Plastic - Other		X
Mixed Plastic		X
CCNR Other		X
Ferrous Cans		X
Ferrous Metal - Other		X
Aluminum Cans		X

(To be continued)

(Continued)

Waste Item	Biomass CO_2	Fossil CO_2
Aluminum - Other		X
Glass - Clear		X
Glass - Brown		X
Glass - Green		X
Mixed Glass		X
CNNR Other		X
Paper - Non-recyclable	X	
Food Waste	X	
CCCN Other	X	
Plastic - Non-Recyclable		X
Misc.		X
CCNN Other		X
Ferrous - Non-recyclable		X
Al - Non-recyclable		X
Glass - Non-recyclable		X
Misc.		X
CNNN Other		X

Selected results of the IGCC system model that will be used for calculation of the LCI for the gasification system for the base case are summarized in Table 3-6, including fuel, methanol, sulfur, slag, and power flow rate and emissions from the IGCC system.

Table 3-6 Selected Results of the IGCC System Model for the Base Case

		RDF/coal blend	Contribution of RDF
Material			
Methanol	(lb/hr)	10,000	6,354
Fuel	(lb/hr)	481,969	361,476
Sulfur	(lb/hr)	5,164	2,292
Slag	(lb/hr)	69,862	61,442
Power			
Power to Grid	(MW)	452.6	287.6
Emissions			
SO_2	(lb/hr)	9.40E-01	7.17E-03
CO_2 (Biomass)	(lb/hr)	4.21E+05	3.21E+03
CO_2 (Fossil)	(lb/hr)	3.17E+05	2.42E+03
NO_x	(lb/hr)	388.5	2.96E+00
CO	(lb/hr)	211.9	1.62E+00
PM	(lb/hr)	23.6	1.80E-01
HC	(lb/hr)	20.5	1.56E-01

3.2.3.2 Material and Energy Flows of the MSW/Coal Blends Gasification System

Based on the RDF demand calculated in section 3.2.3.1, the MSW demand to the gasification system for the base case, and the MSW residual produced, the ferrous & aluminum recovered and the power consumed associated with such amount of MSW are calculated by using the RDF process model. Hence, the material and energy flows for calculation of the LCI of the gasification system for the base case are calculated and summarized in Table 3-7.

Table 3-7 Material and Energy Flows Attributed to RDF of the MSW/Coal Blends Gasification System

MSW Input	(Ton/day)	7,776
RDF Produced	(Ton/day)	4,338
MSW Residual	(Ton/day)	3,012
Fe Recovered	(Ton/day)	329
Al Recovered	(Ton/day)	98
Slag from IGCC	(Ton/day)	737
Sulfur Produced	(Ton/day)	28
Methanol Produced	(Ton/day)	76
Power Consumed in RDF Plant	(MWh/day)	391
Net Power from IGCC	(MWh/day)	6902

These material and energy flows provide the basis for calculation of the LCI of the MSW/coal gasification system. The MSW feed rate will determine emissions from the RDF plant; the MSW residual is assumed to be buried in a traditional landfill and results in emissions from disposal; the slag from IGCC assumed to be buried in an ash landfill and results in emissions from disposal; the power consumption in RDF plants is subtracted from the power produced in the IGCC system, which results in the net power production of the overall system. There are avoided emissions associated with the methanol production, sulfur production, ferrous and aluminum recovered, and net power production of the gasification system. The avoided emissions associated with the sulfur production are not considered because of lack of LCI coefficients. As such, the LCI of the entire system is an overestimate of emissions since the emissions avoided from conventional sulfur production are not subtracted.

3.2.3.3 The LCI Results of the MSW/Coal Blends Gasification System (Base Case)

The results of the overall LCI for an MSW gasification system for the base case are presented in Tables 3-8 and 3-9 for a landfill with and without energy recovery, respectively.

In both cases, for all the pollutants including atmospheric, waterborne and solid waste emissions, the total emissions are negative, with the exception of biomass CO_2 and BOD. The reason is that the emission offsets of the electricity, the aluminum and the ferrous make the largest contribution to the total emissions of the gasification system LCI. While for Biomass CO_2, the largest contributor to its emission is the direction emissions from the IGCC based polygeneration system. For BOD, the largest contributor to its emission is the direction emissions associated with the MSW disposal in the landfill. The reason is due to the lechate release from the landfill. A lechate collection system efficiency of 99% was assumed for the landfill process model so that 1% of lechate generated is also released to the environment directly. Both treated and untreated lechate releases are included in the landfill emissions presented in Tables 3-8 and 3-9.

The emissions in Case 2 are less than those in Case 1 because in case 2 the LFG from traditional landfill is converted to energy and there are avoided emissions associated with the recovered energy. However, the difference between landfill with and without energy recovery is negligible to the total emissions. This is partly due to largest contributor to the total emissions of most pollutants is the offset emissions associated with the electricity, aluminum and ferrous, instead of the direction emissions from the landfill. Another reason is due to the fact that paper is the largest biodegradable component of MSW and paper is in the RDF used for gasification, and not in the residual stream.

Because the emission offsets of sulfur are not considered, the total emissions of the MSW/coal blends gasification system are overestimated.

One assumption was made for the offset emissions associated with the methanol production that the biomass CO_2 emission is zero because in conventional methanol plants, very few biomass CO_2 emission is produced.

Table 3-8 LCI Results of the MSW/Coal Blends Gasification System (Base Case / Landfill with no Energy Recovery)[a,b] (Lbs/day)

	Coal Precomb.	IGCC Plant	RDF Plant	Traditional Landfill	Ash Landfill	Electricity Offset	Methanol Offset[c]	Transport[d]	(Al + Fe) Offset	Total
Airborne Releases										
Carbon monoxide	1.30E+02	3.23E+03	2.83E+02	1.23E+02	1.84E+01	-3.87E+03	-1.15E+03	1.77E+02	-1.80E+04	-1.91E+04
Nitrogen oxides	1.66E+02	5.92E+03	4.40E+02	1.95E+01	5.43E+01	-5.12E+04	-5.43E+02	1.79E+02	-6.30E+03	-5.13E+04
Total particulates	1.85E+03	3.60E+02	4.87E+01	1.37E+01	4.99E+00	-1.75E+04	-8.42E+01	2.58E+01	-8.63E+03	-2.39E+04
Carbon dioxide (fossil fuel)	2.94E+04	4.81E+06	7.09E+03	1.06E+03	3.88E+03	-1.36E+07	-2.39E+05	2.09E+04	-2.75E+06	-1.17E+07
Carbon dioxide (biomass fuel)	2.17E+02	6.46E+06	7.15E+04	1.21E+05	9.15E-01	-1.92E+03	0.00E+00	5.00E+00	0.00E+00	6.65E+06
Sulfur oxides	1.66E+02	1.43E+01	1.03E+02	5.12E+00	9.24E+00	-9.05E+04	-5.60E+03	5.08E+01	-1.78E+04	-1.14E+05
Hydrocarbons	6.15E+01	3.12E+02	2.02E+02	3.06E+00	1.39E+01	-2.63E+03	N/A	7.21E+01	-3.21E+03	N/A
Methane	3.39E+03	N/A	1.09E+01	1.06E+03	6.88E-01	-3.00E+04	-1.35E+03	3.32E+00	-3.76E+03	-3.06E+04
Lead	1.95E-03	N/A	3.78E-04	1.50E-05	2.10E-05	-5.84E-01	N/A	1.15E-04	4.04E-01	N/A
Ammonia	6.29E-02	N/A	1.08E-01	2.41E-03	6.00E-03	-1.14E+01	N/A	3.28E-02	-6.45E+00	N/A
Hydrochloric acid	7.95E-01	N/A	6.75E-02	1.59E+00	4.64E-03	-1.10E+03	N/A	2.05E-02	-3.87E+02	N/A
GHE[e] (Tons/day)	1.37E+01	N/A	9.98E-01	3.18E+00	5.31E-01	-1.94E+03	-3.65E+01	2.86E+00	-3.86E+02	-2.34E+03
Waterborne Releases										
Dissolved Solids	5.93E+01	N/A	9.39E+01	1.41E+00	5.22E+00	-1.15E+04	N/A	2.85E+01	-9.47E+03	N/A
Suspended solids	1.02E+03	N/A	2.13E+00	1.98E-01	2.09E-01	-9.56E+03	-5.14E+01	6.48E-01	-1.03E+03	-9.62E+03
Bio-chemical Oxygen Demand	8.68E-02	N/A	3.51E-01	3.41E+01	3.98E-02	-1.14E+01	-7.47E+00	1.07E-01	-1.41E+01	1.69E+00
Chemical Oxygen Demand	9.40E-01	N/A	2.35E+00	9.48E+01	2.75E+01	-1.62E+02	-5.31E+01	7.13E-01	-2.13E+02	-3.02E+02
Oil	1.08E+00	N/A	2.19E+00	2.08E+01	5.50E+01	-2.02E+02	N/A	6.64E-01	-1.68E+02	N/A
Sulfuric Acid	1.81E-01	N/A	1.86E-02	1.68E+00	1.03E-03	-1.35E+02	N/A	5.66E-03	-1.09E+01	N/A
Iron	8.68E+01	N/A	5.13E-02	1.14E-02	2.85E-03	-7.30E+02	N/A	1.56E-02	-5.76E+01	N/A
Ammonia	1.01E-02	N/A	3.78E-02	1.09E+00	5.10E-03	-2.96E-01	N/A	1.15E-02	-3.42E+01	N/A
Copper	0.00E+00	N/A	0.00E+00	0.00E+00	0.00E+00	0.00E+00	N/A	0.00E+00	0.00E+00	N/A

(To be Continued)

(Continued)

	Coal Precomb.	IGCC Plants	RDF Plant	Traditional Landfill	Ash Landfill	Electricity Offset	Methanol Offset[C]	Transport[d]	(Al + Fe) Offset	Total
Cadmium	2.60E-03	N/A	3.51E-03	5.86E-05	1.95E-04	-5.22E-01	N/A	1.07E-03	-4.02E-01	N/A
Arsenic	0.00E+00	N/A	0.00E+00	2.10E-05	0.00E+00	0.00E+00	N/A	0.00E+00	0.00E+00	N/A
Mercury	2.02E-07	N/A	2.64E-07	2.97E-07	1.47E-08	-4.10E-05	N/A	8.03E-08	-3.60E-04	N/A
Phosphate	8.68E-02	N/A	9.44E-03	7.95E-03	5.25E-04	-6.76E+01	N/A	2.87E-03	-3.79E+00	N/A
Selenium	0.00E+00	N/A	0.00E+00	6.79E-06	0.00E+00	0.00E+00	N/A	0.00E+00	0.00E+00	N/A
Chromium	2.60E-03	N/A	3.51E-03	1.13E-04	1.95E-04	-5.22E-01	N/A	1.07E-03	-4.02E-01	N/A
Lead	4.12E-06	N/A	4.05E-05	9.76E-06	2.25E-06	-3.86E-05	N/A	1.23E-05	-2.08E-03	N/A
Zinc	9.40E-04	N/A	1.75E-03	2.58E-05	9.75E-05	-1.79E-01	N/A	5.33E-04	-1.45E-01	N/A
Solid Waste	2.49E+05	N/A	3.59E+02	1.83E+02	2.79E+01	-2.60E+06	-2.91E+04	1.09E+02	-9.53E+05	-3.33E+06

[a] The term "N/A" means that data for that item are not available.

[b] Based on material flows given in Table 3-7.

[c] This is offset from net energy production from IGCC based polygeneration system after subtracting the RDF plant demand.

[d] LCI associated with the transportation from RDF plants to remanufacturing plants

e The GHE are given as carbon equivalents, calculated using equation: GHE = 12/44*(fossil CO_2 + 21*methane)/2000

Table 3-9 LCI Results of the MSW/Coal Blends Gasification System (Base Case / Landfill with Energy Recovery)[a,b] (Lbs/day)

	Coal Precomb.	IGCC Plant	RDF Plant	Traditional Landfill	Ash Landfill	Electricity Offset	Methanol Offset[C]	Transport[d]	(Al + Fe) Offset	Total
Airborne Releases										
Carbon monoxide	1.30E+02	3.23E+03	2.83E+02	3.90E+01	1.84E+01	-3.87E+03	-1.15E+03	1.77E+02	-1.80E+04	-1.91E+04
Nitrogen oxides	1.66E+02	5.92E+03	4.40E+02	2.32E+00	5.43E+01	-5.12E+04	-5.43E+02	1.79E+02	-6.30E+03	-5.13E+04
Total particulates	1.85E+03	3.60E+02	4.87E+01	-1.11E+01	4.99E+00	-1.75E+04	-8.42E+01	2.58E+01	-8.63E+03	-2.39E+04
Carbon dioxide (fossil fuel)	2.94E+04	4.81E+06	7.09E+03	-5.42E+03	3.88E+03	-1.36E+07	-2.39E+05	2.09E+04	-2.75E+06	-1.18E+07
Carbon dioxide (biomass fuel)	2.17E+02	6.46E+06	7.15E+04	3.37E+05	9.15E-01	-1.92E+03	0.00E+00	5.00E+00	0.00E+00	6.87E+06
Sulfur oxides	1.66E+02	1.43E+01	1.03E+02	-3.79E+01	9.24E+00	-9.05E+04	-5.60E+03	5.08E+01	-1.78E+04	-1.14E+05
Hydrocarbons	6.15E+01	3.12E+02	2.02E+02	1.81E+00	1.39E+01	-2.63E+03	N/A	7.21E+01	-3.21E+03	N/A
Methane	3.39E+03	N/A	1.09E+01	1.05E+03	6.88E-01	-3.00E+04	-1.35E+03	3.32E+00	-3.76E+03	-3.06E+04
Lead	1.95E-03	N/A	3.78E-04	-2.63E-04	2.10E-05	-5.84E-01	N/A	1.15E-04	4.04E-01	N/A
Ammonia	6.29E-02	N/A	1.08E-01	-3.03E-03	6.00E-03	-1.14E+01	N/A	3.28E-02	-6.45E+00	N/A
Hydrochloric acid	7.95E-01	N/A	6.75E-02	1.10E+00	4.64E-03	-1.10E+03	N/A	2.05E-02	-3.87E+02	N/A
GHE[e] (Tons/day)	1.37E+01	N/A	9.98E-01	2.26E+00	5.31E-01	-1.94E+03	-3.65E+01	2.86E+00	-3.86E+02	-2.35E+03
Waterborne Releases										
Dissolved Solids	5.93E+01	N/A	9.39E+01	-4.08E+00	5.22E+00	-1.15E+04	N/A	2.85E+01	-9.47E+03	N/A
Suspended solids	1.02E+03	N/A	2.13E+00	-4.35E+00	2.09E-01	-9.56E+03	-5.14E+01	6.48E-01	-1.03E+03	-9.63E+03
Bio-chemical Oxygen Demand	8.68E-02	N/A	3.51E-01	3.41E+01	3.98E-02	-1.14E+01	-7.47E+00	1.07E-01	-1.41E+01	1.69E+00
Chemical Oxygen Demand	9.40E-01	N/A	2.35E+00	9.47E+01	2.75E+01	-1.62E+02	-5.31E+01	7.13E-01	-2.13E+02	-3.02E+02
Oil	1.08E+00	N/A	2.19E+00	2.07E+01	5.50E+01	-2.02E+02	N/A	6.64E-01	-1.68E+02	N/A
Sulfuric Acid	1.81E-01	N/A	1.86E-02	1.62E+00	1.03E-03	-1.35E+02	N/A	5.66E-03	-1.09E+01	N/A
Iron	8.68E+01	N/A	5.13E-02	-3.36E-01	2.85E-03	-7.30E+02	N/A	1.56E-02	-5.76E+01	N/A
Ammonia	1.01E-02	N/A	3.78E-02	1.09E+00	5.10E-03	-2.96E-01	N/A	1.15E-02	-3.42E+01	N/A
Copper	0.00E+00	N/A	0.00E+00	0.00E+00	0.00E+00	0.00E+00	N/A	0.00E+00	0.00E+00	N/A

(To be Continued)

(Continued)

	Coal Precomb.	IGCC Plants	RDF Plant	Traditional Landfill	Ash Landfill	Electricity Offset	Methanol Offset[C]	Transport[d]	(Al + Fe) Offset	Total
Cadmium	2.60E-03	N/A	3.51E-03	-1.90E-04	1.95E-04	-5.22E-01	N/A	1.07E-03	-4.02E-01	N/A
Arsenic	0.00E+00	N/A	0.00E+00	2.10E-05	0.00E+00	0.00E+00	N/A	0.00E+00	0.00E+00	N/A
Mercury	2.02E-07	N/A	2.64E-07	2.78E-07	1.47E-08	-4.10E-05	N/A	8.03E-08	-3.60E-04	N/A
Phosphate	8.68E-02	N/A	9.44E-03	-2.42E-02	5.25E-04	-6.76E+01	N/A	2.87E-03	-3.79E+00	N/A
Selenium	0.00E+00	N/A	0.00E+00	6.79E-06	0.00E+00	0.00E+00	N/A	0.00E+00	0.00E+00	N/A
Chromium	2.60E-03	N/A	3.51E-03	-1.35E-04	1.95E-04	-5.22E-01	N/A	1.07E-03	-4.02E-01	N/A
Lead	4.12E-06	N/A	4.05E-05	9.75E-06	2.25E-06	-3.86E-05	N/A	1.23E-05	-2.08E-03	N/A
Zinc	9.40E-04	N/A	1.75E-03	-5.96E-05	9.75E-05	-1.79E-01	N/A	5.33E-04	-1.45E-01	N/A
Solid Waste	2.49E+05	N/A	3.59E+02	-1.05E+03	2.79E+01	-2.60E+06	-2.91E+04	1.09E+02	-9.53E+05	-3.33E+06

[a] The term "N/A" means that data for that item are not available.
[b] Based on material flows given in Table 3-7.
[c] This is offset from net energy production from IGCC based polygeneration system after subtracting the RDF plant demand.
[d] LCI associated with the transportation from RDF plants to remanufacturing plants.
e The GHE are given as carbon equivalents, calculated using equation: GHE = 12/44*(fossil CO_2 + 21*methane)/2000

3.3 Sensitivity Analysis for the LCI Model

The objective of this chapter is to report the results of a sensitivity analysis on selected parameters in the overall LCI model. The effects of changing selected parameters will be evaluated based on corresponding changes of the LCI of the gasification system.

Four parameters were selected for the sensitivity analysis: 1) RDF percentage in RDF/coal blends; 2) incoming MSW composition; 3) purge gas recycle ratio from the methanol plant; and 4) saturation level of the fuel gas to the gas turbines. In all cases, the LCI of the gasification system is reported for a landfill without energy recovery.

3.3.1 Incoming MSW Compositions

There can be great variability in the composition of MSW with respect to the time and areas of waste generation. Thus, it was relevant to investigate the robustness of the overall LCI model to different MSW compositions. Three MSW compositions were selected to do the analysis: 1) The composition used by Solano, et al., 2002, which represents the national average waste composition; 2) The composition reported by the State of Minnesota which represents Minnesota statewide aggregate waste composition including both residential sector and the industrial/commercial/institutional (ICI) sector; and 3) The composition reported for Los Angeles city which represents the overall residential waste composition of Los Angeles city in 1999. Table 3-10 and Table 3-11 illustrate the comparison of the waste composition and the ultimate analysis of these three MSWs, respectively.

Table 3-10 Comparison of Three Reported Waste Compositions (wet wt %)

WASTE ITEM	MSW[a]	MN-MSW[b]	LA-MSW[c]
Leaves	5.6	1.3	6.5
Grass	9.3	1.3	6.5
Branches	3.7	0.2	3.2
Old Newsprint	6.7	4.9	8.0
Old Corr. Cardboard	2.1	7.5	3.7
Office Paper	1.3	3.7	2.1
Phone Books	0.2	0.0	0.5
Books	0.9	0.0	0.0
Old Magazines	1.7	3.0	2.5
3rd Class Mail	2.2	0.0	0.0
Paper Other	17.1	22.0	17.3
HDPE - Translucent	0.4	0.4	0.7
HDPE - Pigmented	0.5	0.2	0.7
PET	0.4	0.7	0.7
Plastic - Other	9.9	12.3	8.8
Ferrous Cans	1.5	1.1	1.7
Ferrous Metal - Other	3.2	3.5	1.4
Aluminum Cans	0.9	0.8	0.5
Aluminum - Other	0.5	0.6	0.0
Glass - Clear	3.9	1.6	2.5
Glass - Brown	1.6	0.5	1.0
Glass - Green	1.0	0.4	0.9
Food Waste	4.9	15.0	24.8
CCCN Other	0.0	0.0	0.0
Plastic - Non-Recyclable	0.0	0.0	0.0
Misc.	7.5	0.0	0.0
Glass - Non-recyclable	0.7	0.8	0.5
Misc.	12.3	18.2	5.6

a – Solano, et. al, 2002
b – Minnesota Pollution Control Agency, 2000
c – http://www.ciwmb.ca.gov/WasteChar/

Table 3-11 Comparison of Ultimate Analysis of Different MSWs

Proximate Analysis, dry wt%	**MSW**[a]	**MN-MSW**[b]	**Relative Difference**	**LA-MSW**[c]	**Relative Difference**
Moisture (wt%)	21.00	18.68	11.0%	30.59	45.7%
Fixed Carbon + Volatile Matter	71.35	77.20	8.2%	78.07	9.4%
Ash	28.65	22.80	20.4%	21.93	23.4%
Ultimate Analysis, dry wt%					
Carbon	38.32	41.41	8.1%	41.85	9.2%
Hydrogen	5.19	5.69	9.5%	5.70	9.8%
Nitrogen	0.60	0.60	0.6%	0.79	32.2%
Chlorine	0.88	1.01	14.8%	0.95	7.6%
Sulfur	0.39	0.38	1.4%	0.28	27.8%
Oxygen	25.97	28.10	8.2%	28.49	9.7%
Ash	28.65	22.80	20.4%	21.93	23.4%
HHV – Dry Basis (BTU/lb)	4,693	4,769	1.6%	5,505	17.3%

a – Solano, et. al, 2002
b – Minnesota Pollution Control Agency, 2000
c – http://www.ciwmb.ca.gov/WasteChar/

The three MSWs vary in the ultimate analysis. However, in the context of gasification, MSW is first processed to produce RDF, which is fed as a feedstock to the IGCC based polygeneration system. Therefore, the appropriate comparison of the RDF produced by the MSW was compared. Table 3-12 presents the comparison of the ultimate analysis of these three RDFs.

Table 3-12 Comparison of Ultimate Analysis of Different RDFs

Proximate Analysis, dry wt%	**RDF**	**MN-RDF**	**Relative Difference**	**LA-RDF**	**Relative Difference**
Moisture (wt%)	14.42	9.67	33.0%	14.83	2.8%
Fixed Carbon + Volatile Matter	86.54	87.69	1.3%	89.29	3.2%
Ash	13.46	12.31	8.6%	10.71	20.4%
Ultimate Analysis, dry wt%					
Carbon	46.96	47.42	1.0%	48.36	3.0%
Hydrogen	6.39	6.51	1.8%	6.59	3.0%
Nitrogen	0.58	0.52	9.8%	0.57	1.1%
Chlorine	1.19	1.22	2.5%	1.18	0.2%
Sulfur	0.41	0.38	6.3%	0.31	23.1%
Oxygen	31.01	31.64	2.0%	32.26	4.0%
Ash	13.46	12.31	8.6%	10.71	20.4%
HHV – Dry Basis (BTU/lb)	7,791	7,768	0.3%	8,514	9.3%

Based on Table 3-11 and Table 3-12, a conclusion can be drawn that the RDF plant has an equalization effect on the MSW compositions, that is, the variability in MSW compositions will be greatly eliminated by processing in the RDF plant. Therefore, due to this equalization effect, the three MSWs were not used to conduct the sensitivity analysis.

To offset the equalization effect of the RDF plant, a methodology was developed to simulate different MSW compositions by adjusting the paper to plastics ratio in the waste stream. The basis for this idea is that the two major components of the RDF are paper and plastics. Thus, the composition of the RDF will change in response to a change in the paper to plastic ratio in MSW.

To adjust the paper to plastic ratio, the proximate analysis and the ultimate analysis of the paper and plastic were calculated based on data in Table 3-13.

Table 3-13 Proximate Analysis and Ultimate Analysis of Each Component of Paper and Plastics*

Waste Item	Weight Fraction (%)	Proximate Analysis (%, By wet basis)			Ultimate analysis (%, By dry basis)							H_2O
		Ash	VM	FC	C	H	O	N	Cl	S	Ash	
Paper												
Old Newsprint	20.8	5.2	83.8	11.1	43.8	5.9	44.4	0.3	0.1	0.2	5.2	23.2
Old Corr. Cardboard	6.5	2.2	85.8	12.1	46	6.4	44.8	0.3	0.1	0.2	2.2	21.2
Office Paper	4.0	9.1	83.4	7.5	38.1	5.6	46.9	0.2	0.1	0.1	9.1	9.3
Old Magazines	5.3	20.4	71.8	7.9	35	5	39.4	0.1	0.1	0.1	20.4	8.6
Paper Other	63.4	6.3	83.5	10.1	43	6	43.8	0.4	0.2	0.2	6.5	24
Plastic												
HDPE	8.0	2.4	97.4	0.2	81.6	13.6	1.9	0.1	0.2	0.2	2.4	7
PET	3.6	1.3	95	3.6	68.5	8	21.9	0.2	0.1	0.1	1.3	3.6
Plastic - Other	88.4	5.3	93	1.3	76.3	11.5	4.4	0.3	2.4	0.2	4.9	13.3

* Liu, et al., 1999

The MSW composition presented by Solano et al (2002) in Table 3-10 was adjusted to generate three waste compositions with varying paper to plastic ratio. Three waste composition were generated: decreasing the paper component by 20%, 20%, and 20%, while increasing the plastic component by 150%, 100%, and 50%, respectively. In each case, the LCIs were calculated on one ton MSW basis. After adjusting the paper and plastic composition, the waste composition was renormalized to 100%. The resulting waste streams are given in Table 3-14. The proximate analysis and the ultimate analysis of the RDFs produced from the three MSWs are summarized in Table 3-15.

Table 3-14 Comparison of Three Waste Compositions Produced by Adjusting Paper to Plastic Ratio (wet wt %)

WASTE ITEM	**$MSW_{0.2\sim1.5}$** [a]	**$MSW_{0.2\sim1.0}$** [a]	**$MSW_{0.2\sim0.5}$** [a]
Leaves	5.0	5.3	5.7
Grass	8.4	8.9	9.4
Branches	3.3	3.5	3.7
Old Newsprint	4.8	5.1	5.4
Old Corr. Cardboard	1.5	1.6	1.7
Office Paper	0.9	1.0	1.0
Phone Books	0.1	0.2	0.2
Books	0.6	0.7	0.7
Old Magazines	1.2	1.3	1.4
3rd Class Mail	1.6	1.7	1.8
Paper Other	12.3	13.0	13.8
CCCR Other	0.0	0.0	0.0
Mixed Paper	0.0	0.0	0.0
HDPE - Translucent	0.9	0.8	0.6
HDPE - Pigmented	1.1	1.0	0.8
PET	0.9	0.8	0.6
Plastic - Other	22.3	18.8	15.0
Mixed Plastic	0.0	0.0	0.0
CCNR Other	0.0	0.0	0.0
Ferrous Cans	1.5	1.5	1.5
Ferrous Metal - Other	3.2	3.2	3.2
Aluminum Cans	0.9	0.9	0.9
Aluminum - Other	0.5	0.5	0.5
Glass - Clear	3.5	3.7	3.9
Glass - Brown	1.4	1.5	1.6
Glass - Green	0.9	1.0	1.0
Mixed Glass	0.0	0.0	0.0
CNNR Other	0.0	0.0	0.0
Paper - Non-recyclable	0.0	0.0	0.0
Food Waste	4.4	4.7	4.9
CCCN Other	0.0	0.0	0.0
Plastic - Non-Recyclable	0.0	0.0	0.0
Misc.	6.8	7.1	7.6
CCNN Other	0.0	0.0	0.0
Ferrous - Non-recyclable	0.0	0.0	0.0
Al - Non-recyclable	0.0	0.0	0.0
Glass - Non-recyclable	0.6	0.7	0.7
Misc.	11.1	11.7	12.4
CNNN Other	0.0	0.0	0.0

a The first subscript represents the fraction decrease in paper and the second subscript represents the fraction increase in plastics.

Table 3-15 Proximate Analysis and Ultimate Analysis of the RDFs Produced from MSW with Varying Paper to Plastic Ratio

Proximate Analysis, dry wt%	$RDF_{0.2\sim1.5}$[a]	$RDF_{0.2\sim1.0}$[a]	$RDF_{0.2\sim0.5}$[a]
Moisture (wt%)	12.29	13.16	14.18
Fixed Carbon + Volatile Matter	90.34	89.85	89.27
Ash	9.66	10.15	10.73
Ultimate Analysis, dry wt%			
Carbon	56.31	54.40	52.09
Hydrogen	8.18	7.86	7.47
Nitrogen	0.38	0.40	0.41
Chlorine	1.08	0.98	0.86
Sulfur	0.31	0.33	0.34
Oxygen	24.08	25.90	28.09
Ash	9.66	10.15	10.73
HHV – Dry Basis (BTU/lb)	11,385[b]	10,770[b]	10,025[b]

a The first subscript represents the fraction decrease in paper and the second subscript represents the fraction increase in plastics.
b HHV calculated from the ultimate analysis using the Dulong correlation

For the three MSWs with different paper to plastic ratios, the efficiency of the IGCC based polygeneration system, the material flows and the energy flows are summarized in Table 3-16. With the increase of the paper to plastic ratio, the efficiency of the IGCC based polygeneration system decreases because paper has lower carbon and hydrogen contents than plastics. With the decrease in efficiency, given one ton MSW, less electricity and methanol will be produced. The ferrous and aluminum production per ton MSW will remain constant due to the constant RDF plant design parameters and the constant ferrous and aluminum associated MSW composition.

Table 3-16 Comparison Results of Gasification System Performance for Three MSWs

	IGCC					RDF		
	Efficiency (%, HHV basis)	**Electricity** (MWh/ton MSW)	**Methanol** (ton/ton MSW)	**Slag**	**Coal Usage**	**Fe** (ton/ton MSW)	**Al**	**Residual**
$MSW_{0.2\sim1.5}$[a]	39.3	1.47	0.016	0.070	0.217	0.042	0.013	0.359
$MSW_{0.2\sim1.0}$[a]	39.0	1.26	0.014	0.067	0.200	0.042	0.013	0.373
$MSW_{0.2\sim0.5}$[a]	38.8	1.07	0.012	0.065	0.185	0.042	0.013	0.390

a The first subscript represents the fraction decrease in paper and the second subscript represents the fraction increase in plastics.

The LCIs of the gasification system when firing the three MSW generated RDF/coal blends are summarized in Table 3-17 and the detailed LCI is given in Table D.1.1 - Table D.1.3. As illustrated in Table 3-17, all the emissions increase with the increase of paper to plastics ratio and this is consistent with the decrease in the overall IGCC system efficiency, as presented in Table 3-16. Because the offset emissions associated with electricity and methanol production have significant contribution to these emissions, when increasing the paper to plastic ratio, the efficiency decreases and therefore the electricity and methanol production per ton MSW decrease, which results in the increase in emissions.

Table 3-17 LCI Results of Gasification System Firing Four Different RDF/Coal Blends (lb/ton MSW)

	$RDF_{0.2\sim1.5}$[a]	$RDF_{0.2\sim1.0}$[a]	$RDF_{0.2\sim0.5}$[a]
Airborne Releases			
Carbon monoxide	-2.62E+00	-2.56E+00	-2.51E+00
Nitrogen oxides	-1.08E+01	-9.27E+00	-7.90E+00
Total particulates	-4.57E+00	-4.04E+00	-3.55E+00
Carbon dioxide (fossil)	-2.13E+03	-1.94E+03	-1.75E+03
Carbon dioxide (biomass)	1.07E+03	9.94E+02	9.22E+02
Sulfur oxides	-2.32E+01	-2.01E+01	-1.73E+01
Methane	-6.79E+00	-5.83E+00	-4.94E+00
GHE (Ton/lb methanol)	-4.78E-01	-4.15E-01	-3.57E-01
Waterborne Releases			
Suspended solids	-2.08E+00	-1.78E+00	-1.50E+00
BOD	-5.77E-03	-5.19E-03	-4.65E-03
COD	-6.89E-02	-6.23E-02	-5.61E-02
Solid Waste	-6.57E+02	-5.76E+02	-5.01E+02

a The first subscript represents the fraction decrease in paper and the second subscript represents the fraction increase in plastics.

3.3.2 RDF Percentage in the MSW/Coal Blends

Low-BTU wastes may be blended with high-BTU content supplementary fuels such as coal or petroleum coke to maintain the desired gasification temperature in the reactor (Orr, et al., 2000). In this study, the feedstock to the IGCC based polygeneration system is the RDF/coal blend, where RDF has a relatively low BTU value. The RDF percentage in the RDF/coal blends can be changed to meet the requirement for the desired fuel property. Therefore, it is useful to evaluate the effect of the RDF percentage in the RDF/coal blends on the LCI results of the gasification system. The range of the RDF percentage in the RDF/coal blends analyzed was from 25% to 75%. Table 3-18 presents the ultimate analysis, proximate analysis and the heating value of the fuels with different fractions of RDF.

Table 3-18 Proximate Analysis and Ultimate Analysis of Different RDF/Coal Blends for Different RDF Fractions

	RDF Percentage		
	25%	**50%**	**75%**
Proximate Analysis, dry wt%			
Moisture (wt%)	8.11	10.21	12.32
Fixed Carbon + Volatile Matter	87.48	87.18	86.87
Ash	12.52	12.82	13.13
Ultimate Analysis, dry wt%			
Carbon	67.10	60.70	53.99
Hydrogen	5.28	5.63	6.00
Nitrogen	1.19	1.00	0.79
Chlorine	0.28	0.57	0.87
Sulfur	2.70	1.97	1.21
Oxygen	10.94	17.32	24.00
Ash	12.52	12.82	13.13
HHV – Dry Basis (BTU/lb)	12,261*	11029*	9,738*

* HHV calculated from the ultimate analysis using the Dulong correlation

For the three fuels with different RDF fractions, the efficiency of the IGCC based polygeneration system, the material flows and the energy flows are summarized in Table 3-19. The efficiency of the IGCC based polygeneration system decreases as the RDF percentage increases because the carbon and hydrogen content of the fuel decrease. The electricity and methanol production per ton MSW decrease with the efficiency decrease. The ferrous, aluminum, and residual production per ton MSW remain constant due to the constant RDF plant design parameters and the constant ferrous, aluminum, and residual associated MSW composition. Coal usage per ton MSW decreases with the increase in the RDF percentage because less coal will contained in the RDF/coal blends.

Table 3-19 Comparison Results of Gasification System Performance for Three Fuels with Different RDF Percentage in the RDF/Coal Blends

	IGCC					RDF		
	Efficiency	**Electricity**	**Methanol**	**Slag**	**Coal Usage**	**Fe**	**Al**	**Residual**
	(%, HHV basis)	(MWh/ton MSW)	(ton/ton MSW)			(ton/ton MSW)		
25%	40.0	0.93	0.0101	0.082	0.558	0.042	0.013	0.387
50%	39.2	0.91	0.0100	0.081	0.279	0.042	0.013	0.387
75%	38.5	0.89	0.0098	0.095	0.186	0.042	0.013	0.387

The LCIs of the gasification system when firing the RDF/coal blends with different RDF percentage were summarized in Table 3-20 and the detailed LCI is given in Table D.2.1 – Table D.2.3. As illustrated in Table 3-20, the pollutants can be categorized into two groups. Group A includes NO_x, fossil CO_2, SO_x, GHE, BOD, and COD. Emissions of group A increase with the increase of RDF percentage in RDF/coal blends. For pollutants in group A, the largest contributor to their emissions is the offset emissions of electricity. As illustrated in Table 3-19, when increasing the RDF percentage in the RDF/coal blends, the efficiency of the IGCC based polygeneration system decreases. Therefore, less electricity per ton MSW is produced and more emissions are produced for pollutants in group A. Group B includes CO, total PM, methane, biomass CO_2, suspended solid, and solid waste emissions. Emissions of group B decrease with the increase of RDF percentage. In group B, for total PM, methane, and suspended solid, the coal precombustion associated emissions have a large contribution to their emissions. With the increase of the RDF percentage, the coal usage per ton MSW decreases, which results in the decrease of the coal precombustion associated emissions. For CO and biomass CO_2, the emissions from the IGCC based polygeneration system have a large contribution to their emissions. When increasing the RDF percentage, the MSW demand increases, which leads to the decrease of the CO and biomass CO_2 emissions per ton MSW processed.

Table 3-20 LCI Results of Gasification System Firing the RDF/Coal Blends with Different RDF Percentage (lb/ton MSW)

	RDF Percentage		
	25%	**50%**	**75%**
Airborne Releases			
Carbon monoxide	-6.89E+00	-6.74E+00	-6.59E+00
Nitrogen oxides	-2.43E+00	-2.45E+00	-2.45E+00
Total particulates	-2.72E+00	-3.01E+00	-3.07E+00
Carbon dioxide (fossil)	-1.66E+03	-1.62E+03	-1.59E+03
Carbon dioxide (biomass)	1.03E+03	1.01E+03	9.95E+02
Sulfur oxides	-1.52E+01	-1.49E+01	-1.46E+01
Methane	-3.29E+00	-3.82E+00	-3.94E+00
GHE (Ton/Lb Methanol)	-3.12E-01	-3.07E-01	-3.02E-01
Waterborne Releases			
Suspended solids	-1.04E+00	-1.20E+00	-1.24E+00
BOD	1.27E-04	1.71E-04	2.18E-04
COD	-4.04E-02	-3.99E-02	-3.88E-02
Solid Waste	-3.83E+02	-4.21E+02	-4.28E+02

3.3.3 Purge Gas Recycle Ratio from the Methanol Plant

The LPMEOH model is an important component in the gasification system that affects power generation, steam demand, and system efficiency. It is important to analyze the effect of its performance on the LCI of the entire system. The purge gas recycle ratio was selected for study and its range was from 0 to 3. The recycle ratio is 0 when there is no purge gas recycled and a typical value of the recycle ratio is 3.

For different purge gas recycle ratios, the efficiency of the IGCC based polygeneration system, the material flows and the energy flows are summarized in Table 3-21. With the increase of the purge gas recycle ratio, the efficiency of the IGCC based polygeneration system increases because the recycled syngas has a higher H_2/CO ratio than the fresh syngas, which will increase the methanol production efficiency. The electricity and methanol production per ton MSW will increase with the increase in efficiency. The ferrous, aluminum, and residual production per ton MSW remain constant due to the constant RDF plant design parameters and the constant ferrous, aluminum, and residual associated MSW composition.

Table 3-21 Comparison of Results of Gasification System Performance with Different Purge Gas Recycle Ratio from the Methanol Plant

	IGCC					RDF		
	Efficiency (%, HHV basis)	**Electricity** (MWh/ton MSW)	**Methanol** (ton/ton MSW)	**Slag** (ton/ton MSW)	**Coal Usage** (ton/ton MSW)	**Fe** (ton/ton MSW)	**Al** (ton/ton MSW)	**Residual** (ton/ton MSW)
0.0	37.8	0.870	0.0098	0.095	0.186	0.042	0.013	0.387
1.0	38.3	0.883	0.0098	0.095	0.186	0.042	0.013	0.387
2.0	38.4	0.886	0.0098	0.095	0.186	0.042	0.013	0.387
3.0	38.5	0.887	0.0098	0.095	0.186	0.042	0.013	0.387

The LCI of the gasification system when firing the four MSW generated RDF/coal blends were summarized in Table 3-22 and the detailed LCI is given in Table D.3.1 – Table D.3.4. As illustrated in Table 3-22, all the emissions decrease with the increase of purge gas recycle ratio. The offset emissions of the electricity and methanol have a large contribution to the total emissions. As illustrated in Table 3-21, the efficiency of the IGCC based polygeneration system increases with the increase of the purge gas recycle ratio. The electricity and methanol production per ton MSW increase with the increase in efficiency, which leads to the decrease of the total emissions. However, the change is not significant due to the constant offset emissions associated with aluminum and ferrous recovery which has the largest contribution to the total emissions.

Table 3-22 LCI Results of Gasification System with Different Purge Gas Recycle Ratio from the Methanol Plant (lb/ton MSW)

	Purge Gas Recycle Ratio			
	0.0	**1.0**	**2.0**	**3.0**
Airborne Releases				
Carbon monoxide	-2.44E+00	-2.45E+00	-2.45E+00	-2.45E+00
Nitrogen oxides	-6.46E+00	-6.56E+00	-6.59E+00	-6.60E+00
Total particulates	-3.02E+00	-3.06E+00	-3.07E+00	-3.07E+00
Carbon dioxide (fossil)	-1.57E+03	-1.60E+03	-1.61E+03	-1.61E+03
Carbon dioxide (biomass)	9.55E+02	9.55E+02	9.55E+02	9.55E+02
Sulfur oxides	-1.44E+01	-1.45E+01	-1.46E+01	-1.46E+01
Methane	-3.86E+00	-3.92E+00	-3.93E+00	-3.94E+00
GHE (Ton/lb methanol)	-2.96E-01	-3.00E-01	-3.01E-01	-3.01E-01
Waterborne Releases				
Suspended solids	-1.21E+00	-1.23E+00	-1.24E+00	-1.24E+00
BOD	2.48E-04	2.26E-04	2.20E-04	2.18E-04
COD	-3.84E-02	-3.87E-02	-3.88E-02	-3.88E-02
Solid Waste	-4.21E+02	-4.26E+02	-4.28E+02	-4.28E+02

3.3.4 Saturation Level of the Fuel Gas to the Gas Turbines

IGCC system model is the main body of the gasification system. It is crucial to analyze the effect of the performance of IGCC system on the LCI of the gasification system. According to Pickett (2000), the saturation level of the fuel gas to the gas turbines is one of the most important parameters that affect the overall IGCC plant performance. Therefore, this parameter was selected for the sensitivity analysis over the range from 0.35 to 0.55.

For different fuel gas saturation level, the efficiency of the IGCC based polygeneration system, the material flows and the energy flows are summarized in Table 3-23. With the increase of the saturation level, the efficiency of the IGCC based polygeneration system decreases. When increasing the saturation level, more power is produced from the gas turbine, however, the fuel gas saturation area will demand more water from the steam cycle which causes a decrease in power production in the steam turbine. The net power production from IGCC system increases but the efficiency will decrease (Pickett, 2000). Therefore, the electricity and methanol production per ton MSW will decrease with the decrease of the efficiency. The ferrous, aluminum, and residual production per ton MSW will keep constant due to the constant RDF plant design parameters and the constant ferrous, aluminum, and residual associated MSW composition.

Table 3-23 Comparison Results of Gasification System Performance with Different Saturation Level of Fuel Gas to Gas Turbine

	IGCC					RDF		
	Efficiency (%, HHV basis)	**Electricity** (MWh/ton MSW)	**Methanol** (ton/ton MSW)	**Slag**	**Coal Usage**	**Fe** (ton/ton MSW)	**Al**	**Residual**
0.35	37.8	0.890	0.0100	0.095	0.186	0.042	0.013	0.387
0.45	38.3	0.888	0.0098	0.095	0.186	0.042	0.013	0.387
0.55	38.4	0.883	0.0096	0.095	0.186	0.042	0.013	0.387

The LCI of the gasification system when firing the four MSW generated RDF/coal blends were summarized in Table 3-24 and the detailed LCI is given in Table D.4.1 – Table D.4.3. As illustrated in Table 3-24, the pollutants can be categorized into two groups. Group A includes NO_x, total PM, fossil CO_2, SO_x, methane, GHE, suspended solids, BOD, COD, and solid waste emissions. Emissions of group A increase with the increase of the fuel gas saturation level. For pollutants in group A, the offset emissions of the electricity and methanol have large contribution to their emissions. As illustrated in Table 3-23, the efficiency of the IGCC based polygeneration system decreases with the increase of the fuel gas saturation level. Therefore, when increasing the fuel gas saturation level, the electricity and methanol production per ton MSW will decrease, which leads to the increase of the emissions of group A. Group B includes CO and biomass CO_2. Emissions of group B decrease with the increase of the fuel gas saturation level.. For pollutants in group B, the largest contributor to their emissions is the emissions from the IGCC polygeneration system. With the increase of saturation level, the MSW demand increases, therefore, the emissions per ton MSW will decrease for pollutants in group B.

Table 3-24 LCI Results of Gasification System with Different Saturation Level of the Fuel Gas to Gas Turbines (lb/ ton MSW)

	Saturation Level of the Fuel Gas		
	0.35	**0.45**	**0.55**
Airborne Releases			
Carbon monoxide	-2.46E+00	-2.47E+00	-2.47E+00
Nitrogen oxides	-6.63E+00	-6.63E+00	-6.60E+00
Total particulates	-3.07E+00	-3.07E+00	-3.06E+00
Carbon dioxide (fossil)	-1.62E+03	-1.62E+03	-1.62E+03
Carbon dioxide (biomass)	9.54E+02	9.35E+02	9.18E+02
Sulfur oxides	-1.47E+01	-1.46E+01	-1.45E+01
Methane	-3.95E+00	-3.94E+00	-3.92E+00
GHE (Ton/lb methanol)	-3.02E-01	-3.02E-01	-3.00E-01
Waterborne Releases			
Suspended solids	-1.24E+00	-1.24E+00	-1.23E+00
BOD	1.91E-04	2.15E-04	2.42E-04
COD	-3.90E-02	-3.88E-02	-3.86E-02
Solid Waste	-4.29E+02	-4.28E+02	-4.26E+02

4.0 COMPARISON OF MSW TREATMENT BY GASIFICATION AND CONVENTIONAL MASS BURN WASTER TO ENERGY

The objective of this chapter is to present the results of a comparison of MSW treatment by gasification and a conventional mass burn WTE facility. The comparison will be made in three different scenarios, as defined in Chapter 3. In all three scenarios, the input assumptions and the RDF/coal blends for the gasification system are the same, as presented in Table 3-3 and Table 3-4. In each scenario, the LCI associated with the treatment of MSW by both gasification and WTE will be presented and assessments will be made based on the comparison results. The comparison is made based on three scenarios:

Scenario A: Production of 10,000 lb/hr of methanol;
Scenario B: Production of 20,000 lb/hr of methanol;
Scenario C: Production of 40,000 lb/hr of methanol.

As explained in Chapter 3, as more methanol is produced, less electrical energy is exported.

4.1 Comparison Study on Scenario A

In scenario A, the methanol plant size is 10,000 lb/hr. The MSW residual is disposed either in landfills with no energy recovery or in landfills with energy recovery. The material and energy flows of the gasification system are the same as the ones in the base case, as presented in Table 3-6. Also, the LCI results of the gasification system are the same as the ones in the base case, as presented in Table 3-7 (landfill with no energy recovery) and Table 3-8 (landfill with energy recovery).

4.1.1 LCI Results of the WTE system

To produce 10,000 lb/hr of methanol, 7776 ton MSW/day were required. Therefore, the same quantity is fed into the WTE system. The LCI of the WTE system is summarized in Table 4-1.

Table 4-1 LCI Results of the WTE System in Scenario A (Lbs/day)[a]

Atmospheric Emissions	Direct Emissions	Lime Associated Emissions	Avoided Emissions from Electricity	Transport[b]	Avoided Emissions Fe & Al Recovered	Ash Disposal	Total
Carbon Monoxide	7.92E+03	3.84E+01	-2.45E+03	1.75E+02	-1.80E+04	5.63E+01	-1.23E+04
Nitrogen Oxides	1.27E+04	1.43E+02	-3.25E+04	1.78E+02	-6.30E+03	1.66E+02	-2.56E+04
Particulates (Total)	1.52E+03	2.96E+02	-1.11E+04	2.56E+01	-8.63E+03	1.52E+01	-1.78E+04
CO2 (non biomass)	4.75E+06	1.40E+05	-8.64E+06	2.07E+04	-2.75E+06	1.19E+04	-6.46E+06
CO2 (biomass)	1.03E+07	5.21E+00	-1.22E+03	4.96E+00	0.00E+00	2.80E+00	1.03E+07
Sulfur Oxides	5.43E+03	4.00E+02	-5.74E+04	5.04E+01	-1.78E+04	2.82E+01	-6.93E+04
Hydrocarbons (non CH4)	0.00E+00	3.24E+01	-1.67E+03	7.15E+01	-3.21E+03	4.25E+01	-4.73E+03
Methane	2.33E+01	1.04E+02	-1.90E+04	3.29E+00	-3.76E+03	2.10E+00	-2.26E+04
Lead	N/A	N/A	N/A	1.14E-04	4.04E-01	6.42E-05	N/A
Ammonia	0.00E+00	2.19E-02	-7.25E+00	3.25E-02	-6.45E+00	1.83E-02	-1.36E+01
Hydrochloric acid	2.58E+03	N/A	N/A	2.03E-02	-3.87E+02	1.42E-02	N/A
GHE[C] (tons/day)	6.48E+02	1.94E+01	-1.23E+03	2.83E+00	-3.86E+02	1.62E+00	-9.46E+02
Waterborne Emissions							
Dissolved Solids	0.00E+00	1.20E+02	-7.31E+03	2.83E+01	-9.47E+03	1.60E+01	-1.66E+04
Suspended Solids	0.00E+00	4.71E+00	-6.06E+03	6.43E-01	-1.03E+03	6.44E-01	-7.09E+03
BOD	0.00E+00	1.28E-01	-7.22E+00	1.06E-01	-1.41E+01	1.22E-01	-2.10E+01
COD	0.00E+00	1.75E+00	-1.02E+02	7.08E-01	-2.13E+02	8.41E+01	-2.29E+02
Oil	0.00E+00	2.13E+00	-1.28E+02	6.59E-01	-1.68E+02	1.68E+02	-1.25E+02
Sulfuric Acid	0.00E+00	4.26E-01	-8.58E+01	5.61E-03	-1.09E+01	3.15E-03	-9.63E+01
Iron	0.00E+00	2.31E+00	-4.63E+02	1.55E-02	-5.76E+01	1.35E-01	-5.18E+02
Ammonia	0.00E+00	6.45E-03	-1.87E-01	1.14E-02	-3.42E+01	2.88E-01	-3.41E+01
Copper	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.19E-04	5.19E-04
Cadmium	0.00E+00	5.66E-03	-3.31E-01	1.06E-03	-4.02E-01	6.48E-04	-7.26E-01
Arsenic	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.18E-02	1.18E-02
Mercury	0.00E+00	4.35E-07	-2.60E-05	7.97E-08	-3.60E-04	4.49E-08	-3.86E-04
Phosphate	0.00E+00	2.13E-01	-4.29E+01	2.85E-03	-3.79E+00	2.42E-03	-4.64E+01
Selenium	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.74E-03	3.74E-03
Chromium	0.00E+00	5.45E-03	-3.31E-01	1.06E-03	-4.02E-01	6.61E-04	-7.26E-01
Lead	0.00E+00	1.68E-06	-2.45E-05	1.22E-05	-2.08E-03	5.39E-04	-1.55E-03
Zinc	0.00E+00	1.87E-03	-1.14E-01	5.29E-04	-1.45E-01	1.32E-03	-2.55E-01
Solid Waste							
Solid Waste	0.00E+00	9.05E+03	-1.65E+06	1.08E+02	-9.53E+05	8.52E+01	-2.59E+06

[a] Emissions are for a WTE facility processing 7776 Tons MSW/day of the composition specified in Table 3-2. Where emission data were not available for a process, no total emission is reported.

[b] LCI associated with the transportation of recyclables from WTE plants to remanufacturing plants.

c The GHE are given as carbon equivalents, calculated by equation: GHE = 12/44*(fossil CO_2 + 21*methane)/2000

One limitation to the WTE system being studied is that for this system, a curbside recycling program where a portion of aluminum will be recycled is not included. Therefore, no aluminum is recovered in the WTE system. To make the comparison of the gasification system and the WTE system reasonable, one assumption was made that the aluminum recover rate for the WTE system is the same as the rate for the gasification system, that is, given same MSW feed rate, the aluminum recovered in these two systems are the same. As illustrated in Table 4-1, this assumption is important to the comparison results between these two systems because the offset emissions of the aluminum have considerable contribution to the total emissions of the WTE system.

In the WTE system, for the atmospheric emissions, waterborne and solid emissions, the avoided emissions of electricity and ferrous & aluminum make the largest contribution, which results in the negative value of the emissions for most pollutants. Emissions associated with lime production and the ash landfill were generally negligible.

4.1.2 Comparison of Gasification and WTE Results

The comparison results of the gasification system (LF with/without energy recovery) and the WTE system are summarized in Table 4-2.

For atmospheric, waterborne, and solid emissions, the gasification system generates fewer emissions than WTE system. There are several explanations for this:

First, the offset emissions due to the electricity, methanol, ferrous, and aluminum recovered from the gasification system are larger than the offset emissions due to the electricity, ferrous, and aluminum recovered from the WTE system. With the same MSW feed rate and MSW composition, the ferrous (329 ton/day) and the aluminum (98 ton/day) recovered from these two systems and the corresponding offsets are the same. However, the gasification system produces more electricity (6902 MWh/day) than the WTE system (4127 MWh/day). In addition, the gasification system produces 76 ton methanol/day and sets an offset credit for this amount of methanol. Therefore, the total avoided emissions of the gasification system are greater than that of the WTE system.

There are considerable amounts of atmospheric direct emissions from the WTE system, which are higher than the direct emissions from the gasification system (including direct emissions of coal precombustion, IGCC plants, and RDF plants).

One area where the gasification system does generate more emissions than the WTE system is BOD. The reason is that there is high BOD emission produced by the disposal of MSW residuals in the traditional landfill. In the WTE system, only minimal degradable waste is sent to a landfill and there are no BOD emissions.

If the LFG is recovered traditional landfill is converted to energy, then a little less emissions will be produced when compared to the system that include a landfill without energy recovery. LFG energy recovery will improve the environmental performance of gasification system, but it does not have very big effect on the comparison results with WTE system. This is partly due to largest contributor to the total emissions of most pollutants is the offset emissions associated with the electricity, aluminum and ferrous, instead of the direction emissions from the landfill. Another reason is due to the fact that paper is the largest biodegradable component of MSW and paper is in the RDF used for gasification, and not in the residual stream.

The emissions for the gasification system are overestimated because the offset emissions of the sulfur are not included due to lack of data. Therefore, the real environmental performance of the gasification system would be better than what is presented in Table 4-2 considering sulfur production.

For ammonia production, with current data no estimate of its effect on the gasification system can be made because there are direct emissions associated with the process, as well as avoided emissions for the ammonia production. However, the gasification system model can be extended to include the ammonia process model and to make the estimate of the effect of ammonia production.

As presented in Table 4-2, among atmospheric and waterborne emissions, the correlation numbers for most pollutants are between 1.5 and 2. Therefore, for these pollutant species, the gasification system is preferred, with the exception of BOD. The largest contributor to the solid waste emissions is the electricity offset. The gasification system produces about 1.5 times more electricity than the WTE system, which leads to less solid waste emissions from the gasification system.

Table 4-2 Comparison Results between Gasification System and WTE System for Scenario A (Lbs/day)

Atmospheric Emissions	WTE	Gasification[a]	Correlation with WTE[C]	Gasification[b]	Correlation with WTE[C]
Carbon Monoxide	-1.23E+04	-1.91E+04	+1.6	-1.91E+04	+1.6
Nitrogen Oxides	-2.56E+04	-5.13E+04	+2.0	-5.13E+04	+2.0
Particulates (Total)	-1.78E+04	-2.39E+04	+1.3	-2.39E+04	+1.3
CO_2 (non biomass)	-6.46E+06	-1.18E+07	+1.8	-1.17E+07	+1.8
CO_2 (biomass)	1.03E+07	6.87E+06	+1.5	6.65E+06	+1.5
Sulfur Oxides	-6.93E+04	-1.14E+05	+1.6	-1.14E+05	+1.6
Hydrocarbons (non CH_4)	-4.73E+03	N/A	N/A	N/A	N/A
Methane	-2.26E+04	-3.06E+04	+1.4	-3.06E+04	+1.4
Lead	N/A	N/A	N/A	N/A	N/A
Ammonia	-1.36E+01	N/A	N/A	N/A	N/A
Hydrochloric acid	N/A	N/A	N/A	N/A	N/A
GHE[d] (Tons/day)	-9.46E+02	-2.35E+03	+2.5	-2.34E+03	+2.5
Waterborne Emissions					
Dissolved Solids	-1.66E+04	N/A	N/A	N/A	N/A
Suspended Solids	-7.09E+03	-9.63E+03	+1.4	-9.62E+03	+1.4
BOD	-2.10E+01	1.69E+00	-13.4	1.69E+00	-13.4
COD	-2.29E+02	-3.02E+02	+1.3	-3.02E+02	+1.3
Oil	-1.25E+02	N/A	N/A	N/A	N/A
Sulfuric Acid	-9.63E+01	N/A	N/A	N/A	N/A
Iron	-5.18E+02	N/A	N/A	N/A	N/A
Ammonia	-3.41E+01	N/A	N/A	N/A	N/A
Copper	5.19E-04	N/A	N/A	N/A	N/A
Cadmium	-7.26E-01	N/A	N/A	N/A	N/A
Arsenic	1.18E-02	N/A	N/A	N/A	N/A
Mercury	-3.86E-04	N/A	N/A	N/A	N/A
Phosphate	-4.64E+01	N/A	N/A	N/A	N/A
Selenium	3.74E-03	N/A	N/A	N/A	N/A
Chromium	-7.26E-01	N/A	N/A	N/A	N/A
Lead	-1.55E-03	N/A	N/A	N/A	N/A
Zinc	-2.55E-01	N/A	N/A	N/A	N/A
Solid Waste					
Solid Waste	-2.59E+06	-3.33E+06	+1.3	-3.33E+06	+1.3

a Landfill with energy recovery

b Landfill without energy recovery

c The correlation number is the absolute value of emission of the gasification system divided by emission of the WTE system. Positive sign represents that the gasification produces fewer emissions than the WTE system; negative sign represents that the gasification produces more emissions than the WTE system.

d The GHE are given as carbon equivalents, calculated by equation: GHE = 12/44*(fossil CO_2 + 21*methane)/2000

4.2 Comparison Study on Scenario B

In scenario B, the methanol plant size is 20,000 lb/hr. The MSW residual is disposed either in landfills with no energy recovery or in landfills with energy recovery.

The material and energy flows of the gasification system when producing 20,000 lb/hr methanol are summarized in Table 4-3. Compared to Scenario A, all other material and energy flow rates increase with the increase of the plant size with the exception of net power production which decreases. The decrease of the power exported from the IGCC system is due to the increased power consumption in the oxygen and methanol plants.

Table 4-3 Material and Energy Flows Attributed to RDF of the MSW/Coal Blends Gasification System for Scenario B

MSW Input	(Ton/day)	8,012
RDF Produced	(Ton/day)	4,469
MSW Residual	(Ton/day)	3,103
Fe Recovered	(Ton/day)	339
Al Recovered	(Ton/day)	101
Slag from IGCC	(Ton/day)	760
Sulfur Produced	(Ton/day)	28
Methanol Produced	(Ton/day)	153
Power Consumed in RDF Plant	(MWh/day)	403
Net Power from IGCC	(MWh/day)	6,841

4.2.1 LCI Results of the MSW/Coal Blends Gasification System

Based on the material and energy flows calculated, the emission inventory of the MSW/coal blends gasification system is calculated and summarized in Table 4-4 (LF with no energy recovery) and Table 4-5 (LF with energy recovery).

For the LCI of the gasification system in Scenario B, similar analysis results were made as discussed in section 3.2.3.3. When compared with the LCI of gasification system in Scenario A, although fewer emissions are avoided by electricity, the total emissions from the gasification system still decrease due to the increase of the avoided emissions associated with the methanol, ferrous and aluminum, for both cases of landfill with or without energy recovery.

Table 4-4 LCI Results of the MSW/Coal Blends Gasification System (Lbs/day) (Scenario B / Landfill with no Energy Recovery)

	Coal Precomb.	IGCC Plant	RDF Plant	Traditional Landfill	Ash Landfill	Electricity Offset	Methanol Offset[C]	Transport[d]	(Al + Fe) Offset	Total
Airborne Releases										
Carbon monoxide	1.34E+02	3.23E+03	2.92E+02	1.27E+02	1.90E+01	-3.82E+03	-2.30E+03	1.82E+02	-1.85E+04	-2.07E+04
Nitrogen oxides	1.71E+02	5.92E+03	4.53E+02	2.00E+01	5.60E+01	-5.07E+04	-1.09E+03	1.85E+02	-6.49E+03	-5.14E+04
Total Particulates	1.91E+03	3.60E+02	5.02E+01	1.41E+01	5.14E+00	-1.73E+04	-1.68E+02	2.66E+01	-8.89E+03	-2.40E+04
Carbon dioxide (fossil fuel)	3.03E+04	4.87E+06	7.30E+03	1.10E+03	4.00E+03	-1.35E+07	-4.79E+05	2.15E+04	-2.83E+06	-1.19E+07
Carbon dioxide (biomass fuel)	2.23E+02	6.54E+06	7.37E+04	1.25E+05	9.43E-01	-1.90E+03	0.00E+00	5.15E+00	0.00E+00	6.73E+06
Sulfur oxides	1.71E+02	1.45E+01	1.06E+02	5.28E+00	9.52E+00	-8.95E+04	-1.12E+04	5.24E+01	-1.84E+04	-1.19E+05
Hydrocarbons	6.33E+01	3.12E+02	2.08E+02	3.16E+00	1.43E+01	-2.60E+03	N/A	7.42E+01	-3.31E+03	N/A
Methane	3.49E+03	N/A	1.13E+01	1.09E+03	7.09E-01	-2.96E+04	-2.71E+03	3.42E+00	-3.87E+03	-3.16E+04
Lead	2.01E-03	N/A	3.89E-04	1.55E-05	2.16E-05	-5.77E-01	N/A	1.18E-04	4.16E-01	N/A
Ammonia	6.48E-02	N/A	1.11E-01	2.48E-03	6.18E-03	-1.13E+01	N/A	3.38E-02	-6.65E+00	N/A
Hydrochloric acid	8.19E-01	N/A	6.95E-02	1.64E+00	4.78E-03	-1.09E+03	N/A	2.11E-02	-3.99E+02	N/A
GHE[e] (Tons/day)	1.41E+01	N/A	1.03E+00	3.28E+00	5.47E-01	-1.92E+03	-7.31E+01	2.94E+00	-3.98E+02	-2.37E+03
Waterborne Releases										
Dissolved Solids	6.11E+01	N/A	9.67E+01	1.45E+00	5.38E+00	-1.14E+04	N/A	2.94E+01	-9.76E+03	N/A
Suspended solids	1.05E+03	N/A	2.20E+00	2.04E-01	2.16E-01	-9.45E+03	-1.03E+02	6.67E-01	-1.06E+03	-9.57E+03
Bio-chemical Oxygen Demand	8.94E-02	N/A	3.61E-01	3.51E+01	4.10E-02	-1.13E+01	-1.49E+01	1.10E-01	-1.45E+01	-5.03E+00
Chemical Oxygen Demand	9.68E-01	N/A	2.42E+00	9.77E+01	2.83E+01	-1.60E+02	-1.06E+02	7.35E-01	-2.20E+02	-3.56E+02
Oil	1.12E+00	N/A	2.25E+00	2.14E+01	5.67E+01	-2.00E+02	N/A	6.84E-01	-1.73E+02	N/A
Sulfuric Acid	1.86E-01	N/A	1.92E-02	1.74E+00	1.06E-03	-1.34E+02	N/A	5.83E-03	-1.12E+01	N/A
Iron	8.94E+01	N/A	5.28E-02	1.17E-02	2.94E-03	-7.22E+02	N/A	1.60E-02	-5.93E+01	N/A
Ammonia	1.04E-02	N/A	3.89E-02	1.12E+00	5.25E-03	-2.92E-01	N/A	1.18E-02	-3.53E+01	N/A
Copper	0.00E+00	N/A	0.00E+00	0.00E+00	0.00E+00	0.00E+00	N/A	0.00E+00	0.00E+00	N/A

(To be Continued)

(Continued)

	Coal Precomb.	IGCC Plants	RDF Plant	Traditional Landfill	Ash Landfill	Electricity Offset	Methanol Offset[C]	Transport[d]	(Al + Fe) Offset	Total
Cadmium	2.68E-03	N/A	3.61E-03	6.04E-05	2.01E-04	-5.16E-01	N/A	1.10E-03	-4.14E-01	N/A
Arsenic	0.00E+00	N/A	0.00E+00	2.16E-05	0.00E+00	0.00E+00	N/A	0.00E+00	0.00E+00	N/A
Mercury	2.09E-07	N/A	2.72E-07	3.07E-07	1.52E-08	-4.06E-05	N/A	8.28E-08	-3.71E-04	N/A
Phosphate	8.94E-02	N/A	9.73E-03	8.19E-03	5.41E-04	-6.69E+01	N/A	2.96E-03	-3.90E+00	N/A
Selenium	0.00E+00	N/A	0.00E+00	7.00E-06	0.00E+00	0.00E+00	N/A	0.00E+00	0.00E+00	N/A
Chromium	2.68E-03	N/A	3.61E-03	1.17E-04	2.01E-04	-5.16E-01	N/A	1.10E-03	-4.14E-01	N/A
Lead	4.25E-06	N/A	4.17E-05	1.01E-05	2.32E-06	-3.82E-05	N/A	1.27E-05	-2.15E-03	N/A
Zinc	9.68E-04	N/A	1.81E-03	4.34E-05	1.00E-04	-1.77E-01	N/A	5.49E-04	-1.49E-01	N/A
Solid Waste	2.57E+05	N/A	3.70E+02	1.89E+02	2.87E+01	-2.57E+06	-5.83E+04	1.12E+02	-9.82E+05	-3.35E+06

[a] The term "N/A" means that data for that item are not available.
[b] Based on material flows given in Table 4-3.
[c] This is offset from net energy production from IGCC based polygeneration system after subtracting the RDF plant demand
[d] LCI associated with the transportation from RDF plants to remanufacturing plants
e The GHE are given as carbon equivalents, calculated using equation: GHE = 12/44*(fossil CO_2 + 21*methane)/2000

Table 4-5 LCI Results of the MSW/Coal Blends Gasification System (Lbs/day) (Scenario B / Landfill with Energy Recovery)

	Coal Precomb.	**IGCC Plant**	**RDF Plant**	**Traditional Landfill**	**Ash Landfill**	**Electricity Offset**	**Methanol Offset[C]**	**Transport[d]**	**(Al + Fe) Offset**	**Total**
Airborne Releases										
Carbon monoxide	1.34E+02	3.23E+03	2.92E+02	4.02E+01	1.90E+01	-3.82E+03	-2.30E+03	1.82E+02	-1.85E+04	-2.08E+04
Nitrogen oxides	1.71E+02	5.92E+03	4.53E+02	2.39E+00	5.60E+01	-5.07E+04	-1.09E+03	1.85E+02	-6.49E+03	-5.15E+04
Total particulates	1.91E+03	3.60E+02	5.02E+01	-1.14E+01	5.14E+00	-1.73E+04	-1.68E+02	2.66E+01	-8.89E+03	-2.40E+04
Carbon dioxide (fossil fuel)	3.03E+04	4.87E+06	7.30E+03	-5.58E+03	4.00E+03	-1.35E+07	-4.79E+05	2.15E+04	-2.83E+06	-1.19E+07
Carbon dioxide (biomass fuel)	2.23E+02	6.54E+06	7.37E+04	1.25E+05	9.43E-01	-1.90E+03	0.00E+00	5.15E+00	0.00E+00	6.73E+06
Sulfur oxides	1.71E+02	1.45E+01	1.06E+02	-3.91E+01	9.52E+00	-8.95E+04	-1.12E+04	5.24E+01	-1.84E+04	-1.19E+05
Hydrocarbons	6.33E+01	3.12E+02	2.08E+02	1.87E+00	1.43E+01	-2.60E+03	N/A	7.42E+01	-3.31E+03	N/A
Methane	3.49E+03	N/A	1.13E+01	1.08E+03	7.09E-01	-2.96E+04	-2.71E+03	3.42E+00	-3.87E+03	-3.16E+04
Lead	2.01E-03	N/A	3.89E-04	-2.71E-04	2.16E-05	-5.77E-01	N/A	1.18E-04	4.16E-01	N/A
Ammonia	6.48E-02	N/A	1.11E-01	-3.12E-03	6.18E-03	-1.13E+01	N/A	3.38E-02	-6.65E+00	N/A
Hydrochloric acid	8.19E-01	N/A	6.95E-02	1.14E+00	4.78E-03	-1.09E+03	N/A	2.11E-02	-3.99E+02	N/A
GHE[e] (Tons/day)	1.41E+01	N/A	1.03E+00	2.33E+00	5.47E-01	-1.92E+03	-7.31E+01	2.94E+00	-3.98E+02	-2.37E+03
Waterborne Releases										
Dissolved Solids	6.11E+01	N/A	9.67E+01	-1.33E+01	5.38E+00	-1.14E+04	N/A	2.94E+01	-9.76E+03	N/A
Suspended solids	1.05E+03	N/A	2.20E+00	-4.48E+00	2.16E-01	-9.45E+03	-1.03E+02	6.67E-01	-1.06E+03	-9.57E+03
Bio-chemical Oxygen Demand	8.94E-02	N/A	3.61E-01	3.51E+01	4.10E-02	-1.13E+01	-1.49E+01	1.10E-01	-1.45E+01	-5.04E+00
Chemical Oxygen Demand	9.68E-01	N/A	2.42E+00	9.76E+01	2.83E+01	-1.60E+02	-1.06E+02	7.35E-01	-2.20E+02	-3.56E+02
Oil	1.12E+00	N/A	2.25E+00	2.13E+01	5.67E+01	-2.00E+02	N/A	6.84E-01	-1.73E+02	N/A
Sulfuric Acid	1.86E-01	N/A	1.92E-02	1.67E+00	1.06E-03	-1.34E+02	N/A	5.83E-03	-1.12E+01	N/A
Iron	8.94E+01	N/A	5.28E-02	-3.46E-01	2.94E-03	-7.22E+02	N/A	1.60E-02	-5.93E+01	N/A
Ammonia	1.04E-02	N/A	3.89E-02	1.12E+00	5.25E-03	-2.92E-01	N/A	1.18E-02	-3.53E+01	N/A
Copper	0.00E+00	N/A	0.00E+00	0.00E+00	0.00E+00	0.00E+00	N/A	0.00E+00	0.00E+00	N/A

(To be Continued)

(Continued)

	Coal Precomb.	IGCC Plant	RDF Plant	Traditional Landfill	Ash Landfill	Electricity Offset	Methanol Offset[C]	Transport[d]	(Al + Fe) Offset	Total
Cadmium	2.68E-03	N/A	3.61E-03	-1.96E-04	2.01E-04	-5.16E-01	N/A	1.10E-03	-4.14E-01	N/A
Arsenic	0.00E+00	N/A	0.00E+00	2.16E-05	0.00E+00	0.00E+00	N/A	0.00E+00	0.00E+00	N/A
Mercury	2.09E-07	N/A	2.72E-07	2.86E-07	1.52E-08	-4.06E-05	N/A	8.28E-08	-3.71E-04	N/A
Phosphate	8.94E-02	N/A	9.73E-03	-2.50E-02	5.41E-04	-6.69E+01	N/A	2.96E-03	-3.90E+00	N/A
Selenium	0.00E+00	N/A	0.00E+00	7.00E-06	0.00E+00	0.00E+00	N/A	0.00E+00	0.00E+00	N/A
Chromium	2.68E-03	N/A	3.61E-03	-1.39E-04	2.01E-04	-5.16E-01	N/A	1.10E-03	-4.14E-01	N/A
Lead	4.25E-06	N/A	4.17E-05	1.00E-05	2.32E-06	-3.82E-05	N/A	1.27E-05	-2.15E-03	N/A
Zinc	9.68E-04	N/A	1.81E-03	-6.14E-05	1.00E-04	-1.77E-01	N/A	5.49E-04	-1.49E-01	N/A
Solid Waste	2.57E+05	N/A	3.70E+02	-1.08E+03	2.87E+01	-2.57E+06	-5.83E+04	1.12E+02	-9.82E+05	-3.35E+06

[a] The term “N/A” means that data for that item are not available.
[b] Based on material flows given in Table 4-3.
[c] This is offset from net energy production from IGCC based polygeneration system after subtracting the RDF plant demand
[d] LCI associated with the transportation from RDF plants to remanufacturing plants
e The GHE are given as carbon equivalents, calculated using equation: GHE = 12/44*(fossil CO_2 + 21*methane)/2000

4.2.2 LCI Results of the WTE system

To produce 20,000 lb/hr of methanol, 8012 ton MSW/day is fed into the WTE system. The LCI of the WTE system is summarized in Table 4-1.Compared to Scenario A, the total emissions from the WTE system decrease due to the increase of the avoided emissions of the electricity, ferrous, and aluminum as more MSW is fed.

Table 4-6 LCI Results of the WTE System in Scenario B (Lbs/day)

Atmospheric Emissions	**Direct Emissions**	**Lime Associated Emissions**	**Avoided Emissions of Electricity**	**Transport[b]**	**Avoided Emissions Fe & Al**	**Ash Disposal**	**Total**
Carbon Monoxide	8.16E+03	3.96E+01	-2.52E+03	1.81E+02	-1.85E+04	5.80E+01	-1.26E+04
Nitrogen Oxides	1.31E+04	1.47E+02	-3.35E+04	1.83E+02	-6.49E+03	1.71E+02	-2.63E+04
Particulates (Total)	1.57E+03	3.05E+02	-1.14E+04	2.64E+01	-8.89E+03	1.57E+01	-1.84E+04
CO_2 (non biomass)	4.89E+06	1.45E+05	-8.90E+06	2.13E+04	-2.83E+06	1.22E+04	-6.66E+06
CO_2 (biomass)	1.06E+07	5.37E+00	-1.26E+03	5.11E+00	0.00E+00	2.88E+00	1.06E+07
Sulfur Oxides	5.60E+03	4.13E+02	-5.91E+04	5.20E+01	-1.84E+04	2.91E+01	-7.14E+04
Hydrocarbons	0.00E+00	3.33E+01	-1.72E+03	7.37E+01	-3.31E+03	4.37E+01	-4.88E+03
Methane	2.40E+01	1.07E+02	-1.96E+04	3.39E+00	-3.87E+03	2.17E+00	-2.33E+04
Lead	N/A	N/A	N/A	1.17E-04	4.16E-01	6.61E-05	N/A
Ammonia	0.00E+00	2.26E-02	-7.47E+00	3.35E-02	-6.65E+00	1.89E-02	-1.40E+01
Hydrochloric acid	2.66E+03	N/A	N/A	2.10E-02	-3.99E+02	1.46E-02	N/A
GHE[c] (tons/day)	6.67E+02	2.00E+01	-1.27E+03	2.92E+00	-3.98E+02	1.67E+00	-9.75E+02
Waterborne Emissions							
Dissolved Solids	0.00E+00	1.24E+02	-7.53E+03	2.92E+01	-9.76E+03	1.64E+01	-1.71E+04
Suspended Solids	0.00E+00	4.86E+00	-6.24E+03	6.62E-01	-1.06E+03	6.63E-01	-7.30E+03
BOD	0.00E+00	1.32E-01	-7.43E+00	1.09E-01	-1.45E+01	1.25E-01	-2.16E+01
COD	0.00E+00	1.80E+00	-1.06E+02	7.29E-01	-2.20E+02	8.66E+01	-2.36E+02
Oil	0.00E+00	2.20E+00	-1.32E+02	6.79E-01	-1.73E+02	1.73E+02	-1.29E+02
Sulfuric Acid	0.00E+00	4.39E-01	-8.84E+01	5.78E-03	-1.12E+01	3.25E-03	-9.92E+01
Iron	0.00E+00	2.38E+00	-4.77E+02	1.59E-02	-5.93E+01	1.39E-01	-5.33E+02
Ammonia	0.00E+00	6.64E-03	-1.93E-01	1.17E-02	-3.53E+01	2.96E-01	-3.51E+01
Copper	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.35E-04	5.35E-04
Cadmium	0.00E+00	5.83E-03	-3.41E-01	1.09E-03	-4.14E-01	6.67E-04	-7.48E-01
Arsenic	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.22E-02	1.22E-02
Mercury	0.00E+00	4.48E-07	-2.68E-05	8.21E-08	-3.71E-04	4.63E-08	-3.97E-04
Phosphate	0.00E+00	2.19E-01	-4.42E+01	2.93E-03	-3.90E+00	2.50E-03	-4.79E+01
Selenium	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.85E-03	3.85E-03
Chromium	0.00E+00	5.62E-03	-3.41E-01	1.09E-03	-4.14E-01	6.81E-04	-7.48E-01
Lead	0.00E+00	1.73E-06	-2.52E-05	1.26E-05	-2.15E-03	5.55E-04	-1.60E-03
Zinc	0.00E+00	1.93E-03	-1.17E-01	5.45E-04	-1.49E-01	1.36E-03	-2.63E-01
Solid Waste	0.00E+00	9.33E+03	-1.70E+06	1.11E+02	-9.82E+05	8.77E+01	-2.67E+06

[a] Emissions are for a WTE facility processing 8012 Tons MSW/day of the composition specified in Table 4-3. Where emission data were not available, no total emission is reported.

[b] LCI associated with the transportation of recyclables from WTE plants to remanufacturing plants.

[c] The GHE are given as carbon equivalents, calculated by equation: GHE = 12/44*(fossil CO_2 + 21*methane)/2000

4.2.3 Analysis of the Comparison Results

The comparison results of the gasification system (LF with/without energy recovery) and the WTE system are summarized in Table 4-7.

Table 4-7 LCI Comparison Results between Gasification System and WTE System (Scenario B)

Atmospheric Emissions	**WTE**	**Gasification[a]**	**Correlation with WTE[C]**	**Gasification[b]**	**Correlation with WTE[C]**
Carbon Monoxide	-1.26E+04	-2.08E+04	+1.6	-2.07E+04	+1.6
Nitrogen Oxides	-2.63E+04	-5.15E+04	+2.0	-5.14E+04	+1.9
Particulates (Total)	-1.84E+04	-2.40E+04	+1.3	-2.40E+04	+1.3
CO2 (non biomass)	-6.66E+06	-1.19E+07	+1.8	-1.19E+07	+1.8
CO2 (biomass)	1.06E+07	6.73E+06	+1.6	6.73E+06	+1.6
Sulfur Oxides	-7.14E+04	-1.19E+05	+1.7	-1.19E+05	+1.7
Hydrocarbons (non CH4)	-4.88E+03	N/A	N/A	N/A	N/A
Methane	-2.33E+04	-3.16E+04	+1.4	-3.16E+04	+1.4
Lead	N/A	N/A	N/A	N/A	N/A
Ammonia	-1.40E+01	N/A	N/A	N/A	N/A
Hydrochloric acid	N/A	N/A	N/A	N/A	N/A
GHE[d] (Tons/day)	-9.75E+02	-2.37E+03	+2.4	-2.37E+03	+2.4
Waterborne Emissions					
Dissolved Solids	-1.71E+04	N/A	N/A	N/A	N/A
Suspended Solids	-7.30E+03	-9.57E+03	+1.3	-9.57E+03	+1.3
BOD	-2.16E+01	-5.04E+00	-4.3	-5.03E+00	-4.3
COD	-2.36E+02	-3.56E+02	+1.5	-3.56E+02	+1.5
Oil	-1.29E+02	N/A	N/A	N/A	N/A
Sulfuric Acid	-9.92E+01	N/A	N/A	N/A	N/A
Iron	-5.33E+02	N/A	N/A	N/A	N/A
Ammonia	-3.51E+01	N/A	N/A	N/A	N/A
Copper	5.35E-04	N/A	N/A	N/A	N/A
Cadmium	-7.48E-01	N/A	N/A	N/A	N/A
Arsenic	1.22E-02	N/A	N/A	N/A	N/A
Mercury	-3.97E-04	N/A	N/A	N/A	N/A
Phosphate	-4.79E+01	N/A	N/A	N/A	N/A
Selenium	3.85E-03	N/A	N/A	N/A	N/A
Chromium	-7.48E-01	N/A	N/A	N/A	N/A
Lead	-1.60E-03	N/A	N/A	N/A	N/A
Zinc	-2.63E-01	N/A	N/A	N/A	N/A
Solid Waste	-2.67E+06	-3.35E+06	+1.3	-3.35E+06	+1.3

a Landfill with energy recovery

b Landfill without energy recovery

c The correlation number is the absolute value of emission of the gasification system divided by emission of the WTE system. Positive sign represents that the gasification produces fewer emissions than the WTE system; negative sign represents that the gasification produces more emissions than the WTE system.

d The GHE are given as carbon equivalents, calculated by equation: GHE = 12/44*(fossil CO_2 + 21*methane)/2000

Compared to Scenario A, both the emissions from the WTE system and the emissions from the gasification system decrease. However, the comparison results between the gasification system and the WTE system are similar as discussed in section 4.1.2.

4.3 Comparison Study on Scenario C

In scenario C, the methanol plant size is 40,000 lb/hr. The MSW residual is disposed either in landfills with no energy recovery or in landfills with energy recovery. For this scenario, the analysis results of the LCI of the gasification system, the LCI of the WTE system, and the comparison of their LCIs are similar as scenario A and scenario B, as presented in section 4.1 and 4.2. Therefore, in this section, only the results of the LCI and the comparison were presented.

The material and energy flows of the gasification system when producing 40,000 lb/hr methanol are calculated and summarized in Table 4-8.

Table 4-8 Material and Energy Flows of the MSW/Coal Blends Gasification System (Scenario C)

MSW Input	(Ton/day)	8,484
RDF Produced	(Ton/day)	4,733
MSW Residual	(Ton/day)	3,286
Fe Recovered	(Ton/day)	359
Al Recovered	(Ton/day)	107
Slag from IGCC	(Ton/day)	804
Sulfur Produced	(Ton/day)	30
Methanol Produced	(Ton/day)	305
Power Consumed in RDF Plant	(MWh/day)	427
Net Power from IGCC	(MWh/day)	6,716

Based on the material and energy flows calculated, the emission inventory of the MSW/coal blends gasification system is calculated and summarized in Table 4-9 (gasification system/ LF with no energy recovery) and Table 4-10 (gasification system/ LF with energy recovery).

Table 4-9 LCI Results of the MSW/Coal Blends Gasification System (Lbs/day) (Scenario C / Landfill with no Energy Recovery)

	Coal Precomb.	IGCC Plant	RDF Plant	Traditional Landfill	Ash Landfill	Electricity Offset	Methanol Offset[C]	Transport[c]	(Al + Fe) Offset	Total
Airborne Releases										
Carbon monoxide	1.42E+02	3.26E+03	3.09E+02	1.34E+02	2.01E+01	-3.73E+03	-4.59E+03	1.93E+02	-1.96E+04	-2.39E+04
Nitrogen oxides	1.81E+02	5.98E+03	4.80E+02	2.12E+01	5.93E+01	-4.95E+04	-2.17E+03	1.95E+02	-6.87E+03	-5.16E+04
Total particulates	2.02E+03	3.60E+02	5.32E+01	1.49E+01	5.44E+00	-1.69E+04	-3.37E+02	2.81E+01	-9.41E+03	-2.41E+04
Carbon dioxide (fossil fuel)	3.21E+04	4.98E+06	7.73E+03	1.16E+03	4.24E+03	-1.32E+07	-9.58E+05	2.28E+04	-3.00E+06	-1.21E+07
Carbon dioxide (biomass fuel)	2.37E+02	6.69E+06	7.80E+04	1.32E+05	9.99E-01	-1.86E+03	0.00E+00	5.46E+00	0.00E+00	6.90E+06
Sulfur oxides	1.81E+02	1.48E+01	1.12E+02	5.59E+00	1.01E+01	-8.74E+04	-2.24E+04	5.55E+01	-1.94E+04	-1.29E+05
Hydrocarbons	6.70E+01	3.12E+02	2.20E+02	3.34E+00	1.52E+01	-2.54E+03	N/A	7.86E+01	-3.51E+03	N/A
Methane	3.70E+03	N/A	1.19E+01	1.16E+03	7.51E-01	-2.90E+04	-5.42E+03	3.62E+00	-4.10E+03	-3.36E+04
Lead	2.13E-03	N/A	4.12E-04	1.64E-05	2.29E-05	-5.64E-01	N/A	1.25E-04	4.41E-01	N/A
Ammonia	6.86E-02	N/A	1.18E-01	2.63E-03	6.55E-03	-1.10E+01	N/A	3.58E-02	-7.04E+00	N/A
Hydrochloric acid	8.68E-01	N/A	7.36E-02	1.74E+00	5.06E-03	-1.06E+03	N/A	2.24E-02	-4.23E+02	N/A
GHE[e] (Tons/day)	1.50E+01	N/A	1.09E+00	3.47E+00	5.80E-01	-1.88E+03	-1.46E+02	3.12E+00	-4.21E+02	-2.42E+03
Waterborne Releases										
Dissolved Solids	6.47E+01	N/A	1.02E+02	1.53E+00	5.70E+00	-1.11E+04	N/A	3.11E+01	-1.03E+04	N/A
Suspended solids	1.11E+03	N/A	2.33E+00	2.16E-01	2.28E-01	-9.23E+03	-2.06E+02	7.07E-01	-1.13E+03	-9.45E+03
Bio-chemical Oxygen Demand	9.47E-02	N/A	3.83E-01	3.72E+01	4.34E-02	-1.10E+01	-2.99E+01	1.16E-01	-1.54E+01	-1.85E+01
Chemical Oxygen Demand	1.03E+00	N/A	2.56E+00	1.03E+02	3.00E+01	-1.56E+02	-2.12E+02	7.78E-01	-2.33E+02	-4.63E+02
Oil	1.18E+00	N/A	2.38E+00	2.27E+01	6.00E+01	-1.95E+02	N/A	7.25E-01	-1.83E+02	N/A
Sulfuric Acid	1.97E-01	N/A	2.03E-02	1.84E+00	1.13E-03	-1.31E+02	N/A	6.17E-03	-1.19E+01	N/A
Iron	9.47E+01	N/A	5.59E-02	1.24E-02	3.11E-03	-7.05E+02	N/A	1.70E-02	-6.28E+01	N/A
Ammonia	1.10E-02	N/A	4.12E-02	1.19E+00	5.56E-03	-2.86E-01	N/A	1.25E-02	-3.73E+01	N/A
Copper	0.00E+00	N/A	0.00E+00	0.00E+00	0.00E+00	0.00E+00	N/A	0.00E+00	0.00E+00	N/A

(To be Continued)

(Continued)

	Coal Precomb.	IGCC Plants	RDF Plant	Traditional Landfill	Ash Landfill	Electricity Offset	Methanol Offset[C]	Transport[c]	(Al + Fe) Offset	Total
Cadmium	2.84E-03	N/A	3.83E-03	6.39E-05	2.13E-04	-5.05E-01	N/A	1.16E-03	-4.38E-01	N/A
Arsenic	0.00E+00	N/A	0.00E+00	2.29E-05	0.00E+00	0.00E+00	N/A	0.00E+00	0.00E+00	N/A
Mercury	2.21E-07	N/A	2.89E-07	3.25E-07	1.60E-08	-3.96E-05	N/A	8.77E-08	-3.93E-04	N/A
Phosphate	9.47E-02	N/A	1.03E-02	8.67E-03	5.73E-04	-6.53E+01	N/A	3.13E-03	-4.13E+00	N/A
Selenium	0.00E+00	N/A	0.00E+00	7.41E-06	0.00E+00	0.00E+00	N/A	0.00E+00	0.00E+00	N/A
Chromium	2.84E-03	N/A	3.83E-03	1.24E-04	2.13E-04	-5.05E-01	N/A	1.16E-03	-4.39E-01	N/A
Lead	4.50E-06	N/A	4.42E-05	1.07E-05	2.46E-06	-3.73E-05	N/A	1.34E-05	-2.27E-03	N/A
Zinc	1.03E-03	N/A	1.91E-03	2.82E-05	1.06E-04	-1.73E-01	N/A	5.81E-04	-1.58E-01	N/A
Solid Waste	2.72E+05	N/A	3.92E+02	2.00E+02	3.04E+01	-2.51E+06	-1.17E+05	1.19E+02	-1.04E+06	-3.39E+06

[a] The term “N/A” means that data for that item are not available.
[b] Based on material flows given in Table 4-8.
[c] This is offset from net energy production from IGCC based polygeneration system after subtracting the RDF plant demand
[d] LCI associated with the transportation from RDF plants to remanufacturing plants
e The GHE are given as carbon equivalents, calculated using equation: GHE = 12/44*(fossil CO_2 + 21*methane)/2000

Table 4-10 LCI Results of the MSW/Coal Blends Gasification System (Lbs/day) (Scenario C / Landfill with Energy Recovery)

	Coal Precomb.	IGCC Plant	RDF Plant	Traditional Landfill	Ash Landfill	Electricity Offset	Methanol Offset[C]	Transport[c]	(Al + Fe) Offset	Total
Airborne Releases										
Carbon monoxide	1.42E+02	3.26E+03	3.09E+02	4.25E+01	2.01E+01	-3.73E+03	-4.59E+03	1.93E+02	-1.96E+04	-2.40E+04
Nitrogen oxides	1.81E+02	5.98E+03	4.80E+02	2.53E+00	5.93E+01	-4.95E+04	-2.17E+03	1.95E+02	-6.87E+03	-5.16E+04
Total particulates	2.02E+03	3.60E+02	5.32E+01	-1.21E+01	5.44E+00	-1.69E+04	-3.37E+02	2.81E+01	-9.41E+03	-2.42E+04
Carbon dioxide (fossil fuel)	3.21E+04	4.98E+06	7.73E+03	-5.91E+03	4.24E+03	-1.32E+07	-9.58E+05	2.28E+04	-3.00E+06	-1.21E+07
Carbon dioxide (biomass fuel)	2.37E+02	6.69E+06	7.80E+04	1.32E+05	9.99E-01	-1.86E+03	0.00E+00	5.46E+00	0.00E+00	6.90E+06
Sulfur oxides	1.81E+02	1.48E+01	1.12E+02	-4.14E+01	1.01E+01	-8.74E+04	-2.24E+04	5.55E+01	-1.94E+04	-1.29E+05
Hydrocarbons	6.70E+01	3.12E+02	2.20E+02	1.98E+00	1.52E+01	-2.54E+03	N/A	7.86E+01	-3.51E+03	N/A
Methane	3.70E+03	N/A	1.19E+01	1.14E+03	7.51E-01	-2.90E+04	-5.42E+03	3.62E+00	-4.10E+03	-3.36E+04
Lead	2.13E-03	N/A	4.12E-04	-2.87E-04	2.29E-05	-5.64E-01	N/A	1.25E-04	4.41E-01	N/A
Ammonia	6.86E-02	N/A	1.18E-01	-3.31E-03	6.55E-03	-1.10E+01	N/A	3.58E-02	-7.04E+00	N/A
Hydrochloric acid	8.68E-01	N/A	7.36E-02	1.21E+00	5.06E-03	-1.06E+03	N/A	2.24E-02	-4.23E+02	N/A
GHE[e] (Tons/day)	1.50E+01	N/A	1.09E+00	2.46E+00	5.80E-01	-1.88E+03	-1.46E+02	3.12E+00	-4.21E+02	-2.42E+03
Waterborne Releases										
Dissolved Solids	6.47E+01	N/A	1.02E+02	-4.45E+00	5.70E+00	-1.11E+04	N/A	3.11E+01	-1.03E+04	N/A
Suspended solids	1.11E+03	N/A	2.33E+00	-4.75E+00	2.28E-01	-9.23E+03	-2.06E+02	7.07E-01	-1.13E+03	-9.46E+03
Bio-chemical Oxygen Demand	9.47E-02	N/A	3.83E-01	3.72E+01	4.34E-02	-1.10E+01	-2.99E+01	1.16E-01	-1.54E+01	-1.85E+01
Chemical Oxygen Demand	1.03E+00	N/A	2.56E+00	1.03E+02	3.00E+01	-1.56E+02	-2.12E+02	7.78E-01	-2.33E+02	-4.63E+02
Oil	1.18E+00	N/A	2.38E+00	2.26E+01	6.00E+01	-1.95E+02	N/A	7.25E-01	-1.83E+02	N/A
Sulfuric Acid	1.97E-01	N/A	2.03E-02	1.77E+00	1.13E-03	-1.31E+02	N/A	6.17E-03	-1.19E+01	N/A
Iron	9.47E+01	N/A	5.59E-02	-3.66E-01	3.11E-03	-7.05E+02	N/A	1.70E-02	-6.28E+01	N/A
Ammonia	1.10E-02	N/A	4.12E-02	1.19E+00	5.56E-03	-2.86E-01	N/A	1.25E-02	-3.73E+01	N/A
Copper	0.00E+00	N/A	0.00E+00	0.00E+00	0.00E+00	0.00E+00	N/A	0.00E+00	0.00E+00	N/A

(To be Continued)

(Continued)

	Coal Precomb.	IGCC Plants	RDF Plant	Traditional Landfill	Ash Landfill	Electricity Offset	Methanol Offset[C]	Transport[c]	(Al + Fe) Offset	Total
Cadmium	2.84E-03	N/A	3.83E-03	-2.07E-04	2.13E-04	-5.05E-01	N/A	1.16E-03	-4.38E-01	N/A
Arsenic	0.00E+00	N/A	0.00E+00	2.29E-05	0.00E+00	0.00E+00	N/A	0.00E+00	0.00E+00	N/A
Mercury	2.21E-07	N/A	2.89E-07	3.03E-07	1.60E-08	-3.96E-05	N/A	8.77E-08	-3.93E-04	N/A
Phosphate	9.47E-02	N/A	1.03E-02	-2.64E-02	5.73E-04	-6.53E+01	N/A	3.13E-03	-4.13E+00	N/A
Selenium	0.00E+00	N/A	0.00E+00	7.41E-06	0.00E+00	0.00E+00	N/A	0.00E+00	0.00E+00	N/A
Chromium	2.84E-03	N/A	3.83E-03	-1.48E-04	2.13E-04	-5.05E-01	N/A	1.16E-03	-4.39E-01	N/A
Lead	4.50E-06	N/A	4.42E-05	1.06E-05	2.46E-06	-3.73E-05	N/A	1.34E-05	-2.27E-03	N/A
Zinc	1.03E-03	N/A	1.91E-03	-6.50E-05	1.06E-04	-1.73E-01	N/A	5.81E-04	-1.58E-01	N/A
Solid Waste	2.72E+05	N/A	3.92E+02	-1.15E+03	3.04E+01	-2.51E+06	-1.17E+05	1.19E+02	-1.04E+06	-3.39E+06

[a] The term "N/A" means that data for that item are not available.
[b] Based on material flows given in Table 4-8.
[c] This is offset from net energy production from IGCC based polygeneration system after subtracting the RDF plant demand
[d] LCI associated with the transportation from RDF plants to remanufacturing plants
e The GHE are given as carbon equivalents, calculated using equation: GHE = 12/44*(fossil CO_2 + 21*methane)/2000

To produce 40,000 lb/hr of methanol, 8484 ton MSW/day is fed into the WTE system. The LCI results of the WTE system are summarized in Table 4-11.

Table 4-11 LCI Results of the WTE System in Scenario C (Lbs/day)

Atmospheric Emissions	**Direct Emissions**	**Lime Associated Emissions**	**Avoided Emissions from Electricity**	**Transport[b]**	**Avoided Emissions Fe & Al Recovered**	**Ash Disposal**	**Total**
Carbon Monoxide	8.64E+03	4.19E+01	-2.67E+03	1.91E+02	-1.96E+04	6.14E+01	-1.34E+04
Nitrogen Oxides	1.39E+04	1.56E+02	-3.54E+04	1.94E+02	-6.87E+03	1.81E+02	-2.79E+04
Particulates (Total)	1.66E+03	3.23E+02	-1.21E+04	2.79E+01	-9.41E+03	1.66E+01	-1.95E+04
CO2 (non biomass)	5.18E+06	1.53E+05	-9.42E+06	2.26E+04	-3.00E+06	1.29E+04	-7.05E+06
CO2 (biomass)	1.13E+07	5.69E+00	-1.33E+03	5.41E+00	0.00E+00	3.05E+00	1.13E+07
Sulfur Oxides	5.93E+03	4.37E+02	-6.26E+04	5.50E+01	-1.94E+04	3.08E+01	-7.56E+04
Hydrocarbons	0.00E+00	3.53E+01	-1.82E+03	7.80E+01	-3.51E+03	4.63E+01	-5.16E+03
Methane	2.55E+01	1.14E+02	-2.07E+04	3.59E+00	-4.10E+03	2.29E+00	-2.47E+04
Lead	N/A	N/A	N/A	1.24E-04	4.41E-01	7.00E-05	N/A
Ammonia	0.00E+00	2.39E-02	-7.91E+00	3.55E-02	-7.04E+00	2.00E-02	-1.49E+01
Hydrochloric acid	2.82E+03	N/A	N/A	2.22E-02	-4.23E+02	1.55E-02	N/A
GHE[c] (tons/day)	7.07E+02	2.12E+01	-1.34E+03	3.09E+00	-4.21E+02	1.77E+00	-1.03E+03
Waterborne Emissions							
Dissolved Solids	0.00E+00	1.31E+02	-7.98E+03	3.09E+01	-1.03E+04	1.74E+01	-1.81E+04
Suspended Solids	0.00E+00	5.14E+00	-6.61E+03	7.01E-01	-1.13E+03	7.03E-01	-7.73E+03
BOD	0.00E+00	1.40E-01	-7.87E+00	1.15E-01	-1.54E+01	1.33E-01	-2.29E+01
COD	0.00E+00	1.91E+00	-1.12E+02	7.72E-01	-2.33E+02	9.17E+01	-2.50E+02
Oil	0.00E+00	2.33E+00	-1.40E+02	7.19E-01	-1.83E+02	1.83E+02	-1.36E+02
Sulfuric Acid	0.00E+00	4.65E-01	-9.36E+01	6.12E-03	-1.19E+01	3.44E-03	-1.05E+02
Iron	0.00E+00	2.52E+00	-5.05E+02	1.69E-02	-6.28E+01	1.47E-01	-5.65E+02
Ammonia	0.00E+00	7.04E-03	-2.04E-01	1.24E-02	-3.73E+01	3.14E-01	-3.72E+01
Copper	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.66E-04	5.66E-04
Cadmium	0.00E+00	6.17E-03	-3.61E-01	1.15E-03	-4.38E-01	7.07E-04	-7.92E-01
Arsenic	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.29E-02	1.29E-02
Mercury	0.00E+00	4.75E-07	-2.84E-05	8.70E-08	-3.93E-04	4.90E-08	-4.21E-04
Phosphate	0.00E+00	2.32E-01	-4.68E+01	3.11E-03	-4.13E+00	2.64E-03	-5.07E+01
Selenium	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.08E-03	4.08E-03
Chromium	0.00E+00	5.95E-03	-3.61E-01	1.15E-03	-4.39E-01	7.21E-04	-7.92E-01
Lead	0.00E+00	1.84E-06	-2.67E-05	1.33E-05	-2.27E-03	5.88E-04	-1.70E-03
Zinc	0.00E+00	2.04E-03	-1.24E-01	5.77E-04	-1.58E-01	1.44E-03	-2.78E-01
Solid Waste							
Solid Waste	0.00E+00	9.88E+03	-1.80E+06	1.18E+02	-1.04E+06	9.29E+01	-2.83E+06

[a] Emissions are for a WTE facility processing 8484 Tons MSW/day of the composition specified in Table 4-8. Where emission data were not available for a process, no total emission is reported.

[b] LCI associated with the transportation from WTE plants to remanufacturing plants.

[c] The GHE are given as carbon equivalents, calculated by equation: GHE = 12/44*(fossil CO_2 + 21*methane)/2000

The comparison results of the LCI of the gasification system and the WTE system are summarized in Table 4-12.

Table 4-12 LCI Comparison Results between Gasification System and WTE System(Scenario C)

Atmospheric Emissions	WTE	Gasification[a]	Correlation with WTE[C]	Gasification[b]	Correlation with WTE[C]
Carbon Monoxide	-1.34E+04	-2.40E+04	+1.8	-2.39E+04	+1.8
Nitrogen Oxides	-2.79E+04	-5.16E+04	+1.9	-5.16E+04	+1.9
Particulates (Total)	-1.95E+04	-2.42E+04	+1.2	-2.41E+04	+1.2
CO2 (non biomass)	-7.05E+06	-1.21E+07	+1.7	-1.21E+07	+1.7
CO2 (biomass)	1.13E+07	6.90E+06	+1.6	6.90E+06	+1.6
Sulfur Oxides	-7.56E+04	-1.29E+05	+1.7	-1.29E+05	+1.7
Hydrocarbons (non CH4)	-5.16E+03	N/A	N/A	N/A	N/A
Methane	-2.47E+04	-3.36E+04	+1.4	-3.36E+04	+1.4
Lead	N/A	N/A	N/A	N/A	N/A
Ammonia	-1.49E+01	N/A	N/A	N/A	N/A
Hydrochloric acid	N/A	N/A	N/A	N/A	N/A
GHE (Tons/day)	-1.03E+03	-2.42E+03	+2.3	-2.42E+03	+2.3
Waterborne Emissions					
Dissolved Solids	-1.81E+04	N/A	N/A	N/A	N/A
Suspended Solids	-7.73E+03	-9.46E+03	+1.2	-9.45E+03	+1.2
BOD	-2.29E+01	-1.85E+01	-1.2	-1.85E+01	-1.2
COD	-2.50E+02	-4.63E+02	+1.9	-4.63E+02	+1.9
Oil	-1.36E+02	N/A	N/A	N/A	N/A
Sulfuric Acid	-1.05E+02	N/A	N/A	N/A	N/A
Iron	-5.65E+02	N/A	N/A	N/A	N/A
Ammonia	-3.72E+01	N/A	N/A	N/A	N/A
Copper	5.66E-04	N/A	N/A	N/A	N/A
Cadmium	-7.92E-01	N/A	N/A	N/A	N/A
Arsenic	1.29E-02	N/A	N/A	N/A	N/A
Mercury	-4.21E-04	N/A	N/A	N/A	N/A
Phosphate	-5.07E+01	N/A	N/A	N/A	N/A
Selenium	4.08E-03	N/A	N/A	N/A	N/A
Chromium	-7.92E-01	N/A	N/A	N/A	N/A
Lead	-1.70E-03	N/A	N/A	N/A	N/A
Zinc	-2.78E-01	N/A	N/A	N/A	N/A
Solid Waste					
Solid Waste	-2.83E+06	-3.39E+06	+1.2	-3.39E+06	+1.2

a Landfill with energy recovery
b Landfill without energy recovery
c The correlation number is the absolute value of emission of the gasification system divided by emission of the WTE system. Positive sign represents that the gasification produces fewer emissions than the WTE system; negative sign represents that the gasification produces more emissions than the WTE system.
d The GHE are given as carbon equivalents, calculated by equation: GHE = 12/44*(fossil CO_2 + 21*methane)/2000

4.4 Summary of the Results for Scenario A, B, and C

The gasification system was assessed via comparison with WTE system for different methanol plant sizes. In all three scenarios, for most atmospheric pollutants and solid waste, the gasification system had a more favorable LCI than the WTE system. The offset emissions of electricity, methanol, ferrous, and aluminum are the dominant factors on the total emissions of gasification system. However, WTE system is better for waterborne emissions due to the assumed dependence of a traditional landfill in the gasification system. A lechate collection system efficiency of 99% was assumed for the landfill process model so that 1% of lechate generated is also released to the environment directly.

Table 4-13 Comparison of the LCI of the Gasification System (Landfill with Energy Recovery) of Scenario A, B, and C

	Methanol Production (lb/hr)		
	10,000	**20,000**	**40,000**
Airborne Releases			
Carbon monoxide	-1.91E+04	-2.08E+04	-2.40E+04
Nitrogen oxides	-5.13E+04	-5.15E+04	-5.16E+04
Total particulates	-2.39E+04	-2.40E+04	-2.42E+04
Carbon dioxide (fossil fuel)	-1.18E+07	-1.19E+07	-1.21E+07
Carbon dioxide (biomass)	6.87E+06	6.73E+06	6.90E+06
Sulfur oxides	-1.14E+05	-1.19E+05	-1.29E+05
Methane	-3.06E+04	-3.16E+04	-3.36E+04
GHE(Ton/day)	-2.53E+03	-2.56E+03	-2.62E+03
Waterborne Releases			
Suspended solids	-9.63E+03	-9.57E+03	-9.46E+03
BOD	1.69E+00	-5.04E+00	-1.85E+01
COD	-3.02E+02	-3.56E+02	-4.63E+02
Solid Waste	-3.33E+06	-3.35E+06	-3.39E+06

With the increase of the plant size, for gasification system, all of the material and energy flow rates increase with the exception of the power exported from the IGCC system due to the increased power consumption in the oxygen plants and the methanol plants. Although the net power production of the gasification system decreases when increasing the plant size, the emissions of the gasification system keep decreasing due to the increase of avoided emissions of the methanol produced, and ferrous & aluminum recovered, as illustrated in Table 4-13. Therefore, with the increase of the methanol plant size, the gasification system will have a better LCI.

When the LFG from the traditional landfill in the gasification system is recovered, the emissions from the gasification system decrease due to the avoided emissions of the energy recovered from the LFG. However, this improvement has very little effect on the total LCI of the gasification system.

The emissions from the gasification system are overestimated because the avoided emissions of the sulfur produced are not included.

The effect of the ammonia production on the environmental performance of gasification system was not estimated because it has not been integrated with the entire system.

5.0 CONCLUSIONS AND RECOMMENDATIONS

This study developed a model for calculation of the LCI of the MSW/coal blends gasification system, which produces energy, methanol, ferrous & aluminum, and sulfur. A case study was made to assess the environmental performance through comparison of the LCI of the MSW/coal blends gasification system and the WTE system.

The LCI model was comprised of several sub models including: 1) IGCC based polygeneration system model developed by Pickett, 2000 and Vaswani, 2000; 2) RDF process model developed in this study; 3) Landfill process model; and 4) Remanufacturing process model. The IGCC based polygeneration system model firing the RDF/coal blends was calibrated in this study. The LCI model was used to calculate the LCI of the gasification system when producing 10,000 lb methanol/hr, 20,000 lb methanol /hr, and 40,000 lb methanol per hour. For each scenario, the environmental performance of the gasification system was assessed by comparing the LCI with the WTE system.

The following conclusions can be drawn from this study:

1) For most pollutants, in both gasification system and WTE system, the emissions are negative due to the offset emissions.

2) For atmospheric, waterborne, and solid waste pollutants, the largest contributor to emissions is the offset emissions associated with the ferrous and aluminum recovered in the RDF plant. The second largest contributor is the offset emissions associated with the electricity and methanol production. The gasification system has a more favorable LCI than the WTE system in consideration of uncertainties in the data and the model. For all the pollutants except BOD, the WTE system produce about 1.5 ~ 2 times more emissions than the gasification system. Both systems produce same ferrous and ferrous, which make the largest contribution to the total emissions. However, the gasification system produce about 1.5 times more electricity than the WTE system. In addition, the gasification system produces methanol, which is zero for the WTE system. Because the avoided emissions associated with these two products make the second largest contribution to the total emissions, it is concluded that

the gasification system produces less emissions than the WTE system even considering uncertainties.

3) As methanol production in the gasification system is increased, its LCI improves.

4) There is an environmental improvement for the gasification system when the LFG is recovered into energy in the traditional landfill. However, this improvement effect is negligible to the total LCI of the gasification system.

5) The RDF process model has an equalization effect on the variability of different MSW feedstocks.

6) The RDF percentage in the RDF/coal blends can be changed to meet the requirement of the desired gasification temperature.

7) The paper to plastic ratio of the incoming MSWs has the largest effect on the LCI of the gasification system for the parameters studied.

The recommendations for the future work include:

1. Combine the ammonia process model with the gasification system model to produce a bigger model include production of both methanol and ammonia.
2. Develop a conventional ammonia model to calculate the LCI coefficients of ammonia.
3. Develop a conventional sulfur model to calculate the LCI coefficients of sulfur.
4. The probability analysis tools can also be used together with the model to quantify the uncertainty and variability associated with the gasification system.

6.0 REFERENCES

H. Christopher Frey, Morton A. Barlaz, et al., "Progress Report of New Methods for Assessment of Pollution Prevention Technologies", NSF Design, Manufacturing & Industrial Innovation Research Conference, 2001.

D.R. Simbeck, R. L. Dickinson, E.D. Oliver, "Coal Gasification Systems: A Guide to Status, Applications, and Economics". AP-3109 Prepared by Synthetic Fuel Associates, Inc for Electric Power Research Institute, Palo Alto, CA, 1983.

G.J. Stiegel, "Integrated Gasification Combined Cycle," Department of Energy: Office of Fossil Energy – Integrated Gasification Combined Cycle, Department of Energy, 2000 (http://www.fe.doe.gov/coal_power/igcc/igcc_sum.html, the link has been updated).

"Municipal Solid Waste in the United States: 1999 Facts and Figures", US Environmental Protection Agency

"Final Report: Statewide MSW Composition Study – A Study of Discards in the State of Minnesota", Minnesota Pollution Control Agency, March, 2000

http://www.ciwmb.ca.gov/WasteChar/rescomp.asp?J=165&SortBy=Disposal (The link to the 1999 Materials Disposed by Residential Sector in Los Angels city. Sponsored by Integrated Waste Management Board of California).

George Tchobanoglous, Hilary Theisen, Samuel Vigil, "Integrated Solid Waste Management Engineering Principals and Management Issues". McGraw-Hill, Inc. New York, NY, 1993.

Doug Orr, David Maxwell, *A Comparison of Gasification and Incineration of Hazardous Wastes.* Prepared by Radian International LLC, 2000.

Dale Simbeck, Harry Johnson, "World Gasification Survey: Industry Trends & Developments", EPRI/GTC 2001 Gasification Technologies Conference, San Francisco, CA, October.

D.R. Simbeck, R. L. Dickinson, E.D. Oliver, "Coal Gasification Systems: A Guide to Status, Applications, and Economics". AP-3109 Prepared by Synthetic Fuel Associates, Inc for Electric Power Research Institute, Palo Alto, CA, 1983

W.R. Niessen, C.H. Marks, R.E. Sommerlad, P. Shepherd, "Evaluation of Gasification and Novel Thermal Processes for the Treatment of Municipal Solid Waste," Prepared by Camp, Dresser & McKee for National Renewable Energy Laboratories, DE-AC36-83CH10093, Golden CO, 1996.

E.N. Pistikopulos, "A methodology for minimum environmental impact analysis. In: El-Halwagi, Petrides (eds) Pollution prevention via process modifications". The pollution Prevention Resource Center, NY, 1994.

Subba R. Nishtala, RDF and PRF Process Model Documentation, Research Triangle Institute, 1999

P.A. Pechtl *et al.*, "Evaluation of 450-Mwe BGL GCC Power Plants Fueled with Pittsburgh #8 Coal," Prepared by Bechtel Group, Inc.; British Gas plc.; Lurgi Gmbh.; GE Power Generation and Lotepro Corp. for Electric Power Research Institute: Palo Alto, CA, 1992.

E. Solano, S. Ranjithan, M. A. Barlaz, and E. D. Brill, "Life Cycle-Based Solid Waste Management - 1. Model Development," accepted for publication, Journal of Environmental Engineering, 2002.

Kenneth W. Harrison, Robert D. Dumas, and Morton A. Barlaz, "A Life-Cycle Inventory Model of Municipal Solid Waste Combustion", Journal of Air & Waste Management Association, 2000.

David H. F. Liu, Bela G. Liptak, "Environmental Engineer's Handbook", Boca Raton, FL: CRC Press, 1999.

Barbara Ann Sich, "Evaluating the Impact of Landfill Gas Conversion to Electricity on Greenhouse Equivalents, Cost, and Mass Flow Within A Solid Waste Management System", M.S. Thesis, Department of Civil Engineering, North Carolina State University, Raleigh, 2000

M. M. R. Pickett, "Modeling the Performance and Emissions of British Gas/Lurgi-Based Integrated Gasification Combined Cycle Systems", M.S. Thesis, Department of Civil Engineering, North Carolina State University, Raleigh, 2000.

Sudeep Vaswani, "Development of Models for Calculating the Life Cycle Inventory of Methanol by Liquid Phase and Conventional Production Processes". M.S. Thesis, Department of Civil Engineering, North Carolina State University, Raleigh, 2000.

APPENDIX A RDF PROCESS MODEL DOCUMENTATION

A.1 Introduction

The objective of the Refuse Derived Fuel (RDF) process model is to calculate the energy consumption and life-cycle inventory (LCI) parameters for converting MSW into feedstock, which is used to generated syngas for co-production.

A.2 Conceptual Design of Refuse Derived Fuel Facilities

In the RDF facility, refuse that is received either loose or in bags is loaded onto a conveyor and fed to a flail mill. The flail mill opens any unopened bags and reduces the sizes of some of the materials in the refuse. From the flail mill, the refuse passes under a magnet that recovers ferrous materials. The remaining refuse then continues into a trommel for removal of material less than 2 inches in diameter. The trommel removes materials like broken glass, grit, sand, and etc., that have low energy value. From the trommel, refuse is shredded and then routed to an air classifier that separates the “lights”, considered to have the high BTU content, from the “heavies”, which have a relatively low BTU content. The “lights” then flow to an eddy current separator for aluminum removal. The material remaining after aluminum removal is fed into the IGCC based polygenetation system to produce energy and chemicals. Figure A.1 illustrates the process flow diagram.

A.3 Life-cycle Inventory (LCI) for RDF process model

The calculation sequence for the RDF process model is shown in figure A.2.

A.3.1 Mass Balance Equations

The following equations are used to estimate the quantity and composition of materials flowing through the RDF facility (based on 1 ton MSW).

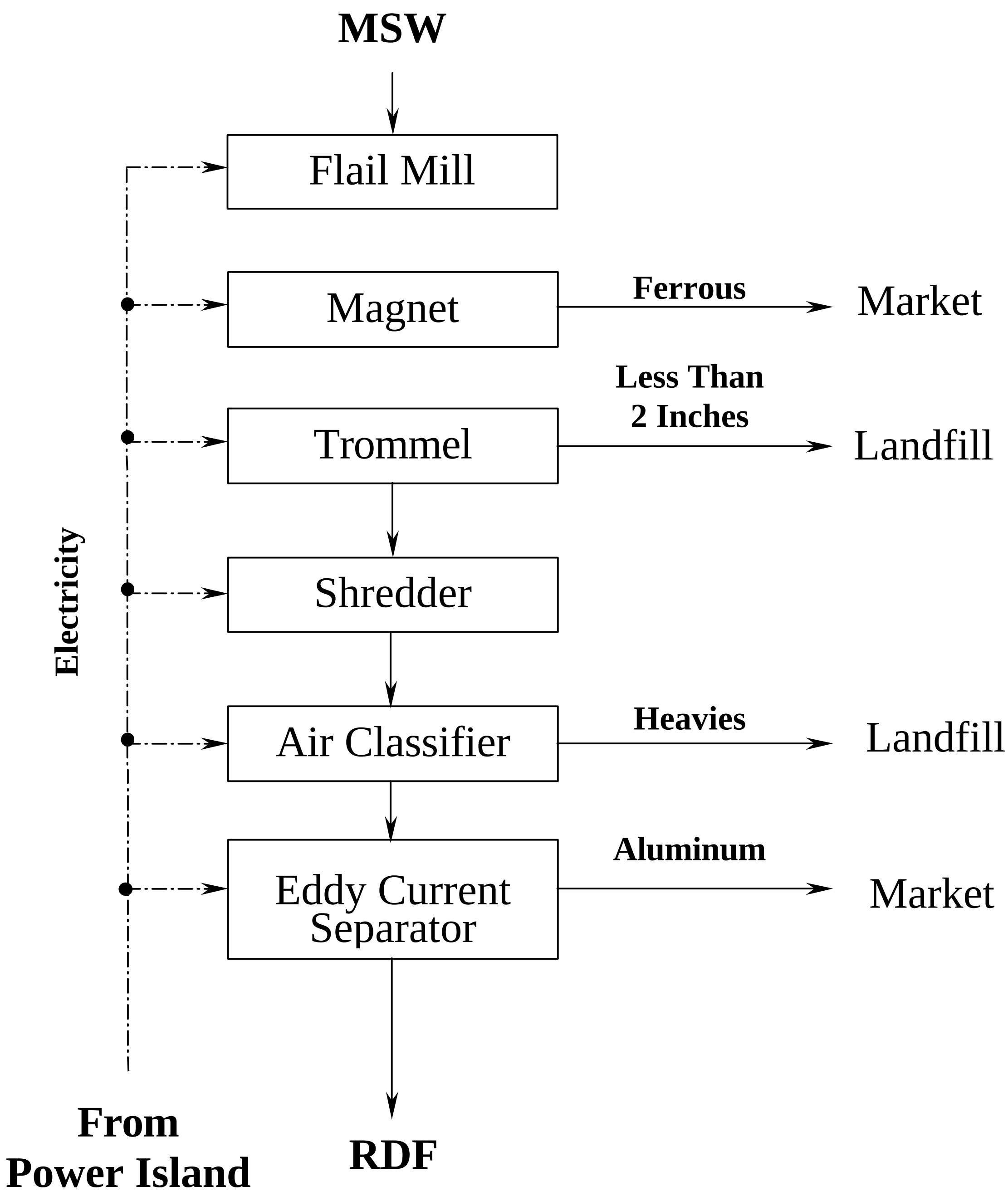


Figure A.1 Process Flow Diagram for Refuse Derived Fuel Production

Tons of item i sent to landfill (removal by trommel and Air classifier)=

RDF_Percent_Removed_by_Trommel + RDF_Percent_removed_as_heavies

RDF used as feedstock to generate syngas

= 1-RDF_Percent_removed_by_first_magnet – RDF_Percent_removed_by_Trommel – RDF_Percent_removed_as_heavies **–** RDF_Aluminum_recovered_per_ton_of_I

Tons of Fe recovered per ton of material processed

= RDF_Percent_removed_by_first_magnet

Tons of Aluminum recovered per ton of material processed

= (1-RDF_Percent_removed_by_first_magnet – RDF_Percent_removed_by_Trommel – RDF_Percent_removed_as_heavies) x RDF_Percent_Removed_by_ECS

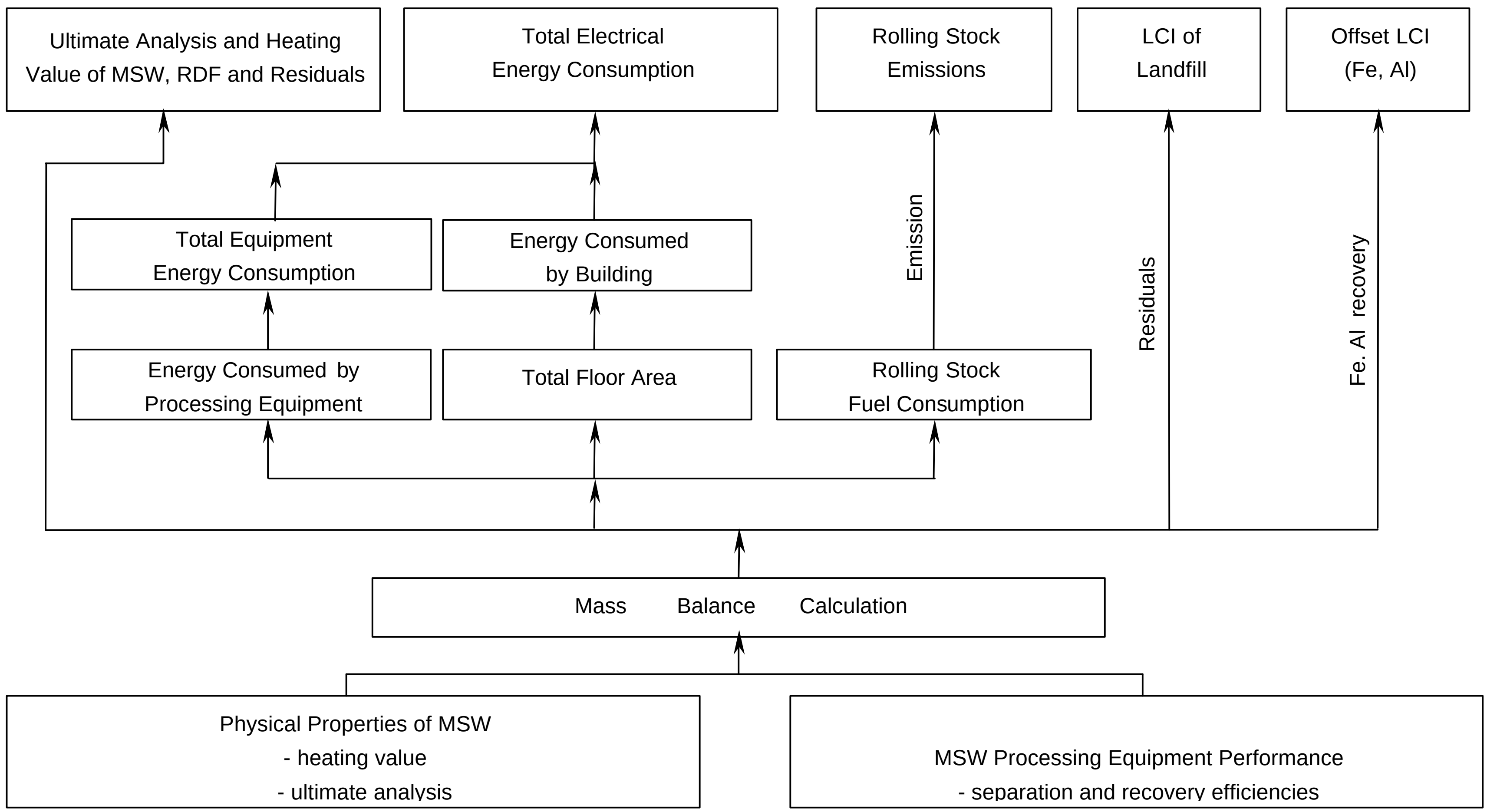


Figure A.2 RDF Process Model Calculation Sequence

A.3.2 Energy Consumption Calculation Equations

Energy is consumed in the production of RDF by both processing equipment such as the shredder and magnet, as well as by rolling stock. Thus both diesel fuel and electrical energy are consumed. For each type of energy, both combustion energy and precombusiton energy is considered. Combustion energy is the energy consumed directly (diesel or electricity), while precombustion energy is the energy that is required to produce the combustion energy. For example, in the case of a magnet, electrical energy is consumed during magnet operation – this is combustion energy. In addition, energy is consumed to extract the fuels used to produce electrical energy (natural gas, coal, uranium, etc.) – this is precombusiton energy. Similarly, there is a precombustion and combustion component to emissions as described in section 3.4.

Total energy consumption for a RDF plant can be calculated as the sum of the energy for rolling stock, the building and processing equipment as given in equation A.3.2.1.

$E_{total} = E_{rolling\ stock} + E_{building} + E_{equipment}$ (Equ A.3.2.1)

E_{total}: Total energy consumption for operating a RDF, Btu/ton MSW
$E_{rolling\ stock}$: Energy consumed to operate rolling stock, Btu/ton MSW
$E_{building}$: Energy consumed to heat and light RDF building, Btu/ton MSW
$E_{equipment}$: Energy consumed to operate equipment in RDF, Btu/ton MSW

A.3.2.1 Energy (Diesel Fuel) Consumed by Rolling Stock

The energy required for operating rolling stock in a RDF is given by Equation A.3.2.2:

$E_{rolling\ stock} = E_{rolling\_comb} + E_{rolling\_precomb}$ (Equ A.3.2.2)

$E_{rolling\ stock}$: Energy consumed to operate rolling stock, Btu/ton MSW
$E_{rolling\_comb}$: combustion energy required to operate rolling stock, Btu/ton MSW
$E_{rolling\_precomb}$: Energy required to produce rolling stock fuel, Btu/ton MSW

The combustion energy required to operate rolling stock in a RDF is given by Equation A.3.2.3, and the precombustion energy required to produce the fuel energy for the rolling stock is given by Equation A.3.2.4. The fuel used for rolling stock is diesel.

$$E\_rolling\_comb = gall\_ton \times Btu\_gall \quad \text{(Equ A.3.2.3)}$$

$$E\_rolling\_precomb = gall\_ton \times E\_precomb\_gall \quad \text{(Equ A.3.2.4)}$$

E_rolling_precomb: Energy required to produce rolling stock fuel, Btu/ton MSW
gall_Ton: Quantity of fuel required in RDF, gallons/Ton MSW
Btu_gall: Btu per gallon of fuel, Btu/gallon
E_precomb_gall: Energy required to produce a gallon of fuel, Btu/gallon

A.3.2.2 Energy (Electricity) Consumed for Heating and Lighting the RDF Building

Energy is used for heating and lighting the RDF building and its enclosed office area. The energy required for this purpose is estimated on a square foot basis. Energy consumption factors are based on national averages for warehouse type buildings, and general office areas. The RDF building consists of the tipping floor area, processing floor area, storage area, and office area. The same energy consumption factor is used for the tipping floor area, storage area, and processing area, while a different factor is used for office area. The energy required for heating and lighting the RDF building for recyclable is given by Equation A.3.2.5. The energy calculated by this equation includes the energy for producing the electricity for heating and lighting the RDF building. For electricity, the precombustion energy requirement is included in the factor R in Equation A.3.2.5. R is the aggregate of combustion and precombustion energy for a user defined regional electricity grid; i.e. T is the energy in Btu it takes to produce a kWh of electricity for a user specified regional grid.

$$E\_building_i = C \times R \times \frac{1}{days/yr} \times \begin{pmatrix} (E1\_sqft \times tipping\_floor\_area_i + processnig\_floor\_area_i \\ + Storage\_area_i) + (E2\_sqft \times Office\_area_i) \end{pmatrix} \text{(Equ A.3.2.5)}$$

C: Factor for converting Btu to kWh, 2.93×10^{-4} kWh/Btu

R: Regional aggregate (combustion + precombustion) energy factor, Btu/kWh, from electric Energy Process Model

Days/yr.: Number of operating days per year

E_building: energy consumed to heat and light the RDF building for recyclable i, Btu/ton waste item i

i: Item of waste

E1_sqft: Energy consumption factor for warehouse type areas, Btu/year-sq ft,

E2_sqft: Energy consumption factor for office type areas, Btu/year-sq ft

Tipping_floor_area: Tipping floor area in RDF for item i, sq ft/TPD

Processing_area: Processing floor area in RDF for item i, sq ft/TPD
Storage_area: Storage area in RDF foe item i, sq ft/TPD
Office_area: Office area in RDF foe item i, sq ft/TPD

A.3.2.2.1 Tipping floor area of the RDF

MSW is unloaded from collection vehicles onto the tipping floor. The tipping floor should be big enough to accommodate more than one truck unloading in the RDF during peak hours. The tipping floor allows for downtime of equipment by including a storage requirement in the estimate. It should be noted that MSW should not be stored for more than a day due to potential health and odor problems. The area required for the tipping floor is calculated assuming an average waste density and a waste pile height. Equation A.3.2.2.1 is used to calculate the tipping floor area.

$$\text{Tipping\_floor\_area}_i = \frac{\text{MF1} \times \text{tipp\_stor} \times 2000}{\text{n1} \times \text{ref\_height}} \quad \text{(Equ A.3.2.2.1)}$$

tipping_floor_area: Area of tipping floor, sq ft/TPD

MF1; Maneuverability factor for the tipping floor, value 2.5

tipp_stor: Storage requirement to allow for equipment downtime, default value is 3 days

N1: Loose density of waste on the tipping floor, default value is 12 lb/cu ft,

ref_height: Height of refuse on the tipping floor, default value is 10 ft

A.3.2.2.2 Processing floor area

The processing floor area consists of area required for magnets, trommels, shredders and balers, and area for loading loose refuse. The loading area includes some area for debagging. The processing area is calculated in Equation A.3.2.2.2.

$$\text{processnig\_area}_i = \text{Floor\_area\_for\_(magnet}_i, \text{trommel}_i, \text{Shredder}_i, \text{baler}_i) + \text{Loading\_area}_i \quad \text{(Equ A.3.2.2.2)}$$

A.3.2.2.3 Office area

The office area includes the front office, meeting rooms, employee rest areas, changing rooms and rest-rooms. Office area is proportional to the quantity of recyclables processed.

Office area = n3 (Equ A.3.2.2.3)

Office area: floor area of office; sq ft/TPD

n3: Office area factor, default value is 20 sq ft/TPD, refer to *Description of the materials recovery facilities process model.*

A.3.2.2.4 Storage area

Baled recovered materials are moved from the baler to be stored in dedicated trailers outside the RDF. This reduces the required floor area in the RDF, and also has an impact on the heating and air conditioning requirements. The number of bales of a waste item i, produced in a day, is given by Equation A.3.2.3.4.

$$storage\_area_i = \frac{MF2 \times footprint \times SE_i \times NO.\,days}{BW_i} \quad \text{(equ A.3.2.3.4)}$$

$Storage\_area_i$: storage area required for bales of recovered materials i, sq ft/TPD

MF2: Maneuverability factor for storage area, value 2.5

No. days: Number of days bales are stored, default value is 3 day

footprint: Area occupied by a bale, default value 20 sq ft

SE_i: sorting efficiency, tons of material recovered per ton of material processed

BW_i: weight of a bale of recovered materials, default values are provided, Tons

A.3.2.3 Energy (Electricity) Consumed by Equipment

Electric energy is consumed by equipment used in the RDF to process and recover recyclable. Energy consumed by the equipment is proportional to the weight of materials processed by the equipment. The energy required to operate the equipment for a waste item i in a RDF is the sum of energy required to run the equipment (combustion energy), and the energy required to produce this energy (precombustion energy), and is given by Equation A.3.2.6.

$$E\_equipment_i = R \quad C \quad \begin{matrix} E\_conveyer_i + E\_trommel_i + E\_magnet_i + E\_thredder_i + E\_air\_classifier_i \\ + E\_eddy\_current\_separator_i + E\_baler_i + E\_flail\_mill_i \end{matrix}$$

E_equipment: Electric energy consumed by equipment in RDF, Btu/ton waste item i

R: Regional aggregate (combustion + precombustion) energy factor, Btu per kWh, from Electric Energy Process Model

C: factor for converting Btu to kWh, 2.93×10^{-4} kWh/Btu

E_conveyer: Energy consumption rate of conveyer, Btu/ton waste item i

E_trommel: Energy consumption rate of trommel Btu/ton waste item i

E_magnet: Energy consumption rate of magnet, Btu/ton waste item i

E_shredder: Energy consumption rate of shredder, Btu/ton waste item i

E_air_classifier: Energy consumption rate of air classifier, Btu/ton waste item i

E_eddy_current_separator: Energy consumption rate of eddy current separator, Btu/ton waste item i

E_baler: Energy consumption rate of baler, Btu/ton waste item i

E_flail_mill: Energy consumption rate of flail mill, Btu/ton waste item i

i: Item of waste

A.3.3 Equations for Ultimate Analysis Calculation

Ultimate analysis (dry wt% basis) was conducted for MSW, RDF, and Landfill Residuals, based on mass balance calculation and the data of ultimate analysis of each waste component and physical properties of MSW.

A.3.3.1 MSW Ultimate Analysis Equations

3.3.1.1 Elemental analysis

$$\text{Mass\_Element}_{ij} = \left(\frac{\text{Mass\_item}_j \times \text{Frac\_element}_{ij}}{1 - \text{Frac\_water}_j}\right) \times (1 - \text{Moisture\_content}_j) \quad \text{(Equ A.3.3.1.1.1)}$$

Mass_Element_{ij}: Tons of element i in waste item j on dry basis(tons/yr)

Mass_item_j: Tons of waste item j processed per year (tons/yr)

Frac_element_{ij}: Fraction of element i in waste item j (%)

Frac_water_j: Fraction of water in waste item j (%)

$\text{Moisture\_content}_j$: Moisture content of waste item j (%)

i: Stand for seven types of element. i = 1, 2, …, 7 (1—Carbon; 2 – Hydrogen; 3 – Oxygen; 4 – Nitrogen; 5 – Chlorine; 6 – Sulfur; 7 – Ash).

$$\text{Mass\_item}_j\text{\_dry} = \sum_{i=1}^{7} \text{Mass\_Element}_{ij} \quad \text{(Equ A.3.3.1.1.2)}$$

$\text{Mass\_item}_j\text{\_dry}$: Dry tons of waste item j processed per year. (tons/yr)

$$\text{Frac\_Element}_i\text{\_MSW} = \frac{\sum_j \text{Mass\_Element}_{ij}}{\sum_j \text{Mass\_item}_j\text{\_dry}} \quad \text{(Equ A.3.3.1.1.3)}$$

Frac_Element$_i$_MSW = Fraction of element I in MSW (Dry wt% basis)

3.3.1.2 MSW heating value calculation

$$\text{Heating\_value\_MSW} = \frac{\sum_i \text{Heating\_value}_i \times \text{Mass\_item}_i}{\sum_i \text{Mass\_item}_i\text{\_dry}} \quad \text{(Equ 3.3.1.2.1)}$$

Heating_value_MSW: Heating value of MSW on dry wt% basis (Btu/lb Dry MSW)

Heating_value$_I$: Heating value of waste item i on wet wt% basis (Btu/ lb wet item i)

Mass_item$_I$: Tons of wet waste item i processed per year (tons/yr)

Mass_item$_I$_dry: Tons of dry waste item i processed per year (tons/yr)

A.3.3.2 RDF Ultimate Analysis Equations

The method of calculations for RDF ultimate analysis are the same as that for MSW ultimate analysis. The mass of RDF item i is from the mass balance calculation.

A.3.3.3 Residuals Ultimate Analysis Equations

The method of calculations for residual ultimate analysis are the same as that for MSW ultimate analysis. The mass of residual item i is from the mass balance calculation.

A.3.4 LCI Calculation Equations

For this RDF facility model, the LCI is comprised of three components: (1) Airborne Release Emissions; (2) Waterborne Release Emissions; (3) Solid Waste Emissions. These emissions come from: (1) Rolling stock pre-combustion; (2) Rolling stock combustion; (3) Emission Offset (Fe and Al recovery); and (4) Landfill Disposal.

A.3.4.1 LCI for Rolling Stock Pre-combustion

$$EM\_precomb = gall\_ton \times Coeff\_precomb_i \times 1000 \times Total\_mass \text{ (Equ A.3.4.1.1)}$$

EM_precomb: Emissions associated with rolling stock precombustion (lbs/yr)

gall_Ton: Quantity of fuel required in RDF, gallons/Ton (gal/ton MSW)

$Coeff\_precomb_i$ = Emission coefficients for rolling stock precombution (lbs/gal)

i = 1, 2, 3.

i = 1: Stand for airborne release emission coefficients

i = 2: Stand for waterborne release emission coefficients

i = 3: Stand for solid waste emission coefficients

Total_mass: Tons of MSW processed per year (tons MSW/yr)

A.3.4.2 LCI for Rolling Stock Combustion

$$EM\_comb = gall\_ton \times Coeff\_comb_i \times 1000 \times Total\_mass \text{ (Equ A.3.4.2.1)}$$

EM_comb: Emissions associated with rolling stock combustion (lbs/yr)

gall_Ton: Quantity of fuel required in RDF, gallons/Ton (gal/ton MSW)

$Coeff\_comb_i$ = Emission coefficients for rolling stock combustion (lbs/gal)

i = 1, 2, 3.

i = 1: Stand for airborne release emission coefficients

i = 2: Stand for waterborne release emission coefficients

i = 3: Stand for solid waste emission coefficients

Total_mass: Tons of MSW processed per year (tons MSW/yr)

A.3.4.3 Offset LCI (Fe and Al recovery)

A.3.4.3.1 Fe recovery

$$EM\_offset\_Fe = Coeff\_offset\_Fe_i \times Fe\_Recovered \text{ (Equ A.3.4.3.1)}$$

EM_offset_Fe: Emissions avoided associated with Fe recovery (lbs/yr).

$Coeff\_offset\_Fe_i$: Emission coefficients for Fe recovery offset (lbs/tons Fe)

i = 1, 2, 3.

i = 1: Stand for airborne release emission coefficients

i = 2: Stand for waterborne release emission coefficients

i = 3: Stand for solid waste emission coefficients

Fe_Recovered: Mass of Fe recovered (tons Fe/yr).

A.3.4.3.1 Al recovery

$$EM\_offset\_Al = Coeff\_offset\_Al_i \times Al\_Recovered \text{ (Equ A.3.4.3.1)}$$

EM_offset_Al: Emissions avoided associated with Al recovery (lbs/yr).

$Coeff\_offset\_Al_i$: Emission coefficients for Al recovery offset (lbs/tons Al)

i = 1, 2, 3.

i = 1: Stand for airborne release emission coefficients

i = 2: Stand for waterborne release emission coefficients

i = 3: Stand for solid waste emission coefficients

Al_Recovered: Mass of Al recovered (tons Al/yr).

A.3.4.4 LCI for Landfill Disposal

The coefficients of landfill emissions were calculated by using Preproc model. Based on the coefficients, LCI for two scenarios--landfill without energy recovery and landfill with energy recovery--was computed.

$$EM\_LF_{ij} = Coeff\_LF_{ij} \times Mass_i \text{ (A.3.4.4.1)}$$

EM_LF_{ij}: Emissions rate of pollutant i from landfill due to disposal of item j (lbs/yr)

$Coeff\_LF_{ij}$: Emission coefficient for pollutant i caused by disposal of item j (lbs/ton item j)

$Mass_j$: Mass of item j (tons item j/yr)

$$EM\_LF_i = \sum_j EM\_LF_{ij} \text{ (A.3.4.4.2)}$$

EM_LF_i: Total emissions of pollutant i per year due to landfill disposal (lbs/yr)

A.4 References

Description of the Material Recovery Facilities process Model, Design, Cost, and Life-Cycle Inventory; Subba Nishtala, Eric solano-Mora, Oct. 1, 1997

PRF and RDF Process Model Documentation; Subba Nishtala, Aug. 9, 1999

Product Literature of RSG INC.

Table A.1 Table of Default Value Used in Energy Calculation

Variable Name	Description	Unit	Value
C	Factor for converting Btu to kWh	kWh/Btu	2.93×10^{-4}
MF1	Maneuverability factor for the tipping floor	Dimensionless	2.5
tipp_stor	Storage requirement to allow for equipment downtime	day	3
N1	Loose density of waste on the tipping floor	lb/cu ft	12
ref_height	Height of refuse on the tipping floor	ft	10
n3	Office area factor	sq ft/TPD	20
MF2	Maneuverability factor for storage area	Dimensionless	2.5
No. days	Number of days bales are stored	day	3
footprint	Area occupied by a bale	sq ft	20
$Coeff\_precomb_i$	Emission coefficients for rolling stock precombustion	lbs/gal	
$Coeff\_comb_i$	Emission coefficients for rolling stock combustion	lbs/gal	
Total_mass:	Tons of MSW processed per year	tons MSW/yr	
$Coeff\_offset\_Fe_i$	Emission coefficients for Fe recovery offset	lbs/tons Fe	
$Coeff\_offset\_Al_i$	Emission coefficients for Al recovery offset	lbs/tons Fe	
Fe_Recovered	Mass of Fe recovered	tons/yr	

Table A.2 Calculation for Air Classifier Electricity Consumption

Classifier (HP)	Fan (HP)	Max Feed (TPH)	Dimensions		
			(ft)	(ft)	(ft)
500	800	350	60	40	75

$$\text{Energy Consumption of Air classifier} = \frac{(500+800)(\text{HP}) \times 0.7457(\text{kW/HP})}{350\,(\text{TPH})} = 2.77\,(\text{kWh/ton})$$

Table A.3 Pollutant Species of LCI

Airborne releases	Waterborne Emissions	Solid Waste
Carbon monoxide	Dissolved Solids	Solid Waste
Nitrogen oxides	Suspended Solids	
Particulates (PM10)	BOD	
Total particulates	COD	
Carbon dioxide (biomass fuel)	Oil	
Carbon dioxide (non-biomass fuel)	Sulfuric Acid	
Sulfur oxides	Iron	
Hydrocarbons (except methane)	Ammonia	
Methane	Copper	
Lead	Cadmium	
Ammonia	Arsenic	
Hydrochloric acid	Mercury	
	Phosphate	
	Selenium	
	Chromium	
	Lead	
	Zinc	

APPENDIX B LCI COEFFICIENTS FOR SUB MODELS OF GASIFICATION SYSTEM

Table B-1 Offset LCI Coefficients for Methanol Using Conventional Process[a]
(lb pollutant / lb methanol produced)

Atmospheric Emissions		LCI Coefficients
	PM	5.52E-04
	PM-10	no data
	SO_2	3.67E-02
	SO_3	no data
	NO_x	3.56E-03
	CO	7.53E-03
	CO_2 (Fossil)	1.57E+00
	CO_2 (Biomass)	no data
	CH_4	8.88E-03
	HCl	no data
	VOC	no data
	NH3	no data
	Hydrocarbons	no data
	CH_3OH	8.65E-07
Liquid Emissions		
	Dissolved Solids	no data
	Suspended Solids	3.37E-04
	BOD	4.90E-05
	COD	3.48E-04
	Oil	no data
	Sulfuric Acid	no data
	Iron	no data
	Ammonia	no data
	Copper	no data
	Cadmium	no data
	Arsenic	no data
	Mercury	no data
	Phosphate	no data
	Selenium	no data
	Chromium	no data
	Lead	no data
	Zinc	no data
Solid Waste		1.91E-01

[a] As presented in Vaswani (2000)

Table B-2 LCI Coefficients for the RDF Plants (lb pollutant / Ton MSW processed)

Pollutant Species	LCI Coefficients
Atmospheric Emissions	
Carbon Monoxide	3.64E-02
Nitrogen Oxides	5.66E-02
PM10	0.00E+00
Particulates (Total)	6.27E-03
CO2 (non biomass)	9.12E-01
CO2 (biomass)	9.20E+00
Sulfur Oxides	1.32E-02
Hydrocarbons (non CH4)	2.59E-02
Methane	1.41E-03
Lead	4.86E-08
Ammonia	1.39E-05
Hydrochloric acid	8.68E-06
GHE (Ton pollutant / ton MSW)	1.36E-04
Waterborne Emissions	
Dissolved Solids	1.21E-02
Suspended Solids	2.74E-04
BOD	4.51E-05
COD	3.02E-04
Oil	2.81E-04
Sulfuric Acid	2.39E-06
Iron	6.59E-06
Ammonia	4.86E-06
Copper	0.00E+00
Cadmium	4.51E-07
Arsenic	0.00E+00
Mercury	3.40E-11
Phosphate	1.21E-06
Selenium	0.00E+00
Chromium	4.51E-07
Lead	5.21E-09
Zinc	2.26E-07
Solid Waste	
Solid Waste	4.62E-02

Table B-3 LCI Coefficients for the Traditional Landfills without Energy Recovery (lb pollutant / Ton MSW processed)

Pollutant Species	LCI Coefficients
Atmospheric Emissions	
Carbon Monoxide	5.49E-01
Nitrogen Oxides	7.13E-02
PM10	0.00E+00
Particulates (Total)	3.58E-02
CO2 (non biomass)	3.62E+00
CO2 (biomass)	5.48E+02
Sulfur Oxides	2.02E-02
Hydrocarbons (non CH4)	9.83E-03
Methane	4.79E+00
Lead	6.12E-08
Ammonia	8.97E-06
Hydrochloric acid	7.19E-03
GHE (Ton pollutant / ton MSW)	1.42E-02
Waterborne Emissions	
Dissolved Solids	4.70E-03
Suspended Solids	8.08E-04
BOD	1.54E-01
COD	4.28E-01
Oil	6.61E-02
Sulfuric Acid	3.36E-03
Iron	5.03E-05
Ammonia	4.91E-03
Copper	0.00E+00
Cadmium	2.03E-07
Arsenic	9.46E-08
Mercury	1.34E-09
Phosphate	3.57E-05
Selenium	3.06E-08
Chromium	4.50E-07
Lead	4.34E-08
Zinc	8.57E-08
Solid Waste	
Solid Waste	8.21E-01

Table B-4 LCI Coefficients for the Traditional Landfills with Energy Recovery (lb pollutant / Ton MSW processed)

Pollutant Species	LCI Coefficients
Atmospheric Emissions	
Carbon Monoxide	1.70E-01
Nitrogen Oxides	-6.02E-03
PM10	0.00E+00
Particulates (Total)	-3.24E-02
CO2 (non biomass)	-2.56E+01
CO2 (biomass)	5.48E+02
Sulfur Oxides	-1.74E-01
Hydrocarbons (non CH4)	4.19E-03
Methane	4.72E+00
Lead	-1.19E-06
Ammonia	-1.56E-05
Hydrochloric acid	4.98E-03
GHE (Ton pollutant / ton MSW)	1.00E-02
Waterborne Emissions	
Dissolved Solids	-2.01E-02
Suspended Solids	-1.97E-02
BOD	1.54E-01
COD	4.27E-01
Oil	6.57E-02
Sulfuric Acid	3.07E-03
Iron	-1.52E-03
Ammonia	4.90E-03
Copper	0.00E+00
Cadmium	-9.18E-07
Arsenic	9.46E-08
Mercury	1.25E-09
Phosphate	-1.09E-04
Selenium	3.06E-08
Chromium	-6.72E-07
Lead	4.33E-08
Zinc	-3.00E-07
Solid Waste	
Solid Waste	-4.76E+00

Table B-5 LCI Coefficients for the Ash Landfills (lb pollutant / Ton ash)

Pollutant Species	LCI Coefficients
Atmospheric Emissions	
Carbon Monoxide	1.15E+01
Nitrogen Oxides	3.40E+01
PM10	0.00E+00
Particulates (Total)	3.12E+00
CO2 (non biomass)	2.43E+03
CO2 (biomass)	5.73E-01
Sulfur Oxides	5.78E+00
Hydrocarbons (non CH4)	8.70E+00
Methane	4.31E-01
Lead	1.31E-05
Ammonia	3.76E-03
Hydrochloric acid	2.90E-03
GHE (Ton pollutant / ton ash)	3.33E-01
Waterborne Emissions	
Dissolved Solids	3.27E+00
Suspended Solids	1.31E-01
BOD	2.49E-02
COD	1.72E+01
Oil	3.44E+01
Sulfuric Acid	6.45E-04
Iron	1.78E-03
Ammonia	3.19E-03
Copper	0.00E+00
Cadmium	1.22E-04
Arsenic	0.00E+00
Mercury	9.20E-09
Phosphate	3.29E-04
Selenium	0.00E+00
Chromium	1.22E-04
Lead	1.41E-06
Zinc	6.10E-05
Solid Waste	
Solid Waste	1.74E+01

Table B-6 Assumed Distance to the Remanufacturing Plant for the RDF Plant and the WTE Plant (Miles)

	The RDF Plant		The WTE Plant	
	Ferrous	**Aluminum**	**Ferrous**	**Aluminum**
Distances	530	400	525	400

Table B-7 Recycled Ferrous and Aluminum Transportation Associated LCI Coefficients for the RDF Plant and the WTE Plant (lb pollutant/ton Fe/Al)

Pollutant Species	**The RDF Plant**		**The WTE Plant**	
	Ferrous	**Aluminum**	**Ferrous**	**Aluminum**
Atmospheric Emissions				
Carbon Monoxide	4.38E-01	3.31E-01	4.34E-01	3.31E-01
Nitrogen Oxides	4.45E-01	3.36E-01	4.40E-01	3.36E-01
PM10	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Particulates (Total)	6.40E-02	4.83E-02	6.34E-02	4.83E-02
CO2 (non biomass)	5.18E+01	3.91E+01	5.13E+01	3.91E+01
CO2 (biomass)	1.24E-02	9.37E-03	1.23E-02	9.37E-03
Sulfur Oxides	1.26E-01	9.52E-02	1.25E-01	9.52E-02
Hydrocarbons (non CH4)	1.79E-01	1.35E-01	1.77E-01	1.35E-01
Methane	8.24E-03	6.22E-03	8.16E-03	6.22E-03
Lead	2.85E-07	2.15E-07	2.82E-07	2.15E-07
Ammonia	8.14E-05	6.14E-05	8.06E-05	6.14E-05
Hydrochloric acid	5.09E-05	3.84E-05	5.04E-05	3.84E-05
GHE (Ton pollutant / ton MSW)	7.09E-03	5.35E-03	7.02E-03	5.35E-03
Waterborne Emissions				
Dissolved Solids	7.08E-02	5.34E-02	7.01E-02	5.34E-02
Suspended Solids	1.61E-03	1.21E-03	1.59E-03	1.21E-03
BOD	2.65E-04	2.00E-04	2.62E-04	2.00E-04
COD	1.77E-03	1.34E-03	1.75E-03	1.34E-03
Oil	1.65E-03	1.24E-03	1.63E-03	1.24E-03
Sulfuric Acid	1.40E-05	1.06E-05	1.39E-05	1.06E-05
Iron	3.87E-05	2.92E-05	3.83E-05	2.92E-05
Ammonia	2.85E-05	2.15E-05	2.82E-05	2.15E-05
Copper	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Cadmium	2.65E-06	2.00E-06	2.62E-06	2.00E-06
Arsenic	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Mercury	1.99E-10	1.51E-10	1.98E-10	1.51E-10
Phosphate	7.12E-06	5.38E-06	7.06E-06	5.38E-06
Selenium	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Chromium	2.65E-06	2.00E-06	2.62E-06	2.00E-06
Lead	3.05E-08	2.30E-08	3.02E-08	2.30E-08
Zinc	1.32E-06	9.98E-07	1.31E-06	9.98E-07
Solid Waste	2.71E-01	2.04E-01	2.68E-01	2.04E-01

Table B-8 Offset LCI Coefficients for Recycled Ferrous and Aluminum (lb pollutant/ton MSW)

Pollutant Species	Recycled Ferrous	Recycled Aluminum
Atmospheric Emissions		
Carbon Monoxide	-2.45E+01	-1.01E+02
Nitrogen Oxides	-1.67E+00	-5.86E+01
PM10	0.00E+00	0.00E+00
Particulates (Total)	-1.00E+01	-5.45E+01
CO2 (non biomass)	-2.06E+03	-2.12E+04
CO2 (biomass)	0.00E+00	0.00E+00
Sulfur Oxides	-3.55E+00	-1.70E+02
Hydrocarbons (non CH4)	-9.77E+00	0.00E+00
Methane	-1.71E+00	-3.26E+01
Lead	1.38E-03	-5.13E-04
Ammonia	0.00E+00	-6.59E-02
Hydrochloric acid	3.61E-02	-4.07E+00
GHE (Ton pollutant / ton MSW)	-2.95E-01	-3.17E+00
Waterborne Emissions		
Dissolved Solids	-1.17E+00	-9.28E+01
Suspended Solids	-4.45E-01	-9.05E+00
BOD	0.00E+00	-1.44E-01
COD	0.00E+00	-2.18E+00
Oil	-1.03E-02	-1.68E+00
Sulfuric Acid	0.00E+00	-1.11E-01
Iron	0.00E+00	-5.88E-01
Ammonia	-1.02E-01	-8.22E-03
Copper	0.00E+00	0.00E+00
Cadmium	0.00E+00	-4.10E-03
Arsenic	0.00E+00	0.00E+00
Mercury	0.00E+00	-3.68E-06
Phosphate	5.29E-03	-5.64E-02
Selenium	0.00E+00	0.00E+00
Chromium	0.00E+00	-4.10E-03
Lead	0.00E+00	-2.13E-05
Zinc	0.00E+00	-1.48E-03
Solid Waste		
Solid Waste	-5.08E+02	-8.02E+03

APPENDIX C CALIBRATION OF IGCC BASED POLYGENERATION MODEL

The IGCC based polygeneration model, the main body of the RDF/coal blend gasification system model, was developed by Pickett and Vaswani in 2000. It was well calibrated to Pittsburgh # 8 coal by Pickett 2000. In this study, due to the difference between the fuel fed to the gasification system, the RDF/coal blend, and Pittsburgh # 8 coal, several case studies were done to verify the performance of the IGCC based polygeneration model firing the RDF/coal blend. In this report, first, case studies were made to reproduce the model results firing Pittsburgh #8 coal in Pickett 2000. Secondly, case studies were done to recalibrate the IGCC model firing German waste and American waste, and comparison was made between the model results firing German waste and the RDF/coal blend in order to verify the model firing the RDF/coal blend. Each case study was described and the modifications made to the model in Pickett 2000 were summarized in this report.

Note: In this report, denote "IGCC_METH" the IGCC based polygeneration model with methanol production in Pickett 2000; denote "IGCC_NO_METH" the IGCC based polygeneration model without methanol production in Pickett 2000.

Part ² Summary of Modifications to the IGCC Based Polygeneration Model

A. Modifications applied to Pittsburgh #8 coal, German waste, American waste, and the RDF/coal blend.

In the process to reproduce the model results in Pickett 2000, modifications were made to the original IGCC based polygeneration model. These modifications were applied to all four fuels.

A.1 FORTRAN code corrected in design specification *IPBFPRO*.

Original code: *C IBREQ = IBGAS + IBCLA + IBLPM*

Corrected code*:* *F IBREQ = IBGAS + IBCLA + IBLPM*

This FORTRAN code sets the target variable (mass flow rate of stream IPBFWPRO) to equal to the sum of mass flow rate of IBGAS, IBCLA, and IBLPM. A “C” will make ASPEN PLUS recognize the sentence as a comment, not an executable one, which is prefixed by “F”.

A.2 Syngas temperature after being quenched that is related to the amount of quench water was corrected. In the Model IGCC_NO_METH, the temperature is set to 297.7 ^{o}F, while in the model IGCC_METH, the value is 299.7 ^{o}F. According to Pickett, 2000, the value of 297.7 ^{o}F is correct.

A.3 Convergence methods in convergences *GC-SPEC2* and *GC-SPEC3* were changed from "SECANT" to "NEWTON". These two convergences have effects on the steam requirement, and steam turbine power output. With their original settings, these two convergences cannot get converged both in model IGCC_METH and IGCC_NO_METH. What we have done is to change their convergence method from "SECANT" to "NEWTON" to make them converged properly.

A.5 Wrong reference to the variable in Pickett's Excel file when he calculated the steam turbine power generation for the case of firing Pittsburgh No. 8 coal with methanol production and purge gas recycle. The steam turbine generate total power is WSTTURB (hp), which is the sum of the power loss WSTLOSS (hp) and the power output WSTPOWER (hp). The correct calculation for the steam turbine power generation is:

Steam turbine power (MW) = WSTPOWER (hp) X 0.0007457 (MW/hp).

But in the case of firing Pittsburgh No. 8 coal with methanol production and purge gas recycle, what Pickett's has done is:

Steam turbine power (MW) = WSTTURB (hp) X 0.0007457 (MW/hp).

A.6 The temperature of stream FGMAKEUP was changed from 75.8 ^{o}F to 78.5 ^{o}F. In model IGCC_METH the value is 78.5 ^{o}F, while in model IGCC_NO_METH the value is 75.8 ^{o}F. The correct value should be 78.5 ^{o}F, which is originally used in the model IGCC_METH. Although there is no mention about the temperature in Matt's thesis, but by checking his sub-model for only Fuel gas saturation area, the value found there is 78.5 ^{o}F.

The temperature has effect on the requirement of steam for saturation heating. The steam for saturation heating (FGSTEAM) through heater SIDEHEAT, together with stream SATWAT through heater FGHEAT1 and QFGHT2, provides the heat for the saturator (SATURTR). Therefore, under the same operation conditions, the sum of heat of heat stream "QFGHT2" and "QSTEAM2" is a constant. While a potion of the heat contained in stream SATWAT is used to heat up the stream FROMGL, and HPMAKUP which is from stream FGMAKEUP after pumping. To heat up the stream HPMAKUP with a lower temperature will need a larger potion of heat from stream SATWAT. Therefore, to keep the sum of the heat of heat stream "QFGHT2" and "QSTEAM2" unchanged; more steam for saturation heating is needed.

A.7 Modification of FORTRAN codes in FORTRAN block *RECYCLE*. These FORTRAN codes have effects on coal feed rate be varying the amount of hydrocarbons recycled back to the combustor.

Original codes (Code No. 1) in IGCC_METH:

```
F     WOIL= 0.9944*XOIL
F     WNAPH = 0.9811*XNAPH
F     WTAR = 0.9987*XTAR*0.3
F     VTAR = 0.9987*XTAR*0.7
```

Where: VTAR is the hydrocarbon recycled via streams RETAR;
WNAPH, WOIL, WTAR are the hydrocarbons recycled via streams RECH.

Original codes (Code No**. 2) in IGCC_NO_METH:**

```
F     VNAPH = 0.8947*XNAPH
F     VOIL = 1.0000*XOIL
F     WTAR = 1.2285*XTAR*0.7810
F     VTAR = 1.2285*XTAR*0.2190
```

Where: VTAR is the hydrocarbon recycled via streams RETAR;
VNAPH, VOIL, WTAR are the hydrocarbons recycled via streams RECH.

For the case of Pittsburgh NO.8 coal, code #2 is recommended. The reason is that code #2 was originally used in model IGCC_NO_METH (IGCC system without methanol production), which was calibrated to Pittsburgh NO.8 coal.

For the case of American waste and German waste, code #1 is recommended. One reason is that when using code #1, the results firing American waste/German waste were reproduced well. The other one is that model IGCC_NO_METH was not calibrated to American waste.

B. Modifications applied to German waste, American waste, and the RDF/coal blend (excluding Pittsburgh # 8 coal).

As shown in Table C.1, among four fuels, German waste, American waste, and the RDF/coal blend have similar properties, which are different from Pittsburgh # 8 coal. The main difference is that higher carbon content than the other three fuels. Therefore, modifications of the operating conditions were required to make to accommodate this fuel difference. The following modifications were applied to German waste, American waste, and the RDF/coal blend, while not applied to Pittsburgh # 8 coal.

Table C.1 Proximate Analysis and Ultimate Analysis of Four Fuels

Proximate Analysis, dry wt%	**Pittsburgh # 8 Coal**	**German Waste**	**RDF/Coal Blend**	**American Waste**
Moisture (wt%)	6	5.1	12.3	9.6
FC & VM	87.8	80.9	86.9	89.5
Ash	12.2	19.1	13.1	10.5
Ultimate Analysis, dry wt%				
Carbon	73.2	52.6	53.99	52.1
Hydrogen	4.9	6.6	6.0	5.9
Nitrogen	1.4	2.5	0.79	0.9
Chlorine	0.0	0.0	0.87	0
Sulfur	3.4	1.4	1.21	0.9
Oxygen	4.9	17.8	24	29.7
Ash	12.2	19.1	13.13	10.3
HHV – Dry Basis (BTU/lb)	13,138	10,026	9,738*	9,970*

* Dulong calculated HHV.

B.1 Combustion zone temperature was changed from 3196 ^{o}F to 3600 ^{o}F. Increasing the combustion zone temperature will cause more heat produced in the combustor and fed to the gasifier.

B.2 Gasification zone temperature was changed from 1300 ^{o}F to 1107 ^{o}F. Decreasing the gasification zone temperature will cause less heat go out of the gasifier.

B.3 The heat loss from the gasifier was changed from 1% to 0.3%. The heat loss from the gasifier is radiate heat and determined by the gasification zone temperature. Therefore, decreasing the gasification zone temperature will cause less heat loss.

B.4 The modifications of the approach temperature were presented in Table C.2. In Pickett 2000, the approach temperature was calibrated by comparison of the syngas composition between German waste and Lurgi data. After making the above modifications, the approach temperature was recalibrated.

Table C.2 Modifications of Approach Temperature for German Waste, the RDF/coal Blend, and American Waste

	Original Value	**Modified Value**
Approach Temperature, °F		
$C + H_2O \leftrightarrow CO + H_2$ (Endothermic)	520	540
$C + CO_2 \leftrightarrow CO$ (Endothermic)	440	485
$C + 2\ H_2 \leftrightarrow CH_4$ (Exothermic)	200	400
$CO + H_2O \leftrightarrow CO_2 + H_2$ (Exothermic)	-200	-170

PART Ï Methodology

In Pickett 2000, IGCC based polygeneration system was calibrated to Pittsburgh # 8 coal. Therefore, model results firing Pittsburgh # 8 coal were reproduced first.

The IGCC based polygeneration system model was comprised of several sub models, such as gasifier island and methanol plant model. These sub models were developed separately and then integrated into one model. Methanol plant sub model was the last one to be integrated, therefore, the first case study was to reproduce Pickett's model results firing Pittsburgh # 8 coal without methanol production (IGCC_NO_METH). With the modifications described in Part ² (A.1–A.7 excluding A.6), the results were well reproduced, as shown in Table C.3.

Table C.3 Reproduced Results and Results in Pickett 2000 for the Case of Pittsburgh # 8 Coal without Methanol Production*

		Pickett's Result	**Reproduced Results**	**Relative Error**
Mass Flow Rate		**Lb/hr**	**Lb/hr**	
To Gasifier				
	Fuel	314540	314545	0.002%
	Oxygen	181368	181369	0.001%
	Steam	106159	106159	0.001%
	Quench Water	513176	513171	0.001%
Crude Syngas		648671	648680	0.001%
Clean Syngas to Saturator		511159	511119	0.008%
Saturated Syngas		943723	943651	0.008%
Air to Gas Turbine		6936730	6935960	0.011%
Fired Fuel Mixture in Gas Turb.		6631940	6631240	0.011%
Overall Consumption of Water		510921	510691	0.045%
Production of Sulfur		9916	9916	0.002%
Slag Production		46113	46114	0.002%
Saturation Water		394417	394187	0.058%
Steam for Sat. Heating		297067	297116	0.016%
		MW		
POWER GENERATION				
Gas Turbines		383.9	383.8	0.010%
Steam Turbines		131.6	131.8	0.091%
Gross Power Generated		515.5	515.6	0.016%
Auxillary Load		48.1	48.1	0.000%
Power to Grid		467.4	467.4	0.018%
OVERALL THERMAL EFF.	HHV BASIS	41.05%	41.06%	0.016%
	LHV BASIS	42.78%	42.79%	0.016%

* This set of results was reproduced by applying modifications from A.1 to A.7, except A.6 in order to fit Pickett's original results without methanol.

After reproducing this set of results, we made 6 modifications (A.1-A.7, excluding A.6) and have the confidence that the model without methanol production in Pickett 2000 (IGCC_NO_METH) is correct, which can be used as the base to calibrate the integrated IGCC model (IGCC system model with methanol production--IGCC_METH) firing Pittsburgh # 8 coal.

With the recognition that the IGCC model results without methanol production is correct, the second case study was to scale down the methanol production in the integrated IGCC model, IGCC_METH, to 1 lb/hr. The objective is to test whether there is error in the integration of methanol model to the IGCC model. When scaling methanol production to 1lb/hr, if the integrated IGCC responses properly, the model results should be similar as the results of IGCC model without methanol production (IGCC_NO_METH).

In this comparison, Code # 2 described in A.7 was used for both models because Code #2 was recommended for Pittsburgh #8 coal and modifications A.1 -A.7 were all included in both models as explained in Part [2].

As illustrated in Table C.4, the model results of IGCC model with 1lb/hr methanol were very similar as the results of IGCC model without methanol. Therefore, from this case study, it was concluded that the integrated IGCC model works properly.

Table C.4 Comparison between IGCC without methanol and with 1 lb/hr methanol for Pittsburgh NO. 8 coal*

	IGCC without methanol	IGCC with 1lb/hr methanol	Relative Error
Mass Flow Rates	**Mass Flow (#/hr)**		
To Gasifier			
Fuel	314545	314535	0.003%
Oxygen	181369	181360	0.005%
Steam	106159	106154	0.005%
Quench Water	513171	513123	0.009%
Crude Syngas	648680	648654	0.004%
Clean Syngas to Saturator	511119	511089	0.006%
Saturated Syngas	943651	943603	0.005%
Air to Gas Turbine	6935960	6935750	0.003%
Fired Fuel Mixture in Gas Turb.	6631240	6630920	0.005%
Overall Consumption of Water	510691	510862	0.034%
Production of Sulfur	9916	9916	0.003%
Slag Production	46114	46112	0.003%
Saturation Water	394187	394367	0.046%
Steam for Sat. Heating	295836	295847	0.004%
POWER GENERATION	**MW**		
Gas Turbines	383.8	383.8	0.004%
Steam Turbines	131.9	131.9	0.021%
Gross Power Generated			
Auxiliary Load	515.7	515.7	0.003%
Power to Grid	48.1	48.1	0.029%
OVERALL THERMAL EFF.	467.6	467.6	0.000%
HHV BASIS	41.07%	41.07%	0.003%
LHV BASIS	42.80%	42.80%	0.003%

* In this comparison: 1) Code No. 2 described in A.7 was used in both models; 2) All modifications through A.1- A.7 were used in both models.

The third case study was to apply the modifications A.1 – A.7 to IGCC model firing Pittsburgh #8 coal with 10,000, 20,000, and 40,000 lb/hr methanol production. The input assumptions were summarized in Table C.5.

Table C.5 Input Assumptions for IGCC Model Firing Pittsburgh #8 Coal w/ Methanol

	Pittsburgh No. 8 Coal
Combustion Zone Temperature	3,357 °F
Gasification Zone Temperature	1,300 °F
Heat Loss from Gasifier	1.00%
Exiting Syngas Temperature	284 °F
Fraction of Carbon in Slag*	1%
Fraction of Sulfur in Slag*	3%
Steam-to-oxygen Molar Ratio	1.0875
Approach temperature (^{0}F):	
$C+H_20 \text{-->} CO + H_2$	520
$C + CO_2 \text{-->} CO$	460
$C+2H_2 \text{-->} CH_4$	150
$CO+H_2O \text{-->} CO_2+H_2$	-360
Proximate Analysis, dry wt%	
Moisture (wt%)	6
Fixed Carbon	48.94
Volatile Matter	38.83
Ash	12.23
Ultimate Analysis, dry wt%	
Carbon	73.21
Hydrogen	4.94
Nitrogen	1.38
Sulfur	3.39
Oxygen	4.85
Ash	12.23
HHV – Dry Basis (BTU/lb)	13,138

Comparisons of reproduced results and Pickett's results were presented in Table C.6.1 - C.6.3. For cases of different methanol productions, the relative differences between the reproduced results and Pickett's results were within 1%. The difference is due to the fact that in ASPEN PLUS, given the same input assumptions, the model can be also affected by some factors such as initial value for a design specification. In the process of reproducing the model results, it is not able to trace every such values. Therefore, there exist some differences between the reproduced results and Pickett's results.

Table C.6.1 Pickett's Results and Reproduced Results for Pittsburgh # 8 Coal with 10k LB/HR Methanol

		Pickett's Result	**Reproduced Results**	**Relative Error**
Mass Flow Rate		**Lb/hr**	**Lb/hr**	
To Gasifier	Fuel	326982	324802	0.67%
	Oxygen	187822	187281	0.29%
	Steam	109936	109620	0.29%
	Quench Water	531464	529885	0.30%
Crude Syngas		671793	669769	0.30%
Clean Syngas to Saturator		473939	472551	0.29%
Clean Syngas to Methanol		55224	55174	0.09%
Total Clean Syngas		531181	529738	0.27%
Feed Syngas to Gas Turbine		957835	955203	0.27%
Air to Gas Turbine		6922200	6925130	0.04%
Purge Gas from Methanol		44862	44824	0.08%
Total Feed to Saturator		518800	517375	0.27%
Fuel Mixture in Gas Turbine		6634040	6633810	0.00%
Methanol		10001	10000	0.01%
Overall Water Consumption		519824	518406	0.27%
Production of Sulfur		10296	10230	0.65%
Slag Production		47937	47618	0.67%
Steam to Methanol Process		7966	7965	0.02%
Saturation Water		399512	398444	0.27%
Steam for Saturation Heating		283925	283137	0.28%
		MW		
Gas Turbines		384.62	384.40	0.06%
Steam Turbines		132.57	132.52	0.04%
Gross Power		517.19	516.92	0.05%
Auxiliary Loads		53.86	53.72	0.26%
Power to Grid		463.33	463.20	0.03%
Methanol Production		11.44	11.44	0.01%
Total Power (w/Methanol)		474.77	474.64	0.03%
Power Thermal Efficiency				
HHV BASIS		39.15%	39.40%	0.64%
LHV BASIS		40.80%	41.06%	0.64%
Combined Thermal Efficiency				
HHV BASIS		40.12%	40.37%	0.64%
LHV BASIS		41.81%	42.07%	0.64%

* 1. Code # 2 was used for Pittsburgh No.8 coal. See A.7.
2. Pickett's results were revised. See A.5.

Table C.6.2 Pickett's Results and Reproduced Results for Pittsburgh # 8 Coal with 20k LB/HR Methanol

		Pickett's Result	Reproduced Results	Relative Error
Mass Flow Rate		**Lb/hr**	**Lb/hr**	
To Gasifier	Fuel	337277	334664	0.77%
	Oxygen	193556	192946	0.31%
	Steam	113293	112936	0.31%
	Quench Water	547690	545831	0.34%
	Crude Syngas	692277	690026	0.33%
Clean Syngas to Saturator		434834	433346	0.34%
Clean Syngas to Methanol		110449	110340	0.10%
Total Clean Syngas		547363	545760	0.29%
Feed Syngas to Gas Turbine		968483	965534	0.30%
Air to Gas Turbine		6912270	6915740	0.05%
Purge Gas from Methanol		89732	89622	0.12%
Total Feed to Saturator		524566	522968	0.30%
Fuel Mixture in Gas Turbine		6636550	6636440	0.00%
Methanol		19999	20000	0.00%
Overall Water Consumption		526842	525248	0.30%
Production of Sulfur		10612	10532	0.75%
Slag Production		49447	49063	0.77%
Steam to Methanol Process		15931	15928	0.02%
Saturation Water		403185	401987	0.30%
Steam for Saturation Heating		270869	269881	0.37%
		MW		
	Gas Turbines	385.09	384.86	0.06%
	Steam Turbines	132.79	132.75	0.03%
	Gross Power	517.88	517.61	0.05%
	Auxiliary Loads	59.39	59.23	0.27%
Power to Grid		458.49	458.38	0.02%
	Methanol Production	22.88	22.88	0.00%
Total Power (w/Methanol)		481.37	481.26	0.02%
Power Thermal Efficiency				
	HHV BASIS	37.56%	37.84%	0.76%
	LHV BASIS	39.14%	39.44%	0.76%
Combined Thermal Efficiency				
	HHV BASIS	39.43%	39.73%	0.76%
	LHV BASIS	41.09%	41.40%	0.76%

* 1. Code # 2 was used for Pittsburgh No.8 coal. See A.7.
2. Pickett's results were revised. See A.5.

Table C.6.3 Pickett's results and Reproduced Results for Pittsburgh # 8 Coal with 40k LB/HR Methanol

		Pickett's Result	**Reproduced Results[2]**	**Relative Error**
Mass Flow Rate		**Lb/hr**	**Lb/hr**	
To Gasifier	Fuel	357844	354373	0.97%
	Oxygen	205008	204302	0.34%
	Steam	119995	119582	0.34%
	Quench Water	580116	577903	0.38%
	Crude Syngas	733184	730543	0.36%
Clean Syngas to Saturator		356482	354936	0.43%
Clean Syngas to Methanol		220992	220667	0.15%
Total Clean Syngas		579677	577798	0.32%
Feed Syngas to Gas Turbine		989678	986177	0.35%
Air to Gas Turbine		6892330	6896500	0.06%
Purge Gas from Methanol		179560	179210	0.19%
Total Feed to Saturator		536042	534146	0.35%
Fuel Mixture in Gas Turbine		6641390	6641310	0.00%
Methanol		39999	39999	0.00%
Overall Water Consumption		540796	538959	0.34%
Production of Sulfur		11241	11135	0.94%
Slag Production		52462	51953	0.97%
Steam to Methanol Process		31873	31856	0.05%
Saturation Water		410485	409089	0.34%
Steam for Saturation Heating		244676	243615	0.43%
		MW		
	Gas Turbines	386.02	385.75	0.07%
	Steam Turbines	133.65	133.66	0.01%
	Gross Power	519.66	519.41	0.05%
	Auxiliary Loads	70.45	70.25	0.29%
Power to Grid		449.22	449.17	0.01%
	Methanol Production	45.77	45.77	0.00%
Total Power (w/Methanol)		494.99	494.94	0.01%
Power Thermal Efficiency				
	HHV BASIS	34.68%	35.02%	0.97%
	LHV BASIS	36.14%	36.49%	0.97%
Combined Thermal Efficiency				
	HHV BASIS	38.22%	38.59%	0.97%
	LHV BASIS	39.83%	40.21%	0.97%

* 1. Code # 2 was used for Pittsburgh No.8 coal. See A.7.
2. Pickett's results were revised. See A.5.

In Pickett 2000, the integrated IGCC model calibrated to Pittsburgh #8 coal was applied to German waste and American waste and calibrated to German waste. However, it was found out that with the original input assumptions in Pickett 2000, the original model results firing German waste and American waste have major errors: there are negative heat produced in the gasifier. Therefore, modification and recalibration was done for German waste and American waste in the process of verification of model firing the RDF/coal blend. Consequently, the modifications B.1- B.4 were made to the model input assumptions and then the model was applied to the RDF/coal blend, German waste, and American waste.

As presented in Pickett 2000, German waste composition and a corresponding syngas composition data were provided by Lurgi Umwelt GmbH FRG. Using this information, the IGCC model firing German waste was calibrated to the Lurgi syngas composition data. In addition, the fuel properties of German waste, the RDF/coal blend, and American waste are similar, as presented in Table C.7. Therefore, to do the verification of model performance to the RDF/coal blend, first, the integrated IGCC model firing German waste was recalibrated to the Lurgi syngas composition data with the modifications A.1-A.7 and B.1-B.4. Then comparison was made between the model results firing German waste and the RDF/coal blend with the same modified input assumptions. Finally, the calibrated model results firing German waste, the RDF/coal blends and American waste were summarized.

Table C.7 Proximate and Ultimate Analysis of the RDF/coal blend and German waste

Proximate Analysis, dry wt%	**German Waste**	**RDF/Coal Blend**	**American Waste**
Moisture (wt%)	5.1	12.3	9.6
FC & VM	80.9	86.9	89.5
Ash	19.1	13.1	10.5
Ultimate Analysis, dry wt%			
Carbon	52.6	53.99	52.1
Hydrogen	6.6	6.0	5.9
Nitrogen	2.5	0.79	0.9
Chlorine	0.0	0.87	0
Sulfur	1.4	1.21	0.9
Oxygen	17.8	24	29.7
Ash	19.1	13.13	10.3
HHV – Dry Basis (BTU/lb)	10,026	9,738*	9,970*

* Dulong calculated HHV.

The major modified input assumptions for German waste, the RDF/coal blend, and American waste were presented in Table C.8.

Table C.8 Recalibrated Input Assumptions for IGCC Model Firing German Waste, the RDF/Coal Blend, and American Waste w/ Methanol

Combustion Zone Temperature	3,600 °F
Gasification Zone Temperature	1,107 °F
Heat Loss from Gasifier	0.3%
Exiting Syngas Temperature	284 °F
Fraction of Carbon in Slag*	1%
Fraction of Sulfur in Slag*	3%
Steam-to-oxygen Molar Ratio	1.0875
Approach temperature (^{0}F):	
$C+H_20 \text{-->} CO + H_2$	540
$C + CO_2 \text{-->} CO$	485
$C+2H_2 \text{-->} CH_4$	400
$CO+H_2O \text{-->} CO_2+H_2$	-170

The combustion zone temperature and gasification zone temperature were determined through trial and error to maintain positive heat production and 0.3% heat loss in the gasifier. The approach temperatures were determined based on the development of the approach temperature curves.

In the gasifier modeled in this study, Equations C-1 to C-5 are specified to model the equilibrium of key components such as CO, CO_2, H_2O, H_2, NH_3 and CH_4. The following equilibrium relations are assumed in the model:

$$C + H_2O \leftrightarrow CO + H_2 \quad \text{(C-1)}$$

$$C + CO_2 \leftrightarrow CO \quad \text{(C-2)}$$

$$C + 2\,H_2 \leftrightarrow CH_4 \quad \text{(C-3)}$$

$$CO + H_2O \leftrightarrow CO_2 + H_2 \quad \text{(C-4)}$$

$$0.5\,N_2 + 1.5\,H_2 \leftrightarrow NH_3 \quad \text{(C-5)}$$

The gasifier modeled is an RGIBBS reactor. The syngas composition can be adjusted by adjusting the approach temperatures of the reactions represented by Equations

(C-1) to (C-4). The major components of the syngas are CO, H_2, CO_2, and CH_4. The calibration curves that show the relationship between the approach temperature of one reaction with the mole percent of the above four components were made, as presented from Figure C-1 to Figure C-4.

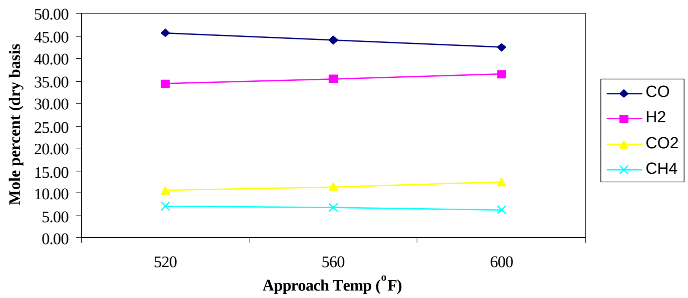


Figure C-1. Syngas Calibration Curves for Reaction: C + H2O = CO + H2 (Endothermic)

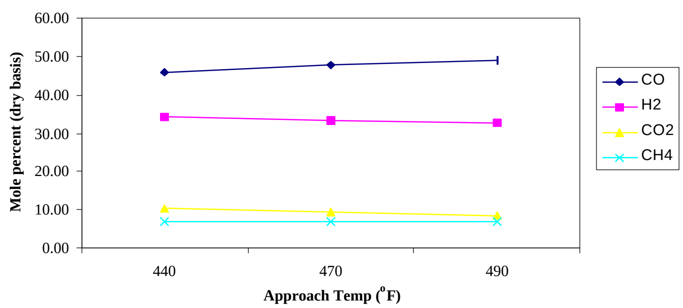


Figure C-2. Syngas Calibration Curves for Reaction: C + CO2 = CO (Endothermic)

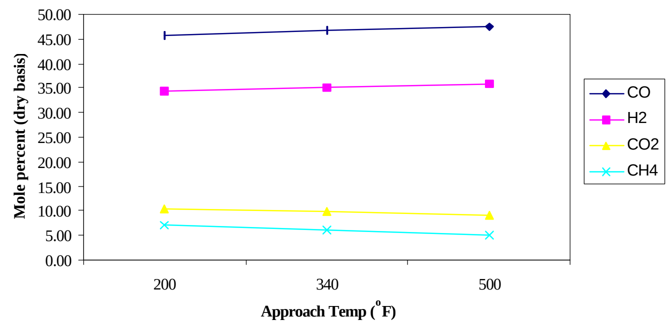


Figure C-3. Syngas Calibration Curves for Reaction: C + 2 H2 = CH4 (Exothermic)

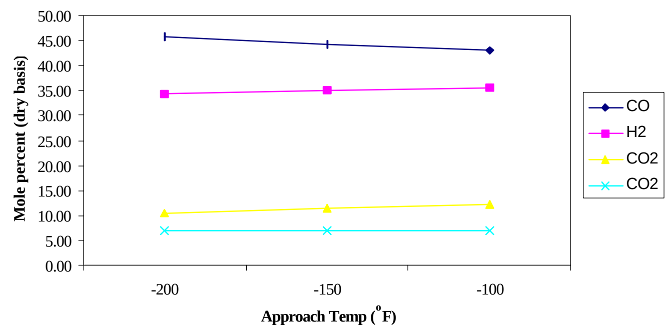


Figure C-4. Syngas Calibration Curves for Reaction: CO + H2O = CO2 + H2 (Exothermic)

Based on the above four syngas calibration curves, through trial and error, the approach temperature for the German waste was modified as presented in Table C.8. The comparison results of the syngas composition of German waste with modified input assumptions and the Lurgi data were presented in Table C.9. The two major components of the syngas of German waste, CO and H_2, were less than 3% different from the Lurgi data.

Table C.9 Crude Syngas Composition Comparison: German Waste V.S. Lurgi Data

Components (dry basis)	**German Waste (mole%)**	**Lurgi Data (mole%)**	**Difference**
CO_2	8.15	7.28	12.0%
CO	47.20	46.26	2.0%
H_2	35.28	36.35	2.9%
CH_4	5.96	5.92	0.7%
C_nH_m	0.36	0.52	29.8%
H_2S	0.61	0.47	29.4%
N_2	2.43	3.2	24.0%

Using same input assumptions as German waste, the integrated IGCC model was applied to the RDF/coal blend. The syngas composition was presented in Table C.10. For CO, the relative difference is 2.1%. For H_2, the relative difference is only 0.6%.

Table C.10 Crude Syngas Composition Comparison: German Waste V.S. RDF/Coal Blends

Components (dry basis)	**RDF/Coal (mole%)**	**German Waste(mole%)**	**Difference**
CO_2	8.77	8.15	7.1%
CO	48.23	47.20	2.1%
H_2	35.08	35.28	0.6%
CH_4	5.48	5.96	8.8%
C_nH_m	0.37	0.36	1.4%
H_2S	0.49	0.61	24.1%
N_2	1.58	2.43	54.0%

The model result comparison between German waste and the RDF/coal blend was presented in Table C.11.

Table C.11 Comparison of IGCC Model Results Firing RDF/coal Blends and German Waste with 10,000 lb/hr Methanol Production

		RDF/Coal blends	German waste	Difference
Mass Flow Rate		lb/hr	lb/hr	
To Gasifier	Fuel	481,969	446,620	7.3%
	Oxygen	195,164	219,195	12.3%
	Steam	114,234	128,300	12.3%
	Quench Water	1,505,680	1,431,760	4.9%
Crude Syngas		730,624	718,850	1.6%
Clean Syngas to Saturator		456,039	454,602	0.3%
Clean Syngas to Methanol		40,487	40,783	0.7%
Total Clean Syngas		498,420	497,275	0.2%
Feed Syngas to Gas Turbine		898,164	895,998	0.2%
Air to Gas Turbine		6,975,550	6,974,450	0.0%
Purge Gas from Methanol		30,172	30,458	0.9%
Total Feed to Saturator		486,211	485,060	0.2%
Fuel Mixture in Gas Turbine		6,618,120	6,615,050	0.0%
Methanol		10,000	10,001	0.0%
Overall Water Consumption		390,841	413,170	5.7%
Production of Sulfur		5,164	5,908	14.4%
Slag Production		69,862	100,297	43.6%
Steam to Methanol Process		5,517	5,651	2.4%
Saturation Water		266,905	274,649	2.9%
Steam for Saturation Heating		222,152	223,613	0.7%
		MW		
Gas Turbines		382.31	382.6	0.1%
Steam Turbines		129.91	134.4	3.5%
Gross Power		511.21	517.0	1.1%
Auxiliary Loads		57.60	61.4	6.6%
Power to Grid		453.60	455.7	0.5%
Methanol Production		11.44	11.44	0.0%
Total Power (w/Methanol)		465.05	467.11	0.4%
Power Thermal Efficiency				
HHV BASIS		37.61%	36.6%	2.7%
LHV BASIS		40.20%	39.1%	2.7%
Combined Thermal Efficiency				
HHV BASIS		38.56%	37.5%	2.7%
LHV BASIS		41.21%	40.1%	2.7%

Analysis of the model results:

1) Fuel feed rate.

More fuel is needed for the RDF/coal blends than German waste. The reason to account for this is that the RDF/coal blends contain more water (12.32%, wet weight) than German waste (5.1%, wet weight). Given similar carbon and hydrogen content, and same input assumptions, to produce same amount of methanol and power, more RDF/coal blends are needed to offset the effect of larger moisture content. If calculated on a dry basis, the fuel demand for RDF/coal blends is 422,590 lb/hr, comparable to the fuel demand for German waste, which is 423,842 lb/hr.

2) Oxygen to gasifier and steam to gasifier.

The oxygen to gasifier is determined by the combustion zone temperature and oxygen content of the fuel. The combustion zone temperature is the same for the RDF/coal blends and German waste, so this factor has negligible effect on the oxygen difference. The principal reason is due to the oxygen content difference of these two fuels. For the RDF/coal blends, the oxygen content is 24.0% (dry basis), while the oxygen content for German waste is 17.8% (dry basis). Therefore, less oxygen is consumed by the RDF/coal blends. The steam to gasifier will increase with the increase of the oxygen because the steam to oxygen ratio is set to a constant number as modeled in this study. Therefore, less steam is consumed by the RDF/coal blends too.

3) Quench water

About 4.9% more quench water is needed for the RDF/coal blends. The quench water is used to quench the exit gas from the gasifier. The reasons for the difference are: 1) The amount of the exit gas for RDF/coal blend (7.80×10^5 lb/hr) is, 0.20×10^5 lb/hr more than German waste (7.60×10^5 lb/hr); 2) The exit gas of RDF/coal blend contains more water (20.7%, mole) than that of German waste (19.8%, mole) and water has a large heat capacity.

4) Clean syngas to methanol

The amount of clean syngas to methanol is determined by the syngas composition (H_2 and CO), specially, the H_2/CO mole ratio. The methanol production increases with the increase of the H_2/CO mole ratio (Vaswani, 2000). To produce 10,000 lb methanol/hr, similar clean syngas demands are needed for both RDF/coal blends and German waste because their H_2/CO mole ratios are similar. The value is 0.727 for RDF/coal blends and 0.747 for German waste.

5) Clean syngas to saturator

The clean syngas will be saturated before it goes to gas turbine to produce power. Because of the similarity of the syngas composition of the RDF/coal blends and German waste, the heating value of the two types of syngas is similar. Therefore, similar amount of syngas will go to the gas turbine due to the constant gas turbine size (i.e., production of power is similar) and the similar heating value of the two types of syngas.

6) Power production

For these two similar fuels, with the same IGCC input assumptions, the power generated from the gas turbine is similar for both fuels due to constant gas turbine size. In German waste case more power from steam turbines is produced. The reason is that German waste has a higher heating value and so it produces more heat in gasifier. With the same heat loss for both fuels, more heat for German waste was recovered to produce jacket steam, which goes to steam turbines to produce more power. German waste consumes more auxiliary power due to more power consumed in the oxygen plant.

7) Slag production

The slag production difference of these two fuels is due to the different ash content: 19.1% (dry basis) for German waste and 13.1% (dry basis) for RDF/coal blends

8) Efficiency

German waste has lower system efficiency partly due to the more jacket steam production. More fuel was used to produce jacket steam and this part of energy input can not be used 100% in the steam turbines. Another reason is due to the more power consumed in the oxygen plants.

The integrated model was reapplied to German waste and American waste with recalibrated input assumptions as presented in Table C.8. The results were summarized in Table C.12 and C.13.

Table C.12 Model Results Firing German Waste with 10k, 20k, and 40k Methanol Production and with Recalibrated Input Assumptions

	10,000 lb/hr	**20,000 lb/hr**		**40,000 lb/hr**	
Mass Flow Rates	**Massflow lb/hr**	**Massflow lb/hr**	**Difference From 10k**	**Massflow lb/hr**	**Difference From 10k**
To Gasifier Fuel	446,620	460,090	3%	487,184	9%
Oxygen	219,195	225,800	3%	239,066	9%
Steam	128,300	132,165	3%	139,931	9%
Quench Water	1,431,760	1,474,840	3%	1,561,450	9%
Crude Syngas	718,850	740,467	3%	783,944	9%
Clean Syngas to Saturator	454,602	428,726	-6%	377,156	-18%
Clean Syngas to Methanol	40,783	81,548	100%	163,069	150%
Total Clean Syngas	497,275	512,220	3%	542,285	9%
Saturated Syngas (Feed to GT)	895,998	904,507	1%	921,743	3%
Air to Gas Turbine	6,974,450	6,965,660	0%	6,949,880	0%
Purge Gas from Methanol	30,458	60,934	100%	121,820	150%
Total Feed to Saturator	485,060	489,660	1%	498,976	3%
Fired Fuel Mixture in Gas Turb.	6,615,050	6,616,350	0%	6,620,650	0%
Methanol	10,001	20,000	100%	39,999	150%
Overall Consumption of Water	413,170	417,341	1%	424,200	3%
Production of Sulfur	5,908	6,077	3%	6,418	8%
Slag Production	100,297	103,322	3%	109,407	9%
Steam to Methanol Process	5,651	11,300	100%	22,596	150%
Saturation Water	274,649	274,976	0%	274,111	0%
Steam for Sat. Heating	223,613	211,333	-5%	186,764	-17%
	MW	**MW**		MW	
Gas Turbines	382.6	383.0	0.1%	383.8	0.3%
Steam Turbines	134.4	134.7	0.2%	135.2	0.6%
Gross Power	517.0	517.7	0.1%	519.1	0.4%
Auxiliary Loads	61.4	66.2	7.8%	75.7	21.6%
Power to Grid	455.7	451.6	-0.9%	443.3	-2.7%
Methanol Production	11.4	22.9	100.9%	45.8	150.2%
Total Power (with Methanol)	467.1	474.5	1.6%	489.1	4.6%
Power Only Thermal Efficiency					
HHV BASIS	36.59%	35.20%	-3.8%	32.63%	-11.3%
LHV BASIS	39.11%	37.62%	-3.8%	34.88%	-11.2%
Combined Thermal Efficiency					
HHV BASIS	37.51%	36.98%	-1.4%	36.00%	-4.1%
LHV BASIS	40.09%	39.53%	-1.4%	38.48%	-4.1%

Table C.13 Model Results Firing American Waste with 10k, 20k, and 40k Methanol Production and with Recalibrated Input Assumptions

	10,000 lb/hr	20,000 lb/hr		40,000 lb/hr	
Mass Flow Rates	**Massflow lb/hr**	**Massflow lb/hr**	**Difference From 10k**	**Massflow lb/hr**	**Difference From 10k**
To Gasifier Fuel	470,414	484,648	3%	513,184	9%
Oxygen	138,189	142,369	3%	150,717	9%
Steam	80,885	83,331	3%	88,218	9%
Quench Water	1,066,430	1,098,680	3%	1,163,050	9%
Crude Syngas	679,325	699,821	3%	740,899	9%
Clean Syngas to Saturator	441,176	411,317	-7%	351,698	-20%
Clean Syngas to Methanol	44,518	89,022	100%	178,006	300%
Total Clean Syngas	487,547	502,248	3%	531,724	9%
Saturated Syngas (Feed to GT)	877,901	885,885	1%	901,998	3%
Air to Gas Turbine	7,002,360	6,994,960	0%	6,980,860	0%
Purge Gas from Methanol	34,178	68,352	100%	136,689	300%
Total Feed to Saturator	475,354	479,670	1%	488,387	3%
Fired Fuel Mixture in Gas Turb.	6,619,840	6,621,750	0%	6,626,300	0%
Methanol	9,999	20,000	100%	40,000	300%
Overall Consumption of Water	397,158	399,205	1%	406,756	2%
Production of Sulfur	3,938	4,049	3%	4,270	8%
Slag Production	55,225	56,896	3%	60,246	9%
Steam to Methanol Process	6,429	12,858	100%	25,711	300%
Saturation Water	305,807	305,422	0%	308,114	1%
Steam for Sat. Heating	231,584	218,652	-6%	193,132	-17%
	MW	**MW**		**MW**	
Gas Turbines	380.3	380.7	0.1%	381.4	0.3%
Steam Turbines	142.7	143.3	0.4%	144.3	1.1%
Gross Power	523.0	523.9	0.2%	525.7	0.5%
Auxiliary Loads	46.8	51.4	9.8%	60.6	29.5%
Power to Grid	476.3	472.6	-0.8%	465.1	-2.4%
Methanol Production	11.4	22.9	100.9%	45.8	301.8%
Total Power (with Methanol)	487.7	495.5	1.6%	510.8	4.7%
Power Only Thermal Efficiency					
HHV BASIS	38.3%	36.9%	-3.7%	34.3%	-10.4%
LHV BASIS	40.8%	39.3%	-3.7%	36.5%	-10.5%
Combined Thermal Efficiency					
HHV BASIS	39.2%	38.7%	-1.3%	37.7%	-3.8%
LHV BASIS	41.8%	41.2%	-1.4%	40.1%	-4.1%

Part Ø Discussions

The IGCC based polygeneration system model was developed to simulate the IGCC system with polygeneration of chemicals such as methanol and ammonia. In this study, the model includes the methanol process. It is easy for users to specify the methanol plant size, which is favorable for the realistic application. Also, it is applicable for the ammonia process to be combined to produce a bigger model. However, there are some limitations associated with this model.

1. The gas turbine size was modeled as a constant, which is not a flexible design.
2. For two considerably different fuels, the model input assumptions needs to be reconfigured and recalibrated, including combustion zone temperature, gasification zone temperature, and approach temperatures. Reconfiguration is often time consuming, for example, to reconfigure the approach temperatures, only trial and error method can be used based on approach temperature curves.
3. Current model does not incorporate the probability analysis tools, which can be used to quantify the uncertainty and variability associated with the model.

Recommendations for future model related work are:

1. Develop one method to make the model automatically adjust the gasification zone temperature for different fuels, instead of using trial and error method.
2. Combine the ammonia process model to generate a bigger model.
3. Incorporate the probability analysis tools with the IGCC based polygeneration model.

APPENDIX D DETAILED LCI DATA FOR FOUR SENSITIVITY ANALYSIS CASES

Table D.1.1 LCI Results of Gasification System Firing MSW[a] $_{0.2\sim1.5}$ with a Landfill without Energy Recovery[b] (Lbs/Ton MSW)

	Coal Precomb.	IGCC Plant	RDF Plant	Traditional Landfill	Ash Landfill	Electricity Offset	Methanol Offset[C]	Transport[d]	(Al + Fe) Offset	Total
Airborne Releases										
Carbon monoxide	1.95E-02	6.73E-01	3.64E-02	1.35E-02	1.76E-03	-8.43E-01	-2.42E-01	2.26E-02	-2.30E+00	-2.62E+00
Nitrogen oxides	2.50E-02	1.23E+00	5.66E-02	2.26E-03	5.19E-03	-1.12E+01	-1.14E-01	2.29E-02	-8.05E-01	-1.08E+01
Total particulates	2.78E-01	7.59E-02	6.27E-03	2.48E-06	4.76E-04	-3.81E+00	-1.77E-02	3.30E-03	-1.10E+00	-4.57E+00
Carbon dioxide (fossil fuel)	4.42E+00	1.23E+03	9.12E-01	3.56E-02	3.71E-01	-2.97E+03	-5.05E+01	2.67E+00	-3.52E+02	-2.13E+03
Carbon dioxide (biomass fuel)	3.26E-02	1.05E+03	9.20E+00	2.86E+00	8.74E-05	-4.20E-01	0.00E+00	6.39E-04	0.00E+00	1.07E+03
Sulfur oxides	2.50E-02	2.58E-03	1.32E-02	9.71E-05	8.82E-04	-1.97E+01	-1.18E+00	6.50E-03	-2.28E+00	-2.32E+01
Hydrocarbons	9.22E-03	6.58E-02	2.59E-02	6.17E-06	1.33E-03	-5.74E-01	N/A	9.21E-03	-4.11E-01	N/A
Methane	5.09E-01	N/A	1.41E-03	8.02E-03	6.57E-05	-6.54E+00	-2.85E-01	4.25E-04	-4.81E-01	-6.79E+00
Lead	2.93E-07	N/A	4.86E-08	1.25E-02	2.01E-09	-1.27E-04	N/A	1.47E-08	5.17E-05	N/A
Ammonia	9.44E-06	N/A	1.39E-05	3.10E-08	5.73E-07	-2.49E-03	N/A	4.19E-06	-8.25E-04	N/A
Hydrochloric acid	1.19E-04	N/A	8.68E-06	1.35E-06	4.43E-07	-2.40E-01	N/A	2.62E-06	-4.95E-02	N/A
GHE[e] (Tons/day)	2.06E-03	N/A	1.28E-04	1.18E-06	5.07E-05	-4.24E-01	-7.70E-03	3.65E-04	-4.93E-02	-4.78E-01
Waterborne Releases										
Dissolved Solids	8.90E-03	N/A	1.21E-02	1.48E-04	4.98E-04	-2.52E+00	N/A	3.65E-03	-1.21E+00	N/A
Suspended solids	1.53E-01	N/A	2.74E-04	1.61E-05	2.00E-05	-2.09E+00	-1.08E-02	8.28E-05	-1.32E-01	-2.08E+00
Bio-chemical Oxygen Demand	1.30E-05	N/A	4.51E-05	1.26E-05	3.80E-06	-2.48E-03	-1.57E-03	1.36E-05	-1.80E-03	-5.77E-03
Chemical Oxygen Demand	1.41E-04	N/A	3.02E-04	1.64E-03	2.63E-03	-3.53E-02	-1.12E-02	9.12E-05	-2.73E-02	-6.89E-02
Oil	1.63E-04	N/A	2.81E-04	7.62E+04	5.25E-03	-4.41E-02	N/A	8.49E-05	-2.14E-02	N/A
Sulfuric Acid	2.71E-05	N/A	2.39E-06	0.00E+00	9.84E-08	-2.95E-02	N/A	7.23E-07	-1.39E-03	N/A
Iron	1.30E-02	N/A	6.59E-06	0.00E+00	2.72E-07	-1.59E-01	N/A	1.99E-06	-7.36E-03	N/A
Ammonia	1.52E-06	N/A	4.86E-06	0.00E+00	4.87E-07	-6.45E-05	N/A	1.47E-06	-4.38E-03	N/A
Copper	0.00E+00	N/A	0.00E+00	0.00E+00	0.00E+00	0.00E+00	N/A	0.00E+00	0.00E+00	N/A

(To be Continued)

(Continued)

	Coal Precomb.	IGCC Plants	RDF Plant	Traditional Landfill	Ash Landfill	Electricity Offset	Methanol Offset[C]	Transport[d]	(Al + Fe) Offset	Total
Cadmium	3.91E-07	N/A	4.51E-07	0.00E+00	1.86E-08	-1.14E-04	N/A	1.36E-07	-5.14E-05	N/A
Arsenic	0.00E+00	N/A	0.00E+00	0.00E+00	0.00E+00	0.00E+00	N/A	0.00E+00	0.00E+00	N/A
Mercury	3.04E-11	N/A	3.40E-11	0.00E+00	1.40E-12	-8.95E-09	N/A	1.03E-11	-4.61E-08	N/A
Phosphate	1.30E-05	N/A	1.21E-06	0.00E+00	5.01E-08	-1.48E-02	N/A	3.67E-07	-4.84E-04	N/A
Selenium	0.00E+00	N/A	0.00E+00	0.00E+00	0.00E+00	0.00E+00	N/A	0.00E+00	0.00E+00	N/A
Chromium	3.91E-07	N/A	4.51E-07	0.00E+00	1.86E-08	-1.14E-04	N/A	1.36E-07	-5.14E-05	N/A
Lead	6.18E-10	N/A	5.21E-09	0.00E+00	2.15E-10	-8.42E-09	N/A	1.57E-09	-2.66E-07	N/A
Zinc	1.41E-07	N/A	2.26E-07	0.00E+00	9.31E-09	-3.92E-05	N/A	6.81E-08	-1.85E-05	N/A
Solid Waste	3.74E+01	N/A	4.62E-02	2.85E-03	2.66E-03	-5.67E+02	-6.14E+00	1.39E-02	-1.22E+02	-6.57E+02

[a] The first subscript represents the fraction decrease in paper and the second subscript represents the fraction increase in plastics.

[b] The term “N/A” means that data for that item are not available.

[c] This is offset from net energy production from IGCC based polygeneration system after subtracting the RDF plant demand.

[d] LCI associated with the transportation from RDF plants to remanufacturing plants

e The GHE are given as carbon equivalents, calculated using equation: GHE = 12/44*(fossil CO_2 + 21*methane)

Table D.1.2 LCI Results of Gasification System Firing MSW[a] $_{0.2\sim1.0}$ with a Landfill without Energy Recovery[b] (Lbs/Ton MSW)

	Coal Precomb.	IGCC Plant	RDF Plant	Traditional Landfill	Ash Landfill	Electricity Offset	Methanol Offset[C]	Transport[d]	(Al + Fe) Offset	Total
Airborne Releases										
Carbon monoxide	1.80E-02	5.79E-01	3.64E-02	1.43E-02	1.68E-03	-7.19E-01	-2.08E-01	2.26E-02	-2.31E+00	-2.56E+00
Nitrogen oxides	2.30E-02	1.06E+00	5.66E-02	2.36E-03	4.96E-03	-9.54E+00	-9.84E-02	2.30E-02	-8.07E-01	-9.27E+00
Total particulates	2.56E-01	6.52E-02	6.27E-03	2.61E-06	4.55E-04	-3.25E+00	-1.53E-02	3.31E-03	-1.11E+00	-4.04E+00
Carbon dioxide (fossil fuel)	4.07E+00	9.84E+02	9.12E-01	3.75E-02	3.54E-01	-2.53E+03	-4.34E+01	2.68E+00	-3.53E+02	-1.94E+03
Carbon dioxide (biomass fuel)	3.00E-02	9.82E+02	9.20E+00	3.02E+00	8.35E-05	-3.58E-01	0.00E+00	6.41E-04	0.00E+00	9.94E+02
Sulfur oxides	2.30E-02	2.22E-03	1.32E-02	1.02E-04	8.43E-04	-1.68E+01	-1.01E+00	6.52E-03	-2.29E+00	-2.01E+01
Hydrocarbons	8.51E-03	5.65E-02	2.59E-02	6.40E-06	1.27E-03	-4.89E-01	N/A	9.24E-03	-4.12E-01	N/A
Methane	4.70E-01	N/A	1.41E-03	8.48E-03	6.28E-05	-5.58E+00	-2.45E-01	4.26E-04	-4.82E-01	-5.83E+00
Lead	2.70E-07	N/A	4.86E-08	1.29E-02	1.92E-09	-1.09E-04	N/A	1.47E-08	5.18E-05	N/A
Ammonia	8.71E-06	N/A	1.39E-05	3.02E-08	5.48E-07	-2.13E-03	N/A	4.21E-06	-8.28E-04	N/A
Hydrochloric acid	1.10E-04	N/A	8.68E-06	1.42E-06	4.23E-07	-2.05E-01	N/A	2.63E-06	-4.97E-02	N/A
GHE[e] (Tons/day)	1.90E-03	N/A	1.28E-04	1.25E-06	4.85E-05	-3.62E-01	-6.62E-03	3.66E-04	-4.95E-02	-4.15E-01
Waterborne Releases										
Dissolved Solids	8.21E-03	N/A	1.21E-02	1.39E-04	4.77E-04	-2.15E+00	N/A	3.66E-03	-1.21E+00	N/A
Suspended solids	1.41E-01	N/A	2.74E-04	1.69E-05	1.91E-05	-1.78E+00	-9.32E-03	8.31E-05	-1.33E-01	-1.78E+00
Bio-chemical Oxygen Demand	1.20E-05	N/A	4.51E-05	1.33E-05	3.63E-06	-2.12E-03	-1.35E-03	1.37E-05	-1.81E-03	-5.19E-03
Chemical Oxygen Demand	1.30E-04	N/A	3.02E-04	1.74E-03	2.51E-03	-3.01E-02	-9.62E-03	9.15E-05	-2.73E-02	-6.23E-02
Oil	1.50E-04	N/A	2.81E-04	6.93E+04	5.02E-03	-3.76E-02	N/A	8.52E-05	-2.15E-02	N/A
Sulfuric Acid	2.50E-05	N/A	2.39E-06	0.00E+00	9.41E-08	-2.52E-02	N/A	7.25E-07	-1.40E-03	N/A
Iron	1.20E-02	N/A	6.59E-06	0.00E+00	2.60E-07	-1.36E-01	N/A	2.00E-06	-7.38E-03	N/A
Ammonia	1.40E-06	N/A	4.86E-06	0.00E+00	4.65E-07	-5.50E-05	N/A	1.47E-06	-4.39E-03	N/A
Copper	0.00E+00	N/A	0.00E+00	0.00E+00	0.00E+00	0.00E+00	N/A	0.00E+00	0.00E+00	N/A

(To be Continued)

(Continued)

	Coal Precomb.	IGCC Plants	RDF Plant	Traditional Landfill	Ash Landfill	Electricity Offset	Methanol Offset[C]	Transport[d]	(Al + Fe) Offset	Total
Cadmium	3.60E-07	N/A	4.51E-07	0.00E+00	1.78E-08	-9.72E-05	N/A	1.37E-07	-5.15E-05	N/A
Arsenic	0.00E+00	N/A	0.00E+00	0.00E+00	0.00E+00	0.00E+00	N/A	0.00E+00	0.00E+00	N/A
Mercury	2.80E-11	N/A	3.40E-11	0.00E+00	1.34E-12	-7.63E-09	N/A	1.03E-11	-4.62E-08	N/A
Phosphate	1.20E-05	N/A	1.21E-06	0.00E+00	4.79E-08	-1.26E-02	N/A	3.68E-07	-4.86E-04	N/A
Selenium	0.00E+00	N/A	0.00E+00	0.00E+00	0.00E+00	0.00E+00	N/A	0.00E+00	0.00E+00	N/A
Chromium	3.60E-07	N/A	4.51E-07	0.00E+00	1.78E-08	-9.72E-05	N/A	1.37E-07	-5.16E-05	N/A
Lead	5.71E-10	N/A	5.21E-09	0.00E+00	2.05E-10	-7.18E-09	N/A	1.58E-09	-2.67E-07	N/A
Zinc	1.30E-07	N/A	2.26E-07	0.00E+00	8.90E-09	-3.34E-05	N/A	6.83E-08	-1.86E-05	N/A
Solid Waste	3.45E+01	N/A	4.62E-02	3.01E-03	2.54E-03	-4.83E+02	-5.28E+00	1.40E-02	-1.22E+02	-5.76E+02

[a] The first subscript represents the fraction decrease in paper and the second subscript represents the fraction increase in plastics.

[b] The term “N/A” means that data for that item are not available.

[c] This is offset from net energy production from IGCC based polygeneration system after subtracting the RDF plant demand.

[d] LCI associated with the transportation from RDF plants to remanufacturing plants

e The GHE are given as carbon equivalents, calculated using equation: GHE = 12/44*(fossil CO_2 + 21*methane)

Table D.1.3 LCI Results of Gasification System Firing MSW[a] $_{0.2\sim0.5}$ with a Landfill without Energy Recovery[b] (Lbs/Ton MSW)

	Coal Precomb.	IGCC Plant	RDF Plant	Traditional Landfill	Ash Landfill	Electricity Offset	Methanol Offset[C]	Transport[d]	(Al + Fe) Offset	Total
Airborne Releases										
Carbon monoxide	1.66E-02	4.91E-01	3.64E-02	1.51E-02	1.62E-03	-6.04E-01	-1.77E-01	2.27E-02	-2.32E+00	-2.51E+00
Nitrogen oxides	2.13E-02	9.01E-01	5.66E-02	2.47E-03	4.77E-03	-8.01E+00	-8.35E-02	2.30E-02	-8.10E-01	-7.90E+00
Total particulates	2.37E-01	5.54E-02	6.27E-03	2.77E-06	4.38E-04	-2.73E+00	-1.29E-02	3.32E-03	-1.11E+00	-3.55E+00
Carbon dioxide (fossil fuel)	3.76E+00	7.59E+02	9.12E-01	3.95E-02	3.41E-01	-2.13E+03	-3.68E+01	2.69E+00	-3.54E+02	-1.75E+03
Carbon dioxide (biomass fuel)	2.77E-02	9.10E+02	9.20E+00	3.20E+00	8.04E-05	-3.01E-01	0.00E+00	6.43E-04	0.00E+00	9.22E+02
Sulfur oxides	2.13E-02	1.88E-03	1.32E-02	1.08E-04	8.11E-04	-1.42E+01	-8.61E-01	6.54E-03	-2.29E+00	-1.73E+01
Hydrocarbons	7.86E-03	4.80E-02	2.59E-02	6.64E-06	1.22E-03	-4.11E-01	N/A	9.27E-03	-4.13E-01	N/A
Methane	4.34E-01	N/A	1.41E-03	8.98E-03	6.04E-05	-4.69E+00	-2.08E-01	4.27E-04	-4.84E-01	-4.94E+00
Lead	2.50E-07	N/A	4.86E-08	1.34E-02	1.84E-09	-9.13E-05	N/A	1.48E-08	5.20E-05	N/A
Ammonia	8.05E-06	N/A	1.39E-05	2.92E-08	5.27E-07	-1.79E-03	N/A	4.22E-06	-8.30E-04	N/A
Hydrochloric acid	1.02E-04	N/A	8.68E-06	1.51E-06	4.07E-07	-1.72E-01	N/A	2.64E-06	-4.98E-02	N/A
GHE[e] (Tons/day)	1.76E-03	N/A	1.28E-04	1.32E-06	4.66E-05	-3.04E-01	-5.62E-03	3.68E-04	-4.96E-02	-3.57E-01
Waterborne Releases										
Dissolved Solids	7.58E-03	N/A	1.21E-02	1.29E-04	4.58E-04	-1.80E+00	N/A	3.67E-03	-1.22E+00	N/A
Suspended solids	1.30E-01	N/A	2.74E-04	1.79E-05	1.84E-05	-1.49E+00	-7.90E-03	8.33E-05	-1.33E-01	-1.50E+00
Bio-chemical Oxygen Demand	1.11E-05	N/A	4.51E-05	1.41E-05	3.49E-06	-1.78E-03	-1.15E-03	1.37E-05	-1.81E-03	-4.65E-03
Chemical Oxygen Demand	1.20E-04	N/A	3.02E-04	1.84E-03	2.42E-03	-2.53E-02	-8.16E-03	9.18E-05	-2.74E-02	-5.61E-02
Oil	1.39E-04	N/A	2.81E-04	6.16E+04	4.83E-03	-3.16E-02	N/A	8.54E-05	-2.16E-02	N/A
Sulfuric Acid	2.31E-05	N/A	2.39E-06	0.00E+00	9.05E-08	-2.12E-02	N/A	7.28E-07	-1.40E-03	N/A
Iron	1.11E-02	N/A	6.59E-06	0.00E+00	2.50E-07	-1.14E-01	N/A	2.00E-06	-7.41E-03	N/A
Ammonia	1.29E-06	N/A	4.86E-06	0.00E+00	4.48E-07	-4.62E-05	N/A	1.48E-06	-4.40E-03	N/A
Copper	0.00E+00	N/A	0.00E+00	0.00E+00	0.00E+00	0.00E+00	N/A	0.00E+00	0.00E+00	N/A

(To be Continued)

(Continued)

	Coal Precomb.	IGCC Plants	RDF Plant	Traditional Landfill	Ash Landfill	Electricity Offset	Methanol Offset[C]	Transport[d]	(Al + Fe) Offset	Total
Cadmium	3.33E-07	N/A	4.51E-07	0.00E+00	1.71E-08	-8.17E-05	N/A	1.37E-07	-5.17E-05	N/A
Arsenic	0.00E+00	N/A	0.00E+00	0.00E+00	0.00E+00	0.00E+00	N/A	0.00E+00	0.00E+00	N/A
Mercury	2.59E-11	N/A	3.40E-11	0.00E+00	1.29E-12	-6.41E-09	N/A	1.03E-11	-4.63E-08	N/A
Phosphate	1.11E-05	N/A	1.21E-06	0.00E+00	4.61E-08	-1.06E-02	N/A	3.69E-07	-4.87E-04	N/A
Selenium	0.00E+00	N/A	0.00E+00	0.00E+00	0.00E+00	0.00E+00	N/A	0.00E+00	0.00E+00	N/A
Chromium	3.33E-07	N/A	4.51E-07	0.00E+00	1.71E-08	-8.17E-05	N/A	1.37E-07	-5.17E-05	N/A
Lead	5.27E-10	N/A	5.21E-09	0.00E+00	1.98E-10	-6.03E-09	N/A	1.58E-09	-2.68E-07	N/A
Zinc	1.20E-07	N/A	2.26E-07	0.00E+00	8.56E-09	-2.81E-05	N/A	6.86E-08	-1.86E-05	N/A
Solid Waste	3.19E+01	N/A	4.62E-02	3.18E-03	2.45E-03	-4.06E+02	-4.48E+00	1.40E-02	-1.23E+02	-5.01E+02

[a] The first subscript represents the fraction decrease in paper and the second subscript represents the fraction increase in plastics.

[b] The term “N/A” means that data for that item are not available.

[c] This is offset from net energy production from IGCC based polygeneration system after subtracting the RDF plant demand.

[d] LCI associated with the transportation from RDF plants to remanufacturing plants

e The GHE are given as carbon equivalents, calculated using equation: GHE = 12/44*(fossil CO_2 + 21*methane)

Table D.2.1 LCI Results of Gasification System Firing $MSW^{a}_{25\%}$ with a Landfill without Energy Recovery[b] (Lbs/Ton MSW)

	Coal Precomb.	IGCC Plant	RDF Plant	Traditional Landfill	Ash Landfill	Electricity Offset	Methanol Offset[C]	Transport[d]	(Al + Fe) Offset	Total
Airborne Releases										
Carbon monoxide	5.02E-02	4.32E-01	3.64E-02	1.58E-02	2.04E-03	-5.25E-01	-1.52E-01	2.27E-02	-2.31E+00	-2.43E+00
Nitrogen oxides	6.41E-02	7.93E-01	5.66E-02	2.50E-03	6.01E-03	-6.96E+00	-7.21E-02	2.30E-02	-8.10E-01	-6.89E+00
Total particulates	7.14E-01	4.78E-02	6.27E-03	1.76E-03	5.52E-04	-2.37E+00	-1.12E-02	3.32E-03	-1.11E+00	-2.72E+00
Carbon dioxide (fossil fuel)	1.14E+01	5.59E+02	9.12E-01	1.37E-01	4.29E-01	-1.85E+03	-3.18E+01	2.68E+00	-3.54E+02	-1.66E+03
Carbon dioxide (biomass fuel)	8.37E-02	1.00E+03	9.20E+00	1.56E+01	1.01E-04	-2.61E-01	0.00E+00	6.43E-04	0.00E+00	1.03E+03
Sulfur oxides	6.41E-02	3.36E-03	1.32E-02	6.59E-04	1.02E-03	-1.23E+01	-7.43E-01	6.54E-03	-2.29E+00	-1.52E+01
Hydrocarbons	2.37E-02	4.14E-02	2.59E-02	3.94E-04	1.54E-03	-3.57E-01	N/A	9.27E-03	-4.13E-01	N/A
Methane	1.31E+00	N/A	1.41E-03	1.36E-01	7.61E-05	-4.07E+00	-1.80E-01	4.27E-04	-4.84E-01	-3.29E+00
Lead	7.53E-07	N/A	4.86E-08	1.93E-09	2.32E-09	-7.93E-05	N/A	1.48E-08	5.20E-05	N/A
Ammonia	2.43E-05	N/A	1.39E-05	3.10E-07	6.64E-07	-1.55E-03	N/A	4.22E-06	-8.30E-04	N/A
Hydrochloric acid	3.07E-04	N/A	8.68E-06	2.05E-04	5.13E-07	-1.50E-01	N/A	2.64E-06	-4.98E-02	N/A
GHE[e] (Tons/day)	5.29E-03	N/A	1.28E-04	4.09E-04	5.87E-05	-2.64E-01	-4.85E-03	3.67E-04	-4.96E-02	-3.12E-01
Waterborne Releases										
Dissolved Solids	2.29E-02	N/A	1.21E-02	1.81E-04	5.77E-04	-1.57E+00	N/A	3.67E-03	-1.22E+00	N/A
Suspended solids	3.93E-01	N/A	2.74E-04	2.55E-05	2.32E-05	-1.30E+00	-6.82E-03	8.33E-05	-1.33E-01	-1.04E+00
Bio-chemical Oxygen Demand	3.35E-05	N/A	4.51E-05	4.38E-03	4.40E-06	-1.55E-03	-9.92E-04	1.37E-05	-1.81E-03	1.27E-04
Chemical Oxygen Demand	3.63E-04	N/A	3.02E-04	1.22E-02	3.04E-03	-2.19E-02	-7.04E-03	9.17E-05	-2.74E-02	-4.04E-02
Oil	4.18E-04	N/A	2.81E-04	2.67E-03	6.08E-03	-2.74E-02	N/A	8.54E-05	-2.16E-02	N/A
Sulfuric Acid	6.97E-05	N/A	2.39E-06	2.17E-04	1.14E-07	-1.84E-02	N/A	7.27E-07	-1.40E-03	N/A
Iron	3.35E-02	N/A	6.59E-06	1.46E-06	3.15E-07	-9.91E-02	N/A	2.00E-06	-7.40E-03	N/A
Ammonia	3.90E-06	N/A	4.86E-06	1.40E-04	5.64E-07	-4.01E-05	N/A	1.48E-06	-4.40E-03	N/A
Copper	0.00E+00	N/A	0.00E+00	0.00E+00	0.00E+00	0.00E+00	N/A	0.00E+00	0.00E+00	N/A

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	Coal Precomb.	IGCC Plants	RDF Plant	Traditional Landfill	Ash Landfill	Electricity Offset	Methanol Offset[c]	Transport[d]	(Al + Fe) Offset	Total
Cadmium	1.00E-06	N/A	4.51E-07	7.53E-09	2.16E-08	-7.09E-05	N/A	1.37E-07	-5.17E-05	N/A
Arsenic	0.00E+00	N/A	0.00E+00	2.70E-09	0.00E+00	0.00E+00	N/A	0.00E+00	0.00E+00	N/A
Mercury	7.81E-11	N/A	3.40E-11	3.83E-11	1.63E-12	-5.57E-09	N/A	1.03E-11	-4.63E-08	N/A
Phosphate	3.35E-05	N/A	1.21E-06	1.02E-06	5.81E-08	-9.18E-03	N/A	3.69E-07	-4.87E-04	N/A
Selenium	0.00E+00	N/A	0.00E+00	8.73E-10	0.00E+00	0.00E+00	N/A	0.00E+00	0.00E+00	N/A
Chromium	1.00E-06	N/A	4.51E-07	1.46E-08	2.16E-08	-7.09E-05	N/A	1.37E-07	-5.17E-05	N/A
Lead	1.59E-09	N/A	5.21E-09	1.26E-09	2.49E-10	-5.24E-09	N/A	1.58E-09	-2.68E-07	N/A
Zinc	3.63E-07	N/A	2.26E-07	3.32E-09	1.08E-08	-2.44E-05	N/A	6.85E-08	-1.86E-05	N/A
Solid Waste	9.62E+01	N/A	4.62E-02	2.36E-02	3.08E-03	-3.53E+02	-3.87E+00	1.40E-02	-1.23E+02	-3.83E+02

[a] The subscript represents the RDF percentage in the RDF/coal blends.

[b] The term “N/A” means that data for that item are not available.

[c] This is offset from net energy production from IGCC based polygeneration system after subtracting the RDF plant demand.

[d] LCI associated with the transportation from RDF plants to remanufacturing plants

e The GHE are given as carbon equivalents, calculated using equation: GHE = 12/44*(fossil CO_2 + 21*methane)

Table D.2.2 LCI Results of Gasification System Firing MSW[a] $_{50\%}$ with a Landfill without Energy Recovery[b] (Lbs/Ton MSW)

	Coal Precomb.	IGCC Plant	RDF Plant	Traditional Landfill	Ash Landfill	Electricity Offset	Methanol Offset[C]	Transport[d]	(Al + Fe) Offset	Total
Airborne Releases										
Carbon monoxide	2.51E-02	4.25E-01	3.64E-02	1.58E-02	2.03E-03	-5.10E-01	-1.50E-01	2.27E-02	-2.31E+00	-2.45E+00
Nitrogen oxides	3.21E-02	7.80E-01	5.66E-02	2.50E-03	5.99E-03	-6.76E+00	-7.09E-02	2.30E-02	-8.10E-01	-6.74E+00
Total particulates	3.57E-01	4.70E-02	6.27E-03	1.76E-03	5.50E-04	-2.30E+00	-1.10E-02	3.32E-03	-1.11E+00	-3.01E+00
Carbon dioxide (fossil fuel)	5.68E+00	5.50E+02	9.12E-01	1.37E-01	4.28E-01	-1.80E+03	-3.13E+01	2.68E+00	-3.54E+02	-1.62E+03
Carbon dioxide (biomass fuel)	4.18E-02	9.85E+02	9.20E+00	1.56E+01	1.01E-04	-2.54E-01	0.00E+00	6.43E-04	0.00E+00	1.01E+03
Sulfur oxides	3.21E-02	3.31E-03	1.32E-02	6.59E-04	1.02E-03	-1.19E+01	-7.31E-01	6.54E-03	-2.29E+00	-1.49E+01
Hydrocarbons	1.19E-02	4.07E-02	2.59E-02	3.94E-04	1.53E-03	-3.47E-01	N/A	9.27E-03	-4.13E-01	N/A
Methane	6.54E-01	N/A	1.41E-03	1.36E-01	7.58E-05	-3.95E+00	-1.77E-01	4.27E-04	-4.84E-01	-3.82E+00
Lead	3.77E-07	N/A	4.86E-08	1.93E-09	2.31E-09	-7.70E-05	N/A	1.48E-08	5.20E-05	N/A
Ammonia	1.21E-05	N/A	1.39E-05	3.10E-07	6.61E-07	-1.51E-03	N/A	4.22E-06	-8.30E-04	N/A
Hydrochloric acid	1.53E-04	N/A	8.68E-06	2.05E-04	5.11E-07	-1.45E-01	N/A	2.64E-06	-4.98E-02	N/A
GHE[e] (Tons/day)	2.65E-03	N/A	1.28E-04	4.09E-04	5.85E-05	-2.56E-01	-4.77E-03	3.67E-04	-4.96E-02	-3.07E-01
Waterborne Releases										
Dissolved Solids	1.14E-02	N/A	1.21E-02	1.81E-04	5.75E-04	-1.52E+00	N/A	3.67E-03	-1.22E+00	N/A
Suspended solids	1.97E-01	N/A	2.74E-04	2.55E-05	2.31E-05	-1.26E+00	-6.71E-03	8.33E-05	-1.33E-01	-1.20E+00
Bio-chemical Oxygen Demand	1.67E-05	N/A	4.51E-05	4.38E-03	4.38E-06	-1.50E-03	-9.75E-04	1.37E-05	-1.81E-03	1.71E-04
Chemical Oxygen Demand	1.81E-04	N/A	3.02E-04	1.22E-02	3.03E-03	-2.13E-02	-6.93E-03	9.17E-05	-2.74E-02	-3.99E-02
Oil	2.09E-04	N/A	2.81E-04	2.67E-03	6.06E-03	-2.67E-02	N/A	8.54E-05	-2.16E-02	N/A
Sulfuric Acid	3.49E-05	N/A	2.39E-06	2.17E-04	1.14E-07	-1.78E-02	N/A	7.27E-07	-1.40E-03	N/A
Iron	1.67E-02	N/A	6.59E-06	1.46E-06	3.14E-07	-9.62E-02	N/A	2.00E-06	-7.40E-03	N/A
Ammonia	1.95E-06	N/A	4.86E-06	1.40E-04	5.62E-07	-3.90E-05	N/A	1.48E-06	-4.40E-03	N/A
Copper	0.00E+00	N/A	0.00E+00	0.00E+00	0.00E+00	0.00E+00	N/A	0.00E+00	0.00E+00	N/A

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	Coal Precomb.	IGCC Plants	RDF Plant	Traditional Landfill	Ash Landfill	Electricity Offset	Methanol Offset[C]	Transport[d]	(Al + Fe) Offset	Total
Cadmium	5.02E-07	N/A	4.51E-07	7.53E-09	2.15E-08	-6.89E-05	N/A	1.37E-07	-5.17E-05	N/A
Arsenic	0.00E+00	N/A	0.00E+00	2.70E-09	0.00E+00	0.00E+00	N/A	0.00E+00	0.00E+00	N/A
Mercury	3.90E-11	N/A	3.40E-11	3.83E-11	1.62E-12	-5.41E-09	N/A	1.03E-11	-4.63E-08	N/A
Phosphate	1.67E-05	N/A	1.21E-06	1.02E-06	5.79E-08	-8.92E-03	N/A	3.69E-07	-4.87E-04	N/A
Selenium	0.00E+00	N/A	0.00E+00	8.73E-10	0.00E+00	0.00E+00	N/A	0.00E+00	0.00E+00	N/A
Chromium	5.02E-07	N/A	4.51E-07	1.46E-08	2.15E-08	-6.89E-05	N/A	1.37E-07	-5.17E-05	N/A
Lead	7.95E-10	N/A	5.21E-09	1.26E-09	2.48E-10	-5.09E-09	N/A	1.58E-09	-2.68E-07	N/A
Zinc	1.81E-07	N/A	2.26E-07	3.32E-09	1.07E-08	-2.37E-05	N/A	6.85E-08	-1.86E-05	N/A
Solid Waste	4.81E+01	N/A	4.62E-02	2.36E-02	3.07E-03	-3.43E+02	-3.80E+00	1.40E-02	-1.23E+02	-4.21E+02

[a] The subscript represents the RDF percentage in the RDF/coal blends.

[b] The term “N/A” means that data for that item are not available.

[c] This is offset from net energy production from IGCC based polygeneration system after subtracting the RDF plant demand.

[d] LCI associated with the transportation from RDF plants to remanufacturing plants

e The GHE are given as carbon equivalents, calculated using equation: GHE = 12/44*(fossil CO_2 + 21*methane)

Table D.2.3 LCI Results of Gasification System Firing MSW[a]$_{75\%}$ with a Landfill without Energy Recovery[b] (Lbs/Ton MSW)

	Coal Precomb.	IGCC Plant	RDF Plant	Traditional Landfill	Ash Landfill	Electricity Offset	Methanol Offset[C]	Transport[d]	(Al + Fe) Offset	Total
Airborne Releases										
Carbon monoxide	1.67E-02	4.19E-01	3.64E-02	1.58E-02	2.37E-03	-4.97E-01	-1.48E-01	2.27E-02	-2.31E+00	-2.45E+00
Nitrogen oxides	2.14E-02	7.68E-01	5.66E-02	2.50E-03	6.99E-03	-6.59E+00	-6.98E-02	2.30E-02	-8.10E-01	-6.59E+00
Total particulates	2.38E-01	4.63E-02	6.27E-03	1.76E-03	6.41E-04	-2.25E+00	-1.08E-02	3.32E-03	-1.11E+00	-3.07E+00
Carbon dioxide (fossil fuel)	3.78E+00	5.42E+02	9.12E-01	1.37E-01	4.99E-01	-1.75E+03	-3.08E+01	2.68E+00	-3.54E+02	-1.59E+03
Carbon dioxide (biomass fuel)	2.79E-02	9.70E+02	9.20E+00	1.56E+01	1.18E-04	-2.47E-01	0.00E+00	6.43E-04	0.00E+00	9.95E+02
Sulfur oxides	2.14E-02	3.26E-03	1.32E-02	6.59E-04	1.19E-03	-1.16E+01	-7.20E-01	6.54E-03	-2.29E+00	-1.46E+01
Hydrocarbons	7.90E-03	4.01E-02	2.59E-02	3.94E-04	1.79E-03	-3.38E-01	N/A	9.27E-03	-4.13E-01	N/A
Methane	4.36E-01	N/A	1.41E-03	1.36E-01	8.85E-05	-3.86E+00	-1.74E-01	4.27E-04	-4.84E-01	-3.94E+00
Lead	2.51E-07	N/A	4.86E-08	1.93E-09	2.70E-09	-7.51E-05	N/A	1.48E-08	5.20E-05	N/A
Ammonia	8.09E-06	N/A	1.39E-05	3.10E-07	7.72E-07	-1.47E-03	N/A	4.22E-06	-8.30E-04	N/A
Hydrochloric acid	1.02E-04	N/A	8.68E-06	2.05E-04	5.96E-07	-1.42E-01	N/A	2.64E-06	-4.98E-02	N/A
GHE[e] (Tons/day)	1.76E-03	N/A	1.28E-04	4.09E-04	6.83E-05	-2.50E-01	-4.70E-03	3.67E-04	-4.96E-02	-3.02E-01
Waterborne Releases										
Dissolved Solids	7.62E-03	N/A	1.21E-02	1.81E-04	6.72E-04	-1.48E+00	N/A	3.67E-03	-1.22E+00	N/A
Suspended solids	1.31E-01	N/A	2.74E-04	2.55E-05	2.69E-05	-1.23E+00	-6.61E-03	8.33E-05	-1.33E-01	-1.24E+00
Bio-chemical Oxygen Demand	1.12E-05	N/A	4.51E-05	4.38E-03	5.12E-06	-1.46E-03	-9.61E-04	1.37E-05	-1.81E-03	2.18E-04
Chemical Oxygen Demand	1.21E-04	N/A	3.02E-04	1.22E-02	3.54E-03	-2.08E-02	-6.82E-03	9.17E-05	-2.74E-02	-3.88E-02
Oil	1.39E-04	N/A	2.81E-04	2.67E-03	7.07E-03	-2.60E-02	N/A	8.54E-05	-2.16E-02	N/A
Sulfuric Acid	2.32E-05	N/A	2.39E-06	2.17E-04	1.33E-07	-1.74E-02	N/A	7.27E-07	-1.40E-03	N/A
Iron	1.12E-02	N/A	6.59E-06	1.46E-06	3.67E-07	-9.38E-02	N/A	2.00E-06	-7.40E-03	N/A
Ammonia	1.30E-06	N/A	4.86E-06	1.40E-04	6.56E-07	-3.80E-05	N/A	1.48E-06	-4.40E-03	N/A
Copper	0.00E+00	N/A	0.00E+00	0.00E+00	0.00E+00	0.00E+00	N/A	0.00E+00	0.00E+00	N/A

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	Coal Precomb.	IGCC Plants	RDF Plant	Traditional Landfill	Ash Landfill	Electricity Offset	Methanol Offset[C]	Transport[d]	(Al + Fe) Offset	Total
Cadmium	3.35E-07	N/A	4.51E-07	7.53E-09	2.51E-08	-6.72E-05	N/A	1.37E-07	-5.17E-05	N/A
Arsenic	0.00E+00	N/A	0.00E+00	2.70E-09	0.00E+00	0.00E+00	N/A	0.00E+00	0.00E+00	N/A
Mercury	2.60E-11	N/A	3.40E-11	3.83E-11	1.89E-12	-5.28E-09	N/A	1.03E-11	-4.63E-08	N/A
Phosphate	1.12E-05	N/A	1.21E-06	1.02E-06	6.75E-08	-8.70E-03	N/A	3.69E-07	-4.87E-04	N/A
Selenium	0.00E+00	N/A	0.00E+00	8.73E-10	0.00E+00	0.00E+00	N/A	0.00E+00	0.00E+00	N/A
Chromium	3.35E-07	N/A	4.51E-07	1.46E-08	2.51E-08	-6.72E-05	N/A	1.37E-07	-5.17E-05	N/A
Lead	5.30E-10	N/A	5.21E-09	1.26E-09	2.89E-10	-4.96E-09	N/A	1.58E-09	-2.68E-07	N/A
Zinc	1.21E-07	N/A	2.26E-07	3.32E-09	1.25E-08	-2.31E-05	N/A	6.85E-08	-1.86E-05	N/A
Solid Waste	3.21E+01	N/A	4.62E-02	2.36E-02	3.58E-03	-3.34E+02	-3.75E+00	1.40E-02	-1.23E+02	-4.28E+02

[a] The subscript represents the RDF percentage in the RDF/coal blends.

[b] The term “N/A” means that data for that item are not available.

[c] This is offset from net energy production from IGCC based polygeneration system after subtracting the RDF plant demand.

[d] LCI associated with the transportation from RDF plants to remanufacturing plants

e The GHE are given as carbon equivalents, calculated using equation: GHE = 12/44*(fossil CO_2 + 21*methane)

Table D.3.1 LCI Results of Gasification System Firing $MSW^{a}_{0.0}$ with a Landfill without Energy Recovery[b] (Lbs/Ton MSW)

	Coal Precomb.	IGCC Plant	RDF Plant	Traditional Landfill	Ash Landfill	Electricity Offset	Methanol Offset[C]	Transport[d]	(Al + Fe) Offset	Total
Airborne Releases										
Carbon monoxide	1.67E-02	4.15E-01	3.64E-02	1.58E-02	2.37E-03	-4.87E-01	-1.48E-01	2.27E-02	-2.31E+00	-2.44E+00
Nitrogen oxides	2.14E-02	7.61E-01	5.66E-02	2.50E-03	6.99E-03	-6.46E+00	-6.98E-02	2.30E-02	-8.10E-01	-6.46E+00
Total particulates	2.38E-01	4.63E-02	6.27E-03	1.76E-03	6.41E-04	-2.20E+00	-1.08E-02	3.32E-03	-1.11E+00	-3.02E+00
Carbon dioxide (fossil fuel)	3.78E+00	5.19E+02	9.12E-01	1.37E-01	4.99E-01	-1.72E+03	-3.08E+01	2.68E+00	-3.54E+02	-1.57E+03
Carbon dioxide (biomass fuel)	2.79E-02	9.30E+02	9.20E+00	1.56E+01	1.18E-04	-2.42E-01	0.00E+00	6.43E-04	0.00E+00	9.55E+02
Sulfur oxides	2.14E-02	1.85E-03	1.32E-02	6.59E-04	1.19E-03	-1.14E+01	-7.19E-01	6.54E-03	-2.29E+00	-1.44E+01
Hydrocarbons	7.90E-03	4.01E-02	2.59E-02	3.94E-04	1.79E-03	-3.31E-01	N/A	9.27E-03	-4.13E-01	N/A
Methane	4.36E-01	N/A	1.41E-03	1.36E-01	8.85E-05	-3.78E+00	-1.74E-01	4.27E-04	-4.84E-01	-3.86E+00
Lead	2.51E-07	N/A	4.86E-08	1.93E-09	2.70E-09	-7.36E-05	N/A	1.48E-08	5.20E-05	N/A
Ammonia	8.09E-06	N/A	1.39E-05	3.10E-07	7.72E-07	-1.44E-03	N/A	4.22E-06	-8.30E-04	N/A
Hydrochloric acid	1.02E-04	N/A	8.68E-06	2.05E-04	5.96E-07	-1.39E-01	N/A	2.64E-06	-4.98E-02	N/A
GHE[e] (Tons/day)	1.76E-03	N/A	1.28E-04	4.09E-04	6.83E-05	-2.45E-01	-4.69E-03	3.67E-04	-4.96E-02	-2.96E-01
Waterborne Releases										
Dissolved Solids	7.62E-03	N/A	1.21E-02	1.81E-04	6.72E-04	-1.45E+00	N/A	3.67E-03	-1.22E+00	N/A
Suspended solids	1.31E-01	N/A	2.74E-04	2.55E-05	2.69E-05	-1.20E+00	-6.60E-03	8.33E-05	-1.33E-01	-1.21E+00
Bio-chemical Oxygen Demand	1.12E-05	N/A	4.51E-05	4.38E-03	5.12E-06	-1.43E-03	-9.60E-04	1.37E-05	-1.81E-03	2.48E-04
Chemical Oxygen Demand	1.21E-04	N/A	3.02E-04	1.22E-02	3.54E-03	-2.04E-02	-6.82E-03	9.17E-05	-2.74E-02	-3.84E-02
Oil	1.39E-04	N/A	2.81E-04	2.67E-03	7.07E-03	-2.55E-02	N/A	8.54E-05	-2.16E-02	N/A
Sulfuric Acid	2.32E-05	N/A	2.39E-06	2.17E-04	1.33E-07	-1.70E-02	N/A	7.27E-07	-1.40E-03	N/A
Iron	1.12E-02	N/A	6.59E-06	1.46E-06	3.67E-07	-9.19E-02	N/A	2.00E-06	-7.40E-03	N/A
Ammonia	1.30E-06	N/A	4.86E-06	1.40E-04	6.56E-07	-3.72E-05	N/A	1.48E-06	-4.40E-03	N/A
Copper	0.00E+00	N/A	0.00E+00	0.00E+00	0.00E+00	0.00E+00	N/A	0.00E+00	0.00E+00	N/A

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	Coal Precomb.	IGCC Plants	RDF Plant	Traditional Landfill	Ash Landfill	Electricity Offset	Methanol Offset[C]	Transport[d]	(Al + Fe) Offset	Total
Cadmium	3.35E-07	N/A	4.51E-07	7.53E-09	2.51E-08	-6.58E-05	N/A	1.37E-07	-5.17E-05	N/A
Arsenic	0.00E+00	N/A	0.00E+00	2.70E-09	0.00E+00	0.00E+00	N/A	0.00E+00	0.00E+00	N/A
Mercury	2.60E-11	N/A	3.40E-11	3.83E-11	1.89E-12	-5.17E-09	N/A	1.03E-11	-4.63E-08	N/A
Phosphate	1.12E-05	N/A	1.21E-06	1.02E-06	6.75E-08	-8.52E-03	N/A	3.69E-07	-4.87E-04	N/A
Selenium	0.00E+00	N/A	0.00E+00	8.73E-10	0.00E+00	0.00E+00	N/A	0.00E+00	0.00E+00	N/A
Chromium	3.35E-07	N/A	4.51E-07	1.46E-08	2.51E-08	-6.58E-05	N/A	1.37E-07	-5.17E-05	N/A
Lead	5.30E-10	N/A	5.21E-09	1.26E-09	2.89E-10	-4.86E-09	N/A	1.58E-09	-2.68E-07	N/A
Zinc	1.21E-07	N/A	2.26E-07	3.32E-09	1.25E-08	-2.26E-05	N/A	6.85E-08	-1.86E-05	N/A
Solid Waste	3.21E+01	N/A	4.62E-02	2.36E-02	3.58E-03	-3.27E+02	-3.74E+00	1.40E-02	-1.23E+02	-4.21E+02

[a] The subscript represents the purge gas recycle ratio from the methanol plant.

[b] The term "N/A" means that data for that item are not available.

[c] This is offset from net energy production from IGCC based polygeneration system after subtracting the RDF plant demand.

[d] LCI associated with the transportation from RDF plants to remanufacturing plants

e The GHE are given as carbon equivalents, calculated using equation: GHE = 12/44*(fossil CO_2 + 21*methane)

Table D.3.2 LCI Results of Gasification System Firing MSW[a] $_{1.0}$ with a Landfill without Energy Recovery[b] (Lbs/Ton MSW)

	Coal Precomb.	IGCC Plant	RDF Plant	Traditional Landfill	Ash Landfill	Electricity Offset	Methanol Offset[C]	Transport[d]	(Al + Fe) Offset	Total
Airborne Releases										
Carbon monoxide	1.67E-02	4.15E-01	3.64E-02	1.58E-02	2.37E-03	-4.94E-01	-1.48E-01	2.27E-02	-2.31E+00	-2.45E+00
Nitrogen oxides	2.14E-02	7.62E-01	5.66E-02	2.50E-03	6.99E-03	-6.55E+00	-6.98E-02	2.30E-02	-8.10E-01	-6.56E+00
Total particulates	2.38E-01	4.63E-02	6.27E-03	1.76E-03	6.41E-04	-2.23E+00	-1.08E-02	3.32E-03	-1.11E+00	-3.06E+00
Carbon dioxide (fossil fuel)	3.78E+00	5.19E+02	9.12E-01	1.37E-01	4.99E-01	-1.74E+03	-3.08E+01	2.68E+00	-3.54E+02	-1.60E+03
Carbon dioxide (biomass fuel)	2.79E-02	9.30E+02	9.20E+00	1.56E+01	1.18E-04	-2.46E-01	0.00E+00	6.43E-04	0.00E+00	9.55E+02
Sulfur oxides	2.14E-02	1.85E-03	1.32E-02	6.59E-04	1.19E-03	-1.16E+01	-7.20E-01	6.54E-03	-2.29E+00	-1.45E+01
Hydrocarbons	7.90E-03	4.01E-02	2.59E-02	3.94E-04	1.79E-03	-3.36E-01	N/A	9.27E-03	-4.13E-01	N/A
Methane	4.36E-01	N/A	1.41E-03	1.36E-01	8.85E-05	-3.83E+00	-1.74E-01	4.27E-04	-4.84E-01	-3.92E+00
Lead	2.51E-07	N/A	4.86E-08	1.93E-09	2.70E-09	-7.47E-05	N/A	1.48E-08	5.20E-05	N/A
Ammonia	8.09E-06	N/A	1.39E-05	3.10E-07	7.72E-07	-1.46E-03	N/A	4.22E-06	-8.30E-04	N/A
Hydrochloric acid	1.02E-04	N/A	8.68E-06	2.05E-04	5.96E-07	-1.41E-01	N/A	2.64E-06	-4.98E-02	N/A
GHE[e] (Tons/day)	1.76E-03	N/A	1.28E-04	4.09E-04	6.83E-05	-2.49E-01	-4.70E-03	3.67E-04	-4.96E-02	-3.00E-01
Waterborne Releases										
Dissolved Solids	7.62E-03	N/A	1.21E-02	1.81E-04	6.72E-04	-1.47E+00	N/A	3.67E-03	-1.22E+00	N/A
Suspended solids	1.31E-01	N/A	2.74E-04	2.55E-05	2.69E-05	-1.22E+00	-6.61E-03	8.33E-05	-1.33E-01	-1.23E+00
Bio-chemical Oxygen Demand	1.12E-05	N/A	4.51E-05	4.38E-03	5.12E-06	-1.46E-03	-9.61E-04	1.37E-05	-1.81E-03	2.26E-04
Chemical Oxygen Demand	1.21E-04	N/A	3.02E-04	1.22E-02	3.54E-03	-2.07E-02	-6.82E-03	9.17E-05	-2.74E-02	-3.87E-02
Oil	1.39E-04	N/A	2.81E-04	2.67E-03	7.07E-03	-2.59E-02	N/A	8.54E-05	-2.16E-02	N/A
Sulfuric Acid	2.32E-05	N/A	2.39E-06	2.17E-04	1.33E-07	-1.73E-02	N/A	7.27E-07	-1.40E-03	N/A
Iron	1.12E-02	N/A	6.59E-06	1.46E-06	3.67E-07	-9.33E-02	N/A	2.00E-06	-7.40E-03	N/A
Ammonia	1.30E-06	N/A	4.86E-06	1.40E-04	6.56E-07	-3.78E-05	N/A	1.48E-06	-4.40E-03	N/A
Copper	0.00E+00	N/A	0.00E+00	0.00E+00	0.00E+00	0.00E+00	N/A	0.00E+00	0.00E+00	N/A

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	Coal Precomb.	IGCC Plants	RDF Plant	Traditional Landfill	Ash Landfill	Electricity Offset	Methanol Offset[C]	Transport[d]	(Al + Fe) Offset	Total
Cadmium	3.35E-07	N/A	4.51E-07	7.53E-09	2.51E-08	-6.68E-05	N/A	1.37E-07	-5.17E-05	N/A
Arsenic	0.00E+00	N/A	0.00E+00	2.70E-09	0.00E+00	0.00E+00	N/A	0.00E+00	0.00E+00	N/A
Mercury	2.60E-11	N/A	3.40E-11	3.83E-11	1.89E-12	-5.25E-09	N/A	1.03E-11	-4.63E-08	N/A
Phosphate	1.12E-05	N/A	1.21E-06	1.02E-06	6.75E-08	-8.65E-03	N/A	3.69E-07	-4.87E-04	N/A
Selenium	0.00E+00	N/A	0.00E+00	8.73E-10	0.00E+00	0.00E+00	N/A	0.00E+00	0.00E+00	N/A
Chromium	3.35E-07	N/A	4.51E-07	1.46E-08	2.51E-08	-6.68E-05	N/A	1.37E-07	-5.17E-05	N/A
Lead	5.30E-10	N/A	5.21E-09	1.26E-09	2.89E-10	-4.93E-09	N/A	1.58E-09	-2.68E-07	N/A
Zinc	1.21E-07	N/A	2.26E-07	3.32E-09	1.25E-08	-2.30E-05	N/A	6.85E-08	-1.86E-05	N/A
Solid Waste	3.21E+01	N/A	4.62E-02	2.36E-02	3.58E-03	-3.32E+02	-3.75E+00	1.40E-02	-1.23E+02	-4.26E+02

[a] The subscript represents the purge gas recycle ratio from the methanol plant.

[b] The term "N/A" means that data for that item are not available.

[c] This is offset from net energy production from IGCC based polygeneration system after subtracting the RDF plant demand.

[d] LCI associated with the transportation from RDF plants to remanufacturing plants

e The GHE are given as carbon equivalents, calculated using equation: GHE = 12/44*(fossil CO_2 + 21*methane)

Table D.3.3 LCI Results of Gasification System Firing $MSW^{a}_{2.0}$ with a Landfill without Energy Recovery[b] (Lbs/Ton MSW)

	Coal Precomb.	**IGCC Plant**	**RDF Plant**	**Traditional Landfill**	**Ash Landfill**	**Electricity Offset**	**Methanol Offset[C]**	**Transport[d]**	**(Al + Fe) Offset**	**Total**
Airborne Releases										
Carbon monoxide	1.67E-02	4.16E-01	3.64E-02	1.58E-02	2.37E-03	-4.96E-01	-1.48E-01	2.27E-02	-2.31E+00	-2.45E+00
Nitrogen oxides	2.14E-02	7.62E-01	5.66E-02	2.50E-03	6.99E-03	-6.58E+00	-6.98E-02	2.30E-02	-8.10E-01	-6.59E+00
Total particulates	2.38E-01	4.63E-02	6.27E-03	1.76E-03	6.41E-04	-2.24E+00	-1.08E-02	3.32E-03	-1.11E+00	-3.07E+00
Carbon dioxide (fossil fuel)	3.78E+00	5.19E+02	9.12E-01	1.37E-01	4.99E-01	-1.75E+03	-3.08E+01	2.68E+00	-3.54E+02	-1.61E+03
Carbon dioxide (biomass fuel)	2.79E-02	9.31E+02	9.20E+00	1.56E+01	1.18E-04	-2.47E-01	0.00E+00	6.43E-04	0.00E+00	9.55E+02
Sulfur oxides	2.14E-02	1.85E-03	1.32E-02	6.59E-04	1.19E-03	-1.16E+01	-7.20E-01	6.54E-03	-2.29E+00	-1.46E+01
Hydrocarbons	7.90E-03	4.01E-02	2.59E-02	3.94E-04	1.79E-03	-3.38E-01	N/A	9.27E-03	-4.13E-01	N/A
Methane	4.36E-01	N/A	1.41E-03	1.36E-01	8.85E-05	-3.85E+00	-1.74E-01	4.27E-04	-4.84E-01	-3.93E+00
Lead	2.51E-07	N/A	4.86E-08	1.93E-09	2.70E-09	-7.50E-05	N/A	1.48E-08	5.20E-05	N/A
Ammonia	8.09E-06	N/A	1.39E-05	3.10E-07	7.72E-07	-1.47E-03	N/A	4.22E-06	-8.30E-04	N/A
Hydrochloric acid	1.02E-04	N/A	8.68E-06	2.05E-04	5.96E-07	-1.41E-01	N/A	2.64E-06	-4.98E-02	N/A
GHE[e] (Tons/day)	1.76E-03	N/A	1.28E-04	4.09E-04	6.83E-05	-2.50E-01	-4.70E-03	3.67E-04	-4.96E-02	-3.01E-01
Waterborne Releases										
Dissolved Solids	7.62E-03	N/A	1.21E-02	1.81E-04	6.72E-04	-1.48E+00	N/A	3.67E-03	-1.22E+00	N/A
Suspended solids	1.31E-01	N/A	2.74E-04	2.55E-05	2.69E-05	-1.23E+00	-6.61E-03	8.33E-05	-1.33E-01	-1.24E+00
Bio-chemical Oxygen Demand	1.12E-05	N/A	4.51E-05	4.38E-03	5.12E-06	-1.46E-03	-9.61E-04	1.37E-05	-1.81E-03	2.20E-04
Chemical Oxygen Demand	1.21E-04	N/A	3.02E-04	1.22E-02	3.54E-03	-2.07E-02	-6.82E-03	9.17E-05	-2.74E-02	-3.88E-02
Oil	1.39E-04	N/A	2.81E-04	2.67E-03	7.07E-03	-2.60E-02	N/A	8.54E-05	-2.16E-02	N/A
Sulfuric Acid	2.32E-05	N/A	2.39E-06	2.17E-04	1.33E-07	-1.74E-02	N/A	7.27E-07	-1.40E-03	N/A
Iron	1.12E-02	N/A	6.59E-06	1.46E-06	3.67E-07	-9.37E-02	N/A	2.00E-06	-7.40E-03	N/A
Ammonia	1.30E-06	N/A	4.86E-06	1.40E-04	6.56E-07	-3.80E-05	N/A	1.48E-06	-4.40E-03	N/A
Copper	0.00E+00	N/A	0.00E+00	0.00E+00	0.00E+00	0.00E+00	N/A	0.00E+00	0.00E+00	N/A

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	Coal Precomb.	IGCC Plants	RDF Plant	Traditional Landfill	Ash Landfill	Electricity Offset	Methanol Offset[C]	Transport[d]	(Al + Fe) Offset	Total
Cadmium	3.35E-07	N/A	4.51E-07	7.53E-09	2.51E-08	-6.71E-05	N/A	1.37E-07	-5.17E-05	N/A
Arsenic	0.00E+00	N/A	0.00E+00	2.70E-09	0.00E+00	0.00E+00	N/A	0.00E+00	0.00E+00	N/A
Mercury	2.60E-11	N/A	3.40E-11	3.83E-11	1.89E-12	-5.27E-09	N/A	1.03E-11	-4.63E-08	N/A
Phosphate	1.12E-05	N/A	1.21E-06	1.02E-06	6.75E-08	-8.68E-03	N/A	3.69E-07	-4.87E-04	N/A
Selenium	0.00E+00	N/A	0.00E+00	8.73E-10	0.00E+00	0.00E+00	N/A	0.00E+00	0.00E+00	N/A
Chromium	3.35E-07	N/A	4.51E-07	1.46E-08	2.51E-08	-6.71E-05	N/A	1.37E-07	-5.17E-05	N/A
Lead	5.30E-10	N/A	5.21E-09	1.26E-09	2.89E-10	-4.95E-09	N/A	1.58E-09	-2.68E-07	N/A
Zinc	1.21E-07	N/A	2.26E-07	3.32E-09	1.25E-08	-2.30E-05	N/A	6.85E-08	-1.86E-05	N/A
Solid Waste	3.21E+01	N/A	4.62E-02	2.36E-02	3.58E-03	-3.34E+02	-3.75E+00	1.40E-02	-1.23E+02	-4.28E+02

[a] The subscript represents the purge gas recycle ratio from the methanol plant.

[b] The term "N/A" means that data for that item are not available.

[c] This is offset from net energy production from IGCC based polygeneration system after subtracting the RDF plant demand.

[d] LCI associated with the transportation from RDF plants to remanufacturing plants

e The GHE are given as carbon equivalents, calculated using equation: GHE = 12/44*(fossil CO_2 + 21*methane)

Table D.3.4 LCI Results of Gasification System Firing $MSW^{a}_{3.0}$ with a Landfill without Energy Recovery[b] (Lbs/Ton MSW)

	Coal Precomb.	IGCC Plant	RDF Plant	Traditional Landfill	Ash Landfill	Electricity Offset	Methanol Offset[C]	Transport[d]	(Al + Fe) Offset	Total
Airborne Releases										
Carbon monoxide	1.67E-02	4.16E-01	3.64E-02	1.58E-02	2.37E-03	-4.97E-01	-1.48E-01	2.27E-02	-2.31E+00	-2.45E+00
Nitrogen oxides	2.14E-02	7.62E-01	5.66E-02	2.50E-03	6.99E-03	-6.59E+00	-6.98E-02	2.30E-02	-8.10E-01	-6.60E+00
Total particulates	2.38E-01	4.63E-02	6.27E-03	1.76E-03	6.41E-04	-2.25E+00	-1.08E-02	3.32E-03	-1.11E+00	-3.07E+00
Carbon dioxide (fossil fuel)	3.78E+00	5.19E+02	9.12E-01	1.37E-01	4.99E-01	-1.75E+03	-3.08E+01	2.68E+00	-3.54E+02	-1.61E+03
Carbon dioxide (biomass fuel)	2.79E-02	9.31E+02	9.20E+00	1.56E+01	1.18E-04	-2.47E-01	0.00E+00	6.43E-04	0.00E+00	9.55E+02
Sulfur oxides	2.14E-02	1.85E-03	1.32E-02	6.59E-04	1.19E-03	-1.16E+01	-7.20E-01	6.54E-03	-2.29E+00	-1.46E+01
Hydrocarbons	7.90E-03	4.01E-02	2.59E-02	3.94E-04	1.79E-03	-3.38E-01	N/A	9.27E-03	-4.13E-01	N/A
Methane	4.36E-01	N/A	1.41E-03	1.36E-01	8.85E-05	-3.86E+00	-1.74E-01	4.27E-04	-4.84E-01	-3.94E+00
Lead	2.51E-07	N/A	4.86E-08	1.93E-09	2.70E-09	-7.51E-05	N/A	1.48E-08	5.20E-05	N/A
Ammonia	8.09E-06	N/A	1.39E-05	3.10E-07	7.72E-07	-1.47E-03	N/A	4.22E-06	-8.30E-04	N/A
Hydrochloric acid	1.02E-04	N/A	8.68E-06	2.05E-04	5.96E-07	-1.42E-01	N/A	2.64E-06	-4.98E-02	N/A
GHE[e] (Tons/day)	1.76E-03	N/A	1.28E-04	4.09E-04	6.83E-05	-2.50E-01	-4.70E-03	3.67E-04	-4.96E-02	-3.01E-01
Waterborne Releases										
Dissolved Solids	7.62E-03	N/A	1.21E-02	1.81E-04	6.72E-04	-1.48E+00	N/A	3.67E-03	-1.22E+00	N/A
Suspended solids	1.31E-01	N/A	2.74E-04	2.55E-05	2.69E-05	-1.23E+00	-6.61E-03	8.33E-05	-1.33E-01	-1.24E+00
Bio-chemical Oxygen Demand	1.12E-05	N/A	4.51E-05	4.38E-03	5.12E-06	-1.46E-03	-9.61E-04	1.37E-05	-1.81E-03	2.18E-04
Chemical Oxygen Demand	1.21E-04	N/A	3.02E-04	1.22E-02	3.54E-03	-2.08E-02	-6.82E-03	9.17E-05	-2.74E-02	-3.88E-02
Oil	1.39E-04	N/A	2.81E-04	2.67E-03	7.07E-03	-2.60E-02	N/A	8.54E-05	-2.16E-02	N/A
Sulfuric Acid	2.32E-05	N/A	2.39E-06	2.17E-04	1.33E-07	-1.74E-02	N/A	7.27E-07	-1.40E-03	N/A
Iron	1.12E-02	N/A	6.59E-06	1.46E-06	3.67E-07	-9.38E-02	N/A	2.00E-06	-7.40E-03	N/A
Ammonia	1.30E-06	N/A	4.86E-06	1.40E-04	6.56E-07	-3.80E-05	N/A	1.48E-06	-4.40E-03	N/A
Copper	0.00E+00	N/A	0.00E+00	0.00E+00	0.00E+00	0.00E+00	N/A	0.00E+00	0.00E+00	N/A

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	Coal Precomb.	IGCC Plants	RDF Plant	Traditional Landfill	Ash Landfill	Electricity Offset	Methanol Offset[C]	Transport[d]	(Al + Fe) Offset	Total
Cadmium	3.35E-07	N/A	4.51E-07	7.53E-09	2.51E-08	-6.72E-05	N/A	1.37E-07	-5.17E-05	N/A
Arsenic	0.00E+00	N/A	0.00E+00	2.70E-09	0.00E+00	0.00E+00	N/A	0.00E+00	0.00E+00	N/A
Mercury	2.60E-11	N/A	3.40E-11	3.83E-11	1.89E-12	-5.27E-09	N/A	1.03E-11	-4.63E-08	N/A
Phosphate	1.12E-05	N/A	1.21E-06	1.02E-06	6.75E-08	-8.70E-03	N/A	3.69E-07	-4.87E-04	N/A
Selenium	0.00E+00	N/A	0.00E+00	8.73E-10	0.00E+00	0.00E+00	N/A	0.00E+00	0.00E+00	N/A
Chromium	3.35E-07	N/A	4.51E-07	1.46E-08	2.51E-08	-6.72E-05	N/A	1.37E-07	-5.17E-05	N/A
Lead	5.30E-10	N/A	5.21E-09	1.26E-09	2.89E-10	-4.96E-09	N/A	1.58E-09	-2.68E-07	N/A
Zinc	1.21E-07	N/A	2.26E-07	3.32E-09	1.25E-08	-2.31E-05	N/A	6.85E-08	-1.86E-05	N/A
Solid Waste	3.21E+01	N/A	4.62E-02	2.36E-02	3.58E-03	-3.34E+02	-3.75E+00	1.40E-02	-1.23E+02	-4.28E+02

[a] The subscript represents the purge gas recycle ratio from the methanol plant.

[b] The term "N/A" means that data for that item are not available.

[c] This is offset from net energy production from IGCC based polygeneration system after subtracting the RDF plant demand.

[d] LCI associated with the transportation from RDF plants to remanufacturing plants

e The GHE are given as carbon equivalents, calculated using equation: GHE = 12/44*(fossil CO_2 + 21*methane)

Table D.4.1 LCI Results of Gasification System Firing MSW[a] $_{0.35}$ with a Landfill without Energy Recovery[b] (Lbs/Ton MSW)

	Coal Precomb.	IGCC Plant	RDF Plant	Traditional Landfill	Ash Landfill	Electricity Offset	Methanol Offset[C]	Transport[d]	(Al + Fe) Offset	Total
Airborne Releases										
Carbon monoxide	1.67E-02	4.08E-01	3.64E-02	1.58E-02	2.37E-03	-4.99E-01	-1.51E-01	2.27E-02	-2.31E+00	-2.46E+00
Nitrogen oxides	2.14E-02	7.49E-01	5.66E-02	2.50E-03	6.99E-03	-6.61E+00	-7.14E-02	2.30E-02	-8.10E-01	-6.63E+00
Total particulates	2.38E-01	4.79E-02	6.27E-03	1.76E-03	6.41E-04	-2.25E+00	-1.11E-02	3.32E-03	-1.11E+00	-3.08E+00
Carbon dioxide (fossil fuel)	3.78E+00	5.19E+02	9.12E-01	1.37E-01	4.99E-01	-1.76E+03	-3.15E+01	2.68E+00	-3.54E+02	-1.62E+03
Carbon dioxide (biomass fuel)	2.79E-02	9.30E+02	9.20E+00	1.56E+01	1.18E-04	-2.48E-01	0.00E+00	6.43E-04	0.00E+00	9.54E+02
Sulfur oxides	2.14E-02	1.84E-03	1.32E-02	6.59E-04	1.19E-03	-1.17E+01	-7.36E-01	6.54E-03	-2.29E+00	-1.47E+01
Hydrocarbons	7.90E-03	4.15E-02	2.59E-02	3.94E-04	1.79E-03	-3.39E-01	N/A	9.27E-03	-4.13E-01	N/A
Methane	4.36E-01	N/A	1.41E-03	1.36E-01	8.85E-05	-3.87E+00	-1.78E-01	4.27E-04	-4.84E-01	-3.95E+00
Lead	2.51E-07	N/A	4.86E-08	1.93E-09	2.70E-09	-7.53E-05	N/A	1.48E-08	5.20E-05	N/A
Ammonia	8.09E-06	N/A	1.39E-05	3.10E-07	7.72E-07	-1.47E-03	N/A	4.22E-06	-8.30E-04	N/A
Hydrochloric acid	1.02E-04	N/A	8.68E-06	2.05E-04	5.96E-07	-1.42E-01	N/A	2.64E-06	-4.98E-02	N/A
GHE[e] (Tons/day)	1.76E-03	N/A	1.28E-04	4.09E-04	6.83E-05	-2.51E-01	-4.81E-03	3.67E-04	-4.96E-02	-3.02E-01
Waterborne Releases										
Dissolved Solids	7.62E-03	N/A	1.21E-02	1.81E-04	6.72E-04	-1.49E+00	N/A	3.67E-03	-1.22E+00	N/A
Suspended solids	1.31E-01	N/A	2.74E-04	2.55E-05	2.69E-05	-1.23E+00	-6.76E-03	8.33E-05	-1.33E-01	-1.24E+00
Bio-chemical Oxygen Demand	1.12E-05	N/A	4.51E-05	4.38E-03	5.12E-06	-1.47E-03	-9.83E-04	1.37E-05	-1.81E-03	1.91E-04
Chemical Oxygen Demand	1.21E-04	N/A	3.02E-04	1.22E-02	3.54E-03	-2.08E-02	-6.98E-03	9.17E-05	-2.74E-02	-3.90E-02
Oil	1.39E-04	N/A	2.81E-04	2.67E-03	7.07E-03	-2.61E-02	N/A	8.54E-05	-2.16E-02	N/A
Sulfuric Acid	2.32E-05	N/A	2.39E-06	2.17E-04	1.33E-07	-1.75E-02	N/A	7.27E-07	-1.40E-03	N/A
Iron	1.12E-02	N/A	6.59E-06	1.46E-06	3.67E-07	-9.41E-02	N/A	2.00E-06	-7.40E-03	N/A
Ammonia	1.30E-06	N/A	4.86E-06	1.40E-04	6.56E-07	-3.81E-05	N/A	1.48E-06	-4.40E-03	N/A
Copper	0.00E+00	N/A	0.00E+00	0.00E+00	0.00E+00	0.00E+00	N/A	0.00E+00	0.00E+00	N/A

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	Coal Precomb.	IGCC Plants	RDF Plant	Traditional Landfill	Ash Landfill	Electricity Offset	Methanol Offset[C]	Transport[d]	(Al + Fe) Offset	Total
Cadmium	3.35E-07	N/A	4.51E-07	7.53E-09	2.51E-08	-6.74E-05	N/A	1.37E-07	-5.17E-05	N/A
Arsenic	0.00E+00	N/A	0.00E+00	2.70E-09	0.00E+00	0.00E+00	N/A	0.00E+00	0.00E+00	N/A
Mercury	2.60E-11	N/A	3.40E-11	3.83E-11	1.89E-12	-5.29E-09	N/A	1.03E-11	-4.63E-08	N/A
Phosphate	1.12E-05	N/A	1.21E-06	1.02E-06	6.75E-08	-8.72E-03	N/A	3.69E-07	-4.87E-04	N/A
Selenium	0.00E+00	N/A	0.00E+00	8.73E-10	0.00E+00	0.00E+00	N/A	0.00E+00	0.00E+00	N/A
Chromium	3.35E-07	N/A	4.51E-07	1.46E-08	2.51E-08	-6.74E-05	N/A	1.37E-07	-5.17E-05	N/A
Lead	5.30E-10	N/A	5.21E-09	1.26E-09	2.89E-10	-4.98E-09	N/A	1.58E-09	-2.68E-07	N/A
Zinc	1.21E-07	N/A	2.26E-07	3.32E-09	1.25E-08	-2.31E-05	N/A	6.85E-08	-1.86E-05	N/A
Solid Waste	3.21E+01	N/A	4.62E-02	2.36E-02	3.58E-03	-3.35E+02	-3.83E+00	1.40E-02	-1.23E+02	-4.29E+02

[a] The subscript represents the fuel gas saturation level to the gas turbine.

[b] The term "N/A" means that data for that item are not available.

[c] This is offset from net energy production from IGCC based polygeneration system after subtracting the RDF plant demand.

[d] LCI associated with the transportation from RDF plants to remanufacturing plants

e The GHE are given as carbon equivalents, calculated using equation: GHE = 12/44*(fossil CO_2 + 21*methane)

Table D.4.2 LCI Results of Gasification System Firing MSW[a] $_{0.45}$ with a Landfill without Energy Recovery[b] (Lbs/Ton MSW)

	Coal Precomb.	IGCC Plant	RDF Plant	Traditional Landfill	Ash Landfill	Electricity Offset	Methanol Offset[C]	Transport[d]	(Al + Fe) Offset	Total
Airborne Releases										
Carbon monoxide	1.67E-02	4.00E-01	3.64E-02	1.58E-02	2.37E-03	-4.97E-01	-1.48E-01	2.27E-02	-2.31E+00	-2.47E+00
Nitrogen oxides	2.14E-02	7.33E-01	5.66E-02	2.50E-03	6.99E-03	-6.59E+00	-7.00E-02	2.30E-02	-8.10E-01	-6.63E+00
Total particulates	2.38E-01	4.69E-02	6.27E-03	1.76E-03	6.41E-04	-2.25E+00	-1.08E-02	3.32E-03	-1.11E+00	-3.07E+00
Carbon dioxide (fossil fuel)	3.78E+00	5.08E+02	9.12E-01	1.37E-01	4.99E-01	-1.75E+03	-3.09E+01	2.68E+00	-3.54E+02	-1.62E+03
Carbon dioxide (biomass fuel)	2.79E-02	9.11E+02	9.20E+00	1.56E+01	1.18E-04	-2.47E-01	0.00E+00	6.43E-04	0.00E+00	9.35E+02
Sulfur oxides	2.14E-02	1.80E-03	1.32E-02	6.59E-04	1.19E-03	-1.16E+01	-7.21E-01	6.54E-03	-2.29E+00	-1.46E+01
Hydrocarbons	7.90E-03	4.06E-02	2.59E-02	3.94E-04	1.79E-03	-3.38E-01	N/A	9.27E-03	-4.13E-01	N/A
Methane	4.36E-01	N/A	1.41E-03	1.36E-01	8.85E-05	-3.86E+00	-1.75E-01	4.27E-04	-4.84E-01	-3.94E+00
Lead	2.51E-07	N/A	4.86E-08	1.93E-09	2.70E-09	-7.51E-05	N/A	1.48E-08	5.20E-05	N/A
Ammonia	8.09E-06	N/A	1.39E-05	3.10E-07	7.72E-07	-1.47E-03	N/A	4.22E-06	-8.30E-04	N/A
Hydrochloric acid	1.02E-04	N/A	8.68E-06	2.05E-04	5.96E-07	-1.42E-01	N/A	2.64E-06	-4.98E-02	N/A
GHE[e] (Tons/day)	1.76E-03	N/A	1.28E-04	4.09E-04	6.83E-05	-2.50E-01	-4.71E-03	3.67E-04	-4.96E-02	-3.02E-01
Waterborne Releases										
Dissolved Solids	7.62E-03	N/A	1.21E-02	1.81E-04	6.72E-04	-1.48E+00	N/A	3.67E-03	-1.22E+00	N/A
Suspended solids	1.31E-01	N/A	2.74E-04	2.55E-05	2.69E-05	-1.23E+00	-6.62E-03	8.33E-05	-1.33E-01	-1.24E+00
Bio-chemical Oxygen Demand	1.12E-05	N/A	4.51E-05	4.38E-03	5.12E-06	-1.46E-03	-9.63E-04	1.37E-05	-1.81E-03	2.15E-04
Chemical Oxygen Demand	1.21E-04	N/A	3.02E-04	1.22E-02	3.54E-03	-2.08E-02	-6.84E-03	9.17E-05	-2.74E-02	-3.88E-02
Oil	1.39E-04	N/A	2.81E-04	2.67E-03	7.07E-03	-2.60E-02	N/A	8.54E-05	-2.16E-02	N/A
Sulfuric Acid	2.32E-05	N/A	2.39E-06	2.17E-04	1.33E-07	-1.74E-02	N/A	7.27E-07	-1.40E-03	N/A
Iron	1.12E-02	N/A	6.59E-06	1.46E-06	3.67E-07	-9.39E-02	N/A	2.00E-06	-7.40E-03	N/A
Ammonia	1.30E-06	N/A	4.86E-06	1.40E-04	6.56E-07	-3.80E-05	N/A	1.48E-06	-4.40E-03	N/A
Copper	0.00E+00	N/A	0.00E+00	0.00E+00	0.00E+00	0.00E+00	N/A	0.00E+00	0.00E+00	N/A

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	Coal Precomb.	IGCC Plants	RDF Plant	Traditional Landfill	Ash Landfill	Electricity Offset	Methanol Offset[C]	Transport[d]	(Al + Fe) Offset	Total
Cadmium	3.35E-07	N/A	4.51E-07	7.53E-09	2.51E-08	-6.72E-05	N/A	1.37E-07	-5.17E-05	N/A
Arsenic	0.00E+00	N/A	0.00E+00	2.70E-09	0.00E+00	0.00E+00	N/A	0.00E+00	0.00E+00	N/A
Mercury	2.60E-11	N/A	3.40E-11	3.83E-11	1.89E-12	-5.28E-09	N/A	1.03E-11	-4.63E-08	N/A
Phosphate	1.12E-05	N/A	1.21E-06	1.02E-06	6.75E-08	-8.70E-03	N/A	3.69E-07	-4.87E-04	N/A
Selenium	0.00E+00	N/A	0.00E+00	8.73E-10	0.00E+00	0.00E+00	N/A	0.00E+00	0.00E+00	N/A
Chromium	3.35E-07	N/A	4.51E-07	1.46E-08	2.51E-08	-6.72E-05	N/A	1.37E-07	-5.17E-05	N/A
Lead	5.30E-10	N/A	5.21E-09	1.26E-09	2.89E-10	-4.96E-09	N/A	1.58E-09	-2.68E-07	N/A
Zinc	1.21E-07	N/A	2.26E-07	3.32E-09	1.25E-08	-2.31E-05	N/A	6.85E-08	-1.86E-05	N/A
Solid Waste	3.21E+01	N/A	4.62E-02	2.36E-02	3.58E-03	-3.34E+02	-3.75E+00	1.40E-02	-1.23E+02	-4.28E+02

[a] The subscript represents the fuel gas saturation level to the gas turbine.

[b] The term "N/A" means that data for that item are not available.

[c] This is offset from net energy production from IGCC based polygeneration system after subtracting the RDF plant demand.

[d] LCI associated with the transportation from RDF plants to remanufacturing plants

e The GHE are given as carbon equivalents, calculated using equation: GHE = 12/44*(fossil CO_2 + 21*methane)

Table D.4.3 LCI Results of Gasification System Firing MSW[a] $_{0.55}$ with a Landfill without Energy Recovery[b] (Lbs/Ton MSW)

	Coal Precomb.	IGCC Plant	RDF Plant	Traditional Landfill	Ash Landfill	Electricity Offset	Methanol Offset[C]	Transport[d]	(Al + Fe) Offset	Total
Airborne Releases										
Carbon monoxide	1.67E-02	3.93E-01	3.64E-02	1.58E-02	2.37E-03	-4.94E-01	-1.45E-01	2.27E-02	-2.31E+00	-2.47E+00
Nitrogen oxides	2.14E-02	7.20E-01	5.66E-02	2.50E-03	6.99E-03	-6.55E+00	-6.87E-02	2.30E-02	-8.10E-01	-6.60E+00
Total particulates	2.38E-01	4.60E-02	6.27E-03	1.76E-03	6.41E-04	-2.23E+00	-1.06E-02	3.32E-03	-1.11E+00	-3.06E+00
Carbon dioxide (fossil fuel)	3.78E+00	4.99E+02	9.12E-01	1.37E-01	4.99E-01	-1.74E+03	-3.03E+01	2.68E+00	-3.54E+02	-1.62E+03
Carbon dioxide (biomass fuel)	2.79E-02	8.94E+02	9.20E+00	1.56E+01	1.18E-04	-2.46E-01	0.00E+00	6.43E-04	0.00E+00	9.18E+02
Sulfur oxides	2.14E-02	1.77E-03	1.32E-02	6.59E-04	1.19E-03	-1.16E+01	-7.08E-01	6.54E-03	-2.29E+00	-1.45E+01
Hydrocarbons	7.90E-03	3.99E-02	2.59E-02	3.94E-04	1.79E-03	-3.36E-01	N/A	9.27E-03	-4.13E-01	N/A
Methane	4.36E-01	N/A	1.41E-03	1.36E-01	8.85E-05	-3.83E+00	-1.71E-01	4.27E-04	-4.84E-01	-3.92E+00
Lead	2.51E-07	N/A	4.86E-08	1.93E-09	2.70E-09	-7.47E-05	N/A	1.48E-08	5.20E-05	N/A
Ammonia	8.09E-06	N/A	1.39E-05	3.10E-07	7.72E-07	-1.46E-03	N/A	4.22E-06	-8.30E-04	N/A
Hydrochloric acid	1.02E-04	N/A	8.68E-06	2.05E-04	5.96E-07	-1.41E-01	N/A	2.64E-06	-4.98E-02	N/A
GHE[e] (Tons/day)	1.76E-03	N/A	1.28E-04	4.09E-04	6.83E-05	-2.49E-01	-4.62E-03	3.67E-04	-4.96E-02	-3.00E-01
Waterborne Releases										
Dissolved Solids	7.62E-03	N/A	1.21E-02	1.81E-04	6.72E-04	-1.47E+00	N/A	3.67E-03	-1.22E+00	N/A
Suspended solids	1.31E-01	N/A	2.74E-04	2.55E-05	2.69E-05	-1.22E+00	-6.50E-03	8.33E-05	-1.33E-01	-1.23E+00
Bio-chemical Oxygen Demand	1.12E-05	N/A	4.51E-05	4.38E-03	5.12E-06	-1.46E-03	-9.45E-04	1.37E-05	-1.81E-03	2.42E-04
Chemical Oxygen Demand	1.21E-04	N/A	3.02E-04	1.22E-02	3.54E-03	-2.07E-02	-6.71E-03	9.17E-05	-2.74E-02	-3.86E-02
Oil	1.39E-04	N/A	2.81E-04	2.67E-03	7.07E-03	-2.59E-02	N/A	8.54E-05	-2.16E-02	N/A
Sulfuric Acid	2.32E-05	N/A	2.39E-06	2.17E-04	1.33E-07	-1.73E-02	N/A	7.27E-07	-1.40E-03	N/A
Iron	1.12E-02	N/A	6.59E-06	1.46E-06	3.67E-07	-9.33E-02	N/A	2.00E-06	-7.40E-03	N/A
Ammonia	1.30E-06	N/A	4.86E-06	1.40E-04	6.56E-07	-3.78E-05	N/A	1.48E-06	-4.40E-03	N/A
Copper	0.00E+00	N/A	0.00E+00	0.00E+00	0.00E+00	0.00E+00	N/A	0.00E+00	0.00E+00	N/A

(To be Continued)

(Continued)

	Coal Precomb.	IGCC Plants	RDF Plant	Traditional Landfill	Ash Landfill	Electricity Offset	Methanol Offset[C]	Transport[d]	(Al + Fe) Offset	Total
Cadmium	3.35E-07	N/A	4.51E-07	7.53E-09	2.51E-08	-6.68E-05	N/A	1.37E-07	-5.17E-05	N/A
Arsenic	0.00E+00	N/A	0.00E+00	2.70E-09	0.00E+00	0.00E+00	N/A	0.00E+00	0.00E+00	N/A
Mercury	2.60E-11	N/A	3.40E-11	3.83E-11	1.89E-12	-5.25E-09	N/A	1.03E-11	-4.63E-08	N/A
Phosphate	1.12E-05	N/A	1.21E-06	1.02E-06	6.75E-08	-8.65E-03	N/A	3.69E-07	-4.87E-04	N/A
Selenium	0.00E+00	N/A	0.00E+00	8.73E-10	0.00E+00	0.00E+00	N/A	0.00E+00	0.00E+00	N/A
Chromium	3.35E-07	N/A	4.51E-07	1.46E-08	2.51E-08	-6.68E-05	N/A	1.37E-07	-5.17E-05	N/A
Lead	5.30E-10	N/A	5.21E-09	1.26E-09	2.89E-10	-4.93E-09	N/A	1.58E-09	-2.68E-07	N/A
Zinc	1.21E-07	N/A	2.26E-07	3.32E-09	1.25E-08	-2.30E-05	N/A	6.85E-08	-1.86E-05	N/A
Solid Waste	3.21E+01	N/A	4.62E-02	2.36E-02	3.58E-03	-3.32E+02	-3.68E+00	1.40E-02	-1.23E+02	-4.26E+02

[a] The subscript represents the fuel gas saturation level to the gas turbine.

[b] The term "N/A" means that data for that item are not available.

[c] This is offset from net energy production from IGCC based polygeneration system after subtracting the RDF plant demand.

[d] LCI associated with the transportation from RDF plants to remanufacturing plants

e The GHE are given as carbon equivalents, calculated using equation: GHE = 12/44*(fossil CO_2 + 21*methane)