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Principal Investigator/Project Director: **H. Christopher Frey**

Institution: **North Carolina State University**

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Project Title: New Methods for Assessment of Pollution Prevention Technologies: Integration of Probabilistic Process Modeling and Design; Life-Cycle Analysis; and Regional Environmental Benefits Assessment

Abstract

The objectives of this research are to: (1) develop novel assessment methodologies for evaluation of the risks and potential pay-offs of new technologies that avoid pollutant production; (2) demonstrate the methodology via a detailed case study of one promising new pollution prevention technology; and (3) utilize a tiered approach including process simulation and design optimization, probabilistic analysis, life-cycle analysis, and assessment of selected regional environmental impacts to provide insights regarding the risks and pay-offs of the pollution prevention approach, both at a "micro" process-level and at a "macro" regional environmental level. Toward these objectives, process models have been developed in Microsoft Excel and ASPEN Plus to simulate an integrated gasification combined cycle (IGCC) polygeneration system. Refuse derived fuel (RDF) produced from municipal solid waste (MSW) and coal serve as the raw materials in the IGCC system for the production of syngas which is subsequently converted to methanol and energy. In addition, recyclables are recovered from the MSW during RDF production. A life-cycle inventory (LCI) of the complete processing of MSW and coal into useful products has been completed. In addition, a case study was conducted to compare the environmental burdens associated with MSW processing via the IGCC system and conventional mass burn combustion. In all cases, MSW gasification resulted in lower emissions than a mass burn facility.

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. Because of the long lead times (10-20 years is not unusual), decisions on the direction of process development must necessarily be made with incomplete information. Therefore, technology development is inherently a risky enterprise. Risk is the probability of an adverse outcome. Technological risks include high cost, poor performance, and unacceptable impacts to the environment and human health. Due to limited data, there is significant uncertainty during research, development, and demonstration (RD&D) regarding technological risks.

The objectives of this research are to: (1) develop novel assessment methodologies for evaluation of the risks and potential pay-offs of new technologies that minimize or avoid pollutant production; (2) demonstrate the methodology via a detailed case study of one promising new pollution prevention technology; and (3) utilize process simulation and design optimization, probabilistic analysis, life-cycle analysis, and integrated assessment of regional environmental impacts to provide insights regarding the risks and pay-offs of the pollution prevention approach, both at a "micro" process-level and at a "macro" regional environmental level.

In this paper, the results of a case study based on a new technology for the production of industrial feedstocks from MSW are presented. The technology, waste gasification, has the potential to convey benefits in the areas of avoided chemical production, with additional benefits to electric power generation, production of transportation fuels and avoidance of pollution associated with alternate MSW treatment methodologies. The development of process models to simulate each aspect of a process for the conversion of MSW to useful products by waste gasification is described in the first part of this paper. A LCI for the waste gasification process is then presented and compared to the LCI for a conventional waste-to-energy (WTE) process. This comparison allows quantification of the potential benefits of an emerging technology.

Life-Cycle Inventory Model of the MSW/Coal Blend Gasification System

An integrated gasification combined cycle (IGCC) based polygeneration system model was developed to simulate a system in which MSW is converted into RDF which, with coal, serve as raw materials for the production of synthesis gas (syngas), energy, methanol and other useful products. In combination with solid waste processing models, the IGCC system model was used to calculate the LCI of the MSW/coal blend gasification system. The process is illustrated in Figure 1 and described in this section.

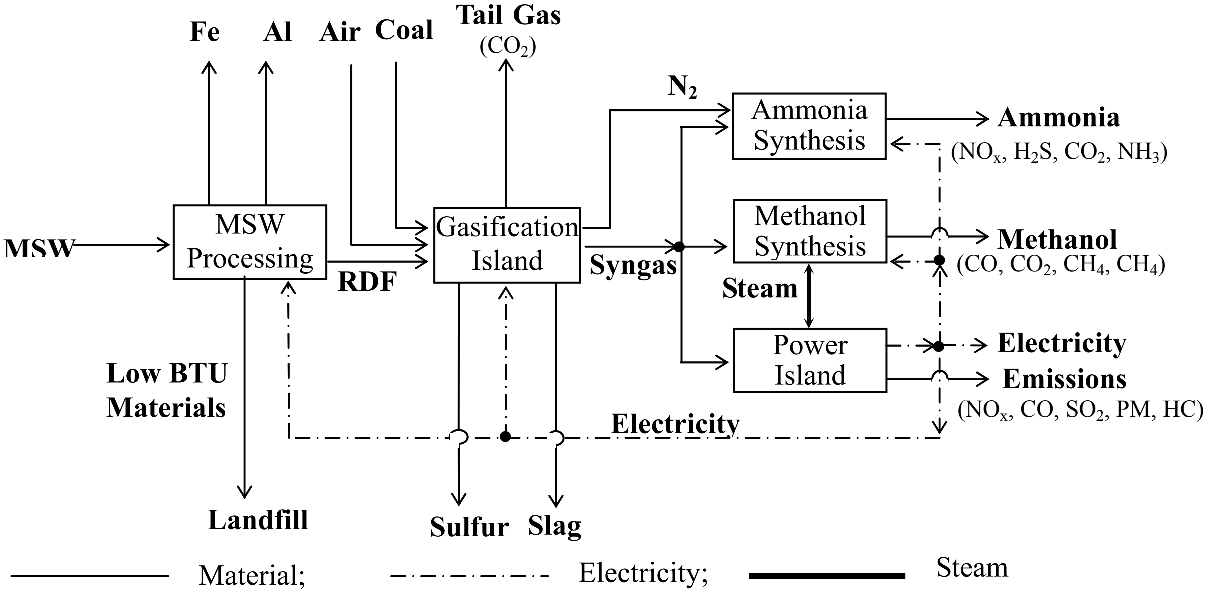

Figure 1 Simplified Process Flow Diagram of the MSW Gasification Process

Initially, MSW is processed to separate it into high and low heating value streams. This step occurs in an 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 the RDF plant and recycled in remanufacturing plants. In the IGCC based polygeneration system, the RDF/coal blend is converted into syngas that can be used to produce energy, methanol, and ammonia. The overall system model includes a number of sub-models to simulate each process and to calculate its LCI. The overall strategy used to calculate a LCI for the MSW/Coal gasification process is described first, followed by brief explanations of each sub-model.

Application of Life-Cycle Inventory Principles to MSW/Coal Gasification

Life-cycle analysis 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 (US EPA, 1993). A LCI represents a compilation of a specific set of inputs and outputs associated with a product or process. In the context of MSW gasification, the processes modeled and emissions and material flows are illustrated in Figure 2. The LCI methodology includes all direct emissions, such as those associated with material transportation, rolling stock emissions at the RDF plant and gaseous emissions from the IGCC system, as well as indirect emissions. Indirect emissions include those associated with the production of the coal used in the gasification process, electrical energy consumption and precombustion emissions associated with raw materials production, i.e., coal mining.

The LCI methodology also includes avoided emissions attributable to the recovery of recyclable materials (ferrous and aluminum), and the production of methanol and electricity from syngas. 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. As illustrated in Figure 2, 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. For example, the CO emissions associated with electrical energy produced from the IGCC system would be calculated as the CO emissions associated with all aspects of the IGCC system, including materials production and residuals disposal, minus the emissions associated with the production of an equivalent amount of electrical energy from conventional fuel sources. A negative LCI indicates that the net emissions are less than emissions associated with a conventional process.

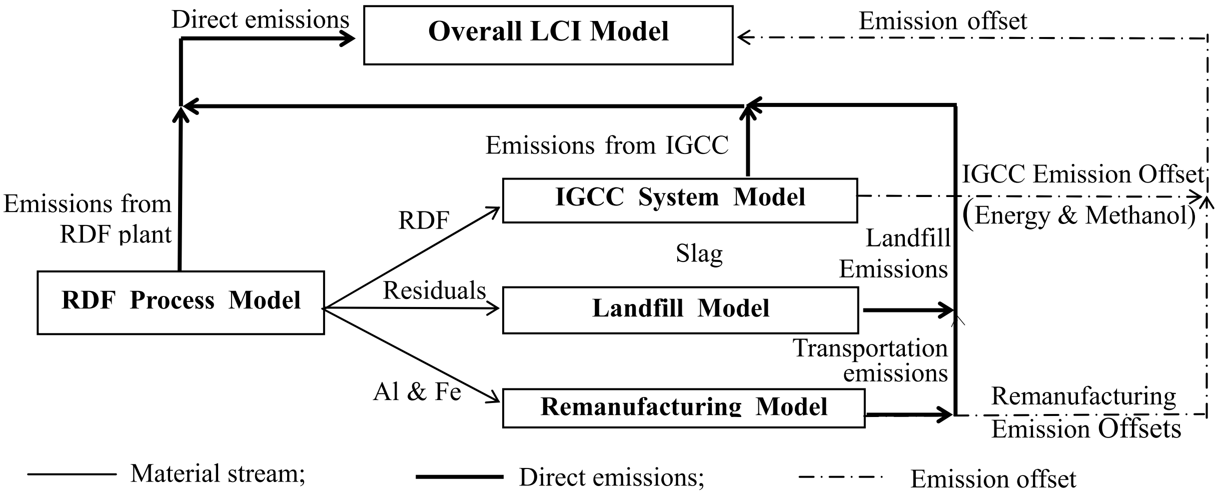

FIGURE 2 Simplified Structure of the Overall LCI Model

IGCC Based Polygeneration System Model

The ASPEN (Advanced Systems for Process Engineering) PLUS process simulator was used to simulate the MSW/coal blend gasification process as an IGCC based polygeneration system model. The simulation model calculates mass and energy balances and emissions for the entire gasification system, including the IGCC plant (Pickett, 2000), and a liquid phase methanol plant (Vaswani, 2000). In this study, the model was calibrated to the MSW/coal blends (Li, 2002). The model consists of sub-modules including a gasification island and a power island. Auxiliary power requirements for each process area and for supporting facilities were 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 and/or to produce chemicals such as methanol and ammonia. To date, methanol is the only chemical product that was modeled. Models for sulfur and ammonia production are under development. The power island includes gas turbines and the steam cycle, in which clean syngas is converted to energy. The IGCC system model consists of 153 unit operation blocks, 24 FORTRAN blocks and 32 design specifications.

Liquid Phase and Conventional Methanol Process Models

A Liquid Phase Methanol Process (LPMEOH^{TM}) model was developed and integrated with the IGCC model. 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 26 unit operation blocks, 4 FORTRAN blocks and 4 design specifications (Vaswani, 2000; Pickett, 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. Conventional methanol production was modeled with natural gas as the feedstock.

RDF Process Model

The RDF process model calculates the materials separation, recyclables recovery and energy consumption associated with the separation of MSW into high (RDF) and low (residual) heating value streams as well as aluminum and ferrous recovery (Li, 2002). The high heating value stream is used for the production of syngas by gasification while the low heating value stream is disposed of by burial in a landfill. Ferrous and aluminum that are recovered are shipped to a remanufacturing plant for conversion to new products. 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 unit operation in the RDF plant (screens, magnet, eddy current separator, etc.). Both diesel fuel and electrical energy are consumed in the production of RDF and this energy consumption and the corresponding emissions are calculated. 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.

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). Emissions are calculated as a function of the carbon content and energy value of each waste. Major air pollutants (CO, PM, NO_x, HCl, SO_2) are assumed to be emitted at the value allowed by regulation. Avoided emissions from conventional power production are subtracted from emissions at the WTE facility to calculate the LCI.

Landfill Model

The landfill process model was used to evaluate two scenarios, a landfill with or without energy recovery (Sich, 2000). 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 the IGCC system, slag is generated and it is managed in an ash landfill. The landfill model considers emissions associated with landfill operation, closure and post-closure, leachate collection and treatment, and gas collection and treatment.

Remanufacturing Model

In the remanufacturing model, emission offsets associated with the recovery of recycled aluminum and ferrous are calculated as the difference in emissions between the manufacturing processes based on virgin and recycled materials (Solano et al., 2002).

Case Studies on the Application of Gasification Technology to MSW

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 4,536, 9,072 and 18,144 kg/hr in scenarios A, B and C, respectively. In each scenario, the size of the two gas turbines modeled in the IGCC system model was held constant. Then a case study was conducted to compare two competing processes for MSW management, one involving MSW gasification and one involving a conventional mass burn WTE facility.

For each scenario, a series of model runs was made to determine (1) material usage, material production, energy production, and the emissions associated with gasification of the RDF/coal blends, (2) material usage, material production, energy production and 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 from RDF production 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.

Input Assumptions and Results of the Base Case

The calculation sequence for the LCI model is described in this section. First, using the RDF process model, the proximate analysis, ultimate analysis and heating value of the RDF were computed based on the user specified MSW composition and physical properties. Second, with a specified RDF/coal blend and methanol plant size, the material usage, material production, and energy production were computed using the IGCC system model. Finally, the total LCI of the MSW/coal blends system was computed using the RDF process model, the IGCC model, the landfill model, the electrical energy model, the remanufacturing model and the conventional methanol production model.

In the base case, the RDF/coal blend was specified as 25 wt. % Pittsburgh #8 coal and 75 wt. % RDF. Initially, the methanol plant size was set to produce 4,596 kg methanol/hr. The proximate analysis, ultimate analysis, and higher heating value of the RDF/coal blend that was fed to the IGCC system are listed in Table 1. The data for RDF was computed in the RDF process model based on the MSW composition presented in Table 2. The heating value for the RDF/coal blends used in this study was calculated by the Dulong correlation. The input assumptions for the IGCC based polygeneration system firing the MSW/coal blends are presented in Table 3.

Table 1. 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	12.32
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

Table 3. Selected 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
Gas Cleaning Process Area	
CO2 in Clean Syngas, mole%	2.0
H2S in Clean Syngas, ppm	1.0
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 (Li, 2002).

Table 2 Composition of MSW Used for RDF Production (wet wt. %)

WASTE ITEM	**MSW**[a]
Leaves	5.6
Grass	9.3
Branches	3.7
Old Newsprint	6.7
Old Corr. Cardboard	2.1
Office Paper	1.3
Phone Books	0.2
Books	0.9
Old Magazines	1.7
3rd Class Mail	2.2
Paper Other	17.1
HDPE - Translucent	0.4
HDPE - Pigmented	0.5
PET	0.4
Plastic - Other	9.9
Ferrous Cans	1.5
Ferrous Metal - Other	3.2
Aluminum Cans	0.9
Aluminum - Other	0.5
Glass - Clear	3.9
Glass - Brown	1.6
Glass - Green	1.0
Food Waste	4.9
CCCN Other	0.0
Plastic - Non-Recyclable	0.0
Misc.	7.5
Glass - Non-recyclable	0.7
Misc.	12.3

a – Solano, *et al*., 2002

The LCI Model Results for the Base Case

To evaluate the contribution of MSW to the calculated emissions, the contribution of RDF to the total material flows, energy flows, and emissions was disaggregated from all totals. The contribution of the RDF was calculated based on the contribution of the RDF to the total energy input, except in two cases: 1) the contribution of the RDF to the fuel, which was calculated based on the weight percentage of RDF and coal; 2) the contribution of the RDF to the ash and sulfur, which was 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 equation used to calculate the contribution of RDF to each total is given by Equation (1). The basis for this calculation is that material production, energy production, and emissions are related to the energy input.

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

Where:

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

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

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

$E_{\_inputRDF}$ = 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

The material and energy flows attributed to the RDF for methanol production of 4,536, 9,072, and 18,144 kg/hr are summarized in Table 4. Approximately 56% of the MSW feed was recovered as RDF with the balance in the residual (39%), Al (1.3%) and Fe (4.2%) streams.

Table 4. Material and Energy Flows Attributed to RDF in the MSW/Coal Blends Gasification System

		Methanol (kg/hr)		
		4,536	**9,072**	**18,144**
MSW Input	(mT/day)	7,054	7,268	7,697
Methanol Produced	(mT/day)	69	139	277
Net Power from IGCC*	(MWh/day)	6,902	6,841	6,716

* Including energy consumed in RDF plant.

The material and energy flows provide the basis for calculation of the LCI of the MSW/coal gasification system. The MSW feed rate determines emissions from the RDF plant and the ash and mixed waste landfills that receive slag and RDF plant residuals, respectively. RDF plant power consumption 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 (which is not calculated here), and ferrous and aluminum recovery. The results of the overall LCI for an MSW gasification system for the base case are presented in Table 5 for landfills with and without energy recovery.

In both cases, for all the pollutants presented, total emissions are negative, with the exception of CO_2-biomass. The reason is that the emission offsets of electrical energy production and the aluminum and ferrous recovered make the largest contribution to the total emissions of the gasification system LCI. In the case of CO_2-biomass, the largest contributor to its emission is the direct emissions from the IGCC based polygeneration system. The emissions in the case where landfill gas is converted to energy are less than those where the gas is flared because there are avoided emissions associated with the recovered energy. However, the difference between the landfill with and without energy recovery is small relative to the total emissions. This is because the offset emissions associated with electricity production, and aluminum and ferrous recovery dominate the overall LCI. In addition, energy recovery from the landfill is reduced because paper, which is the largest biodegradable component of MSW, is recovered in the RDF used for gasification, and not in the residual stream from which methane is produced for energy recovery.

Table 5 Selected LCI Results of the MSW/Coal Blends Gasification System (Base Case)[a, b] (kg/day)

	Coal Precomb.	**IGCC**	**RDF Plant**	**Traditional Landfill**	**Ash Landfill**	**Electricity Offset[C]**	**Methanol Offset**	**Transport[d]**	**(Al + Fe) Offset**	**Total**
Airborne Releases	**Landfill without Energy Recovery**									
Nitrogen oxides	7.53E+01	2.69E+03	2.00E+02	8.85E+00	2.46E+0	-2.32E+04	-2.46E+02	8.12E+01	-2.86E+03	-2.33E+04
Total particulates	8.39E+02	1.63E+02	2.21E+01	6.21E+00	2.26E+0	-7.94E+03	-3.82E+01	1.17E+01	-3.91E+03	-1.08E+04
Sulfur oxides	7.53E+01	6.49E+00	4.67E+01	2.32E+00	4.19E+0	-4.10E+04	-2.54E+03	2.30E+01	-8.07E+03	-5.17E+04
Methane	1.54E+03	N/A	4.94E+00	4.81E+02	3.12E-01	-1.36E+04	-6.12E+02	1.51E+00	-1.71E+03	-1.39E+04
GHE[e] (mT/day)	1.24E+01	N/A	9.05E-01	2.89E+00	4.82E-01	-1.76E+03	-3.31E+01	2.59E+00	-3.50E+02	-2.13E+03
Airborne Releases	**Landfill with Energy Recovery**									
Nitrogen oxides	7.54E+01	2.69E+03	1.99E+02	1.05E+00	2.46E+0	-2.32E+04	-2.46E+02	8.12E+01	-2.86E+03	-2.33E+04
Total particulates	8.39E+02	1.63E+02	2.21E+01	-5.02E+00	2.26E+0	-7.92E+03	-3.82E+01	1.17E+01	-3.91E+03	-1.08E+04
Sulfur oxides	7.54E+01	6.50E+00	4.65E+01	-1.72E+01	4.19E+0	-4.11E+04	-2.54E+03	2.31E+01	-8.09E+03	-5.15E+04
Methane	1.54E+03	N/A	4.96E+00	4.75E+02	3.12E-01	-1.36E+04	-6.14E+02	1.51E+00	-1.71E+03	-1.39E+04
GHE[e] (mT/day)	1.24E+01	N/A	9.05E-01	2.05E+00	4.82E-01	-1.76E+03	-3.31E+01	2.59E+00	-3.50E+02	-2.13E+03

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

[b] Based on material flows given in Table 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*0.9072

Comparison of MSW Treatment by Gasification and Conventional Mass Burn Waste To Energy

MSW treatment by gasification and in a conventional mass burn WTE facility were compared for the case in which 4536 kg/hr of methanol was produced. The input assumptions and the RDF/coal blends for the gasification system are the same as the base case. The results comparing MSW gasification and mass burn are presented in Table 6.

Table 6 Comparison of the LCI of the Gasification System and WTE System

	Gasification		WTE
	Landfill w/ Energy Recovery	Landfill w/o Energy Recovery	
Airborne Emissions (kg/hr)			
Nitrogen oxides	-2.33E+04	-2.33E+04	-1.16E+04
Total particulates	-1.08E+04	-1.08E+04	-8.07E+03
Sulfur oxides	-5.17E+04	-5.17E+04	-3.14E+04
Methane	-1.39E+04	-1.39E+04	-1.03E+04
GHE (mT/day)	-2.30E+03	-2.30E+03	-8.58E+02
Net Electricity Energy (MWh/day)	6,511	6,511	4,127

When MSW is treated by gasification, Al and Fe are recovered for recycling at the RDF plant. To fairly compare WTE and gasification processes, the same amount of Al and Fe was assumed to be recovered from the MSW treated by WTE. In general, the gasification system generates 1.3 – 2.7 times less emissions than the 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 and the aluminum recovered from these two systems and the corresponding offsets are the same. However, the gasification system produces more electricity than the WTE system. In addition, the gasification system receives an offset credit for methanol production. Therefore, the total avoided emissions of the gasification system are greater than that of the WTE system. Second, there are considerable direct atmospheric emissions from the WTE system, which are higher than the direct emissions from the gasification system. Third, because the energy associated with the recovery of landfill gas as an energy source is small for the gasification process, gasification is favorable even when landfill gas is not recovered as an energy source.

Though not presented in Table 7, additional analyses were conducted with increasing methanol production. As methanol production increases, the LCI for the gasification system improves relative to a mass burn WTE facility. This is because of the increased offset associated with increased methanol production. Although the net power production of the gasification system decreases with increasing methanol production, net emissions from the gasification system decrease due to the increase in avoided emissions of methanol production.

Summary and Conclusions

In summary, the case study demonstrated that both the gasification process and mass burn combustion of MSW result in avoided emissions due to the recovery of beneficial products including energy, recyclables, and methanol in the case of gasification. The largest contributors to emissions are the offset emissions associated with the ferrous and aluminum recovered in the RDF plant and the offset emissions associated with the recovered electricity.

The LCI comparison showed that the WTE system produced 1.3 – 2.7 times more emissions than the gasification system for most parameters. The gasification system also produces about 1.5 times more electricity than the WTE system. Sulfur is produced during gas cleanup in the gasification process and no offset was calculated for the recovery of this sulfur. In addition, the product syngas may be used for ammonia production that would also be likely to improve the LCI of waste gasification. As such, the results showing that gasification of MSW coal blends results in reduced emissions relative to a mass burn process are conservative in that they do not fully quantify the environmental benefits of gasification.

Through the case study conducted in this project, the environmental benefits of a new technology have been quantified by the development of appropriate process models and the use of life-cycle analysis.

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