Converting Washington Lignocellulosic Rich Urban Waste to Ethanol[1,2]

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[2] **This report is available on the Department of Ecology's website at www.ecy.wa.gov/beyondwaste/organics. The reader may be interested in the other project reports supported by Organic Waste to Resources and Waste to Fuel Technology funding sponsored by Ecology. These are also available on the "organics" link. The Washington State University Extension Energy Program will make this report accessible in its broader library of bioenergy information on www.pacificbiomass.org. The online Denman Forestry Issues series http://www.uwtv.org/programs/displayseries.aspx?fID=558 is an excellent source of forest ecology, assessment, and climate information.**

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Executive Summary

The objective of this research was to investigate the potential of producing ethanol from municipal waste in Washington State. The approach to the research was to divide the municipal waste into three primary streams and then investigate the potential of converting each into ethanol. This division was made to provide a more fundamental understanding of the issues associated with conversion for each of the major streams. The three primary streams were mixed waste paper, yard waste, and municipal solid waste[4]. For each stream, an experimental study was done to investigate conversion of the biomass into ethanol using bioconversion processes. This experimental work was then accompanied by a Life Cycle Assessment (LCA) to determine the overall environmental impact of the proposed processes. ASPEN models of biorefineries were developed to provide process data for the LCA. An assessment of economic viability was also performed based on the ASPEN models. Following are the main conclusions of the study.

<u>Process Development:</u>

- The paper, yard and municipal solid waste are sugar rich lignocellulosic feedstocks.
- Dilute acid hydrolysis is an effective pretreatment method for paper and municipal solid waste. Steam pretreatment (210°C, 10 min and 3% SO_2) is a good pretreatment method for fractionation of yard waste into hemicellulose, cellulose and lignin rich fractions.
- The water insoluble fractions of municipal solid and paper waste are easily hydrolysable by enzymes. Almost theoretical cellulose to glucose conversion was achieved.
- The water insoluble fraction of yard waste is difficult to hydrolyze by enzymes (41% cellulose to glucose conversion). However, the low cellulose to glucose conversion yields were expected since the biomass was composed of mixture of branches, wood chips, bark, and needles.
- The results obtained during this study demonstrate that the UW developed PTD*3* yeast was able to very efficiently convert yard waste hydrolysate to ethanol with a yield 100% of theoretical during the fermentation process. Pretreated and hydrolyzed sugars of municipal solid, paper and yard waste are readily fermentable by yeast. High ethanol yields were obtained (100% of theoretical). Overall ethanol yields of 105 gallons/ton, 90 gallons/ton, and 55 gallons/ton are estimated for municipal solid waste, paper waste, and yard waste respectively. Typical yields for cellulosic ethanol produced using hydrolysis and fermentation are on the order of 80 gallons per ton but can vary widely depending on biomass feedstock. (See the Theoretical Ethanol Yield Calculator for details - http://www1.eere.energy.gov/biomass/ethanol_yield_calculator.html)

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[4] For this research municipal solid waste (MSW) refers to the organic fraction of residential garbage found in King County. It is similar in composition to garbage where the metal, textiles, and plastics have been removed. The composition of the material is provided in the main body the report.

Life Cycle Assessment:

- Municipal solid waste seems to offer the greatest potential as both a waste management strategy and for bio-fuel production. With over 4 million metric tons of MSW generated in 2007, there is enough lignocellulosic material available to meet the demands of a large capacity biorefinery within the State.
- The greatest contributor to ethanol production environmental flows is chemicals production, specifically lime production. On the other hand, avoidance of dry-mill corn ethanol greatly reduces the environmental flows for ethanol production.
- Landfilled waste offers the least benefit overall, even with production of electricity and avoidance of Washington electric grid. This is related to the fact that the Washington electric grid is largely dominated by clean hydropower and offers little benefit from avoidance.

The process economic analysis suggests that the conversion of MSW to ethanol is economically viable. The ease of conversion and good process yields for this raw material results in reasonable minimum ethanol selling prices even when using conventional Brewer's yeast as a fermentation organism. It should be noted that we did not evaluate the potential for production of high value co-products in this investigation. The process economics could be considerably more favorable with the addition of these product streams.

In general it appears that conversion of material currently sent to landfills would be an excellent feedstock for ethanol production. This material is rich in carbohydrates, can be readily converted to ethanol, and the life cycle impact is reduced by avoiding land filling.

The results of this research are preliminary, however. More work is required to optimize the conversions of each primary stream, especially the recalcitrant yard waste, and conversion research on actual municipal solid waste streams needs to be carried out. The LCA work needs to be expanded to consider all environmental impacts, especially those associated with water usage and aqueous effluents. A more detailed economic analysis is needed to thoroughly assess economic viability. The excellent results obtained from this preliminary study suggest that these more in-depth investigations would be successful and would provide data required to construct a commercial facility.

Converting Washington Lignocellulosic Rich Urban Waste to Ethanol: Part 1, Process Development

Introduction

During the past few decades, global warming has emerged as a major political and scientific issue. This is due primarily to increased emissions of greenhouse gases formed by burning fossil fuels, concurrent with increased energy consumption (Dickerson and Johnson, 2004; Sun and Cheng, 2002). Various studies have shown that ethanol or ethanol-blended transportation fuels produce less harmful emissions, while the production of ethanol from biomass has the advantage of displacing transportation fuels derived from oil with a fuel obtained from a renewable resource (Bergeron, 1996; Galbe and Zacchi, 2002; Tyson, 1993; von Sivers and Zacchi, 1995). In addition to environmental reasons, other motivations, such as fossil fuel exhaustion, geopolitical concerns about reliance on foreign fuel supplies, and the ease of adaptation to a carbon-based fuel are some of the factors influencing the emergence of ethanol as a viable fuel supplement and/or alternative to gasoline. Although the major ethanol producers currently use either sugar cane (Brazil) or corn (North America) as the substrate for the "sugar to ethanol process", various lignocellulosic biomass feedstocks, including: agricultural residues, wood residues, food-processing waste, municipal solid wastes, herbaceous energy crops and pulp and paper industry wastes have the potential to serve as low-cost, abundant feedstocks for the production of fuel ethanol (Wiselogel, et al., 1996).

Approximately four million tons of municipal solid waste is available in Washington State for use a biofuel feedstock (Frear, et al., 2005). Since much of this material is currently sent to landfills, composted, or is recycled, the research proposed here will develop and assess an alternative management system. Specifically, the objective of the proposed research is to evaluate the potential for using urban lignocellulosic waste to produce bioethanol on the basis of potential economic, environmental, and economic development benefits for Washington State. Municipal solid waste, due to its chemical and structural properties, was evaluated as a potential technically viable feedstock that might be used to demonstrate the effectiveness of a biomass to ethanol bioconversion process. For the past year, the Bioenergy group at the College of Forest Resources at the University of Washington has focused on studying the bioconversion process of lignocellulosic rich urban waste to ethanol. The proposed research had one main task: to develop an optimized process for converting lignocellulosic rich urban waste to ethanol. In this study the lignocellulosic rich urban waste was divided into three streams: municipal solid waste, paper waste and yard waste.

Background and methods

Pretreatment-background

Various pretreatment options have been used to fractionate, solubilise, hydrolyse, and separate cellulose, hemicellulose and lignin moieties. These different processes usually exploit a combination of chemical, physical and mechanical treatments that serve to render the lignocellulosics more receptive to subsequent enzymatic hydrolysis. The physical pretreatment techniques do not involve chemical application, and typical examples are milling, irradiation, steam explosion, and hydrothermolysis (high-temperature cooking) (Hsu, 1996). Chemical pretreatment techniques have received the most attention by far among all the categories of pretreatment methods and typical examples include dilute acid, alkali, solvent, ammonia, SO_2, CO_2, other chemicals, steam explosion and pH-controlled hydrothermolysis (McMillan, 1993).

Steam pretreatment is the treatment of biomass with stream at high temperature and pressure for the certain period of time followed by sudden decompression. Previous work has shown that SO_2-catalysed steam explosion can successfully pretreat softwood (Boussaid, et al., 2000; Carrasco, 1992; Clark, et al., 1989; Clark and Mackie, 1987; Schwald, et al., 1989b; Söderström, et al., 2002; Stenberg, et al., 1998; Tengborg, et al., 1998) and hardwood residues (Eklund, et al., 1995; Mackie, et al., 1985; Schwald, et al., 1989a) as part of the overall bioconversion process. In addition, steam explosion is recognized as one the most cost effective pretreatments for lignocellulosic residues prior to enzymatic saccharification (Clark and Mackie, 1987). The impregnation of SO_2 allows lower temperatures and shorter reaction times, and thereby reduces the formation of degradation products (Excoffier, et al., 1991). The use of SO_2 as a catalyst results in improved enzymatic accessibility to cellulose and enhanced recovery of the hemicellulose-derived sugars (Boussaid, et al., 1999; Boussaid, et al., 2000). It was reported that more than 75% of the original hemicellulose-derived sugars can be recovered in the water soluble fraction after steam explosion of Douglas-fir (*Pseudotsuga menziesii*) wood chips at relatively mild conditions (Boussaid, et al., 2000). It has been shown previously that adding SO_2 prior to steam explosion enhanced the carbohydrate hydrolysis rate, while reducing the degree of polymerization of the oligomers and increasing the proportion of monomers in the water soluble stream (Clark, et al., 1989). In addition, a combination of steam explosion with acid hydrolysis increases pore volume and enzyme accessibility, reduces particle size (Boussaid, et al., 2000) and increases the available surface area (Michalowicz, et al., 1991).

In this study steam explosion was employed to pretreate the yard waste and diluted acid pretreatment was employed to pretreat municipal solid and paper waste.

Pretreatment-Methods

The yard waste, mixture of hardwood and softwood with branches, bark, needles (60.0 % moisture content) was obtained from the University of Washington waste facility and stored at 4°C until use. Yard waste was composed of shrubbery cuttings, leaves, needles, tree limbs, and other materials was pretreated by soaking in water overnight prior to SO_2-catalysed steam explosion. Prior to SO_2-catalysed steam explosion, the biomass was kept a sealed plastic container to ensure uniform moisture content. Samples of 300g oven-dried weight (ODW) were impregnated overnight with anhydrous SO_2 in plastic bags. The samples were then loaded, in 50g batches, into a preheated 2L steam gun in Gresham, Oregon and exploded at temperature of 210°C; time 10 minutes and 3% (w/w) SO_2 concentration The recovered slurries were separated by filtration and kept at 4°C until use.

The paper waste was obtained from the Tacoma recycling facility owned by Weyerhaeuser and consisted of the lowest grade paper waste. The municipal solid waste was prepared in the lab due to the safety issues. It's composition was based on the organic fraction of residential waste in King County and is similar to that refuse stream where the metal, textiles, and plastics have been removed. Specifically the composition was 50% food waste and 50% of mixed waste papers including clean hygiene products which also contained incidental plastics. The food waste included banana peels, cereal, coffee grinds, canned corn, and tomato juice.

The paper waste and municipal solid waste were pretreated by diluted sulfuric acid at 60°C for 6 hours. Then the slurry was recovered, separated by filtration and kept at 4°C until use.

Enzymatic hydrolysis-Background

The pretreatment processes are designed only to initiate the breakdown of the biomass structure and partially hydrolyze the carbohydrate polymers, making them accessible to enzymatic attack.

Hydrolysis of cellulose to glucose can be achieved using either inorganic acids or cellulolytic enzymes. Chemical hydrolysis of biomass is relatively efficient and inexpensive, however, it generates fermentation inhibitors (Leathers, 2003). On the other hand, enzymatic hydrolysis, despite its relatively slow rate, is a biocompatible and environmentally friendly option (as it avoids the use of corrosive chemicals).

Cellulases, perform a crucial task during saccharification by catalyzing the hydrolysis of cellulose to soluble and fermentable carbohydrates. They are synthesized mainly by fungi and bacteria and are produced both aerobically and anaerobically. The aerobic mesophilic fungus *Trichoderma reesei* and its mutants have been the most intensively studied source of cellulases (Philippidis, 1996). The enzyme system for the conversion of cellulose to glucose generally comprises three distinct classes of enzyme (Lynd, et al., 2002):

- endoglucanases or 1,4-β-D-glucan-4-glucanohydrolases (EC 3.2.1.4),
- exoglucanases, including 1,4-β-D-glucan glucanohydrolases (also known as cellodextrinases) (EC 3.2.1.74) and 1,4-β-D-glucan cellobiohydrolases (also known as cellobiohydrolases) (EC 3.2.1.91), and
- β-glucosidases or β-glucoside glucohydrolases (EC 3.2.1.21).

Endoglucanases cut at random, at internal amorphous sites in the cellulose polysaccharide chain, and generate oligosaccharides of varying lengths and consequently new chain ends (Mansfield, et al., 1999). Exoglucanases act on the reducing and nonreducing ends of cellulose polysaccharide chains, liberating either glucose (glucanohydrolases) or cellobiose (cellobiohydrolase) as major products (Mansfield, et al., 1999). Exoglucanases can also act on microcrystalline cellulose, presumably peeling cellulose chains from the microcrystalline structure (Lynd, et al., 2002). β-Glucosidases hydrolyse soluble cellodextrins and cellobiose to glucose (Bothast and Saha, 1997).

Cellulase systems exhibit higher collective activity than the sum of the activities of the individual enzymes, a phenomenon known as synergism. Five forms of synergism have been reported:

- endo-exo synergy between endoglucanases and exoglucanases (Lynd, et al., 2002),
- exo-exo synergy between exoglucanases processing from the reducing and non-reducing ends of cellulose chains (Fägerstam and Pettersson, 1980),
- synergy between exoglucanases and β-glucosidases that remove cellobiose (and cellodextrins) as end products of the first two enzymes (Lynd, et al., 2002),
- intramolecular synergy between catalytic domains (CDs) and carbohydrate-binding modules (CDMs) (Lynd, et al., 2002; Teeri, 1997), and
- endo-endo synergy between endoglucanases (Mansfield, et al., 1998).

Enzymatic hydrolysis-Methods

After the pretreatment the steam or acid pretreated solids were enzymatically hydrolyzed at 2 % consistency (w/v) solid concentration. The hydrolysis took place at 50°C with continuous agitation (150 rpm) for a period of up to 72 hours. During hydrolysis, a complete cellulase preparation (Celluclast 1.5L) obtained from the fungi, *Trichoderma reesei*, supplied commercially by Novozymes North America Incorporated (Franklinton, NC, U.S.) was used. Each 125 mL Erlenmeyer flask containing 50 mL of total liquid was also supplemented with additional b-glucosidase enzyme (Novozym-188$^{®}$) originating from *Aspergillus niger*. The hydrolytic reaction mixtures were inoculated with enzymes based on the amount of filter paper units (FPU) g cellulose^{-1}of cellulase. Novozym-188$^{®}$ was loaded to achieve an IU (international units) to FPU ratio of 2:1.

Aliquots of 1 mL were aseptically removed at different reaction intervals, boiled for 5 minutes to inactivate the enzymes, and then centrifuged for 5 min at 15000 ´ *g* and 4°C. The supernatant was filtered using a syringe filter 0.45 mm syringe filter (Restek Corp., Bellefonte, PA, U.S.) and then stored at -20°C until further analysis by HPLC. All hydrolysis experiments were performed in triplicates. In addition, during each experiment, controls were run in parallel (enzymes plus buffer, feedstock hydrolysate plus buffer).

The extent or yield of hydrolysis was expressed as the percentage of the theoretical glucose content in the feedstock at the start of hydrolysis that was recovered as monomeric glucose (i.e., the glucose yield). The determination of the theoretical glucose content of the feedstock was based on Klason analysis of the feedstock solids, and assumed all available glucose was present as cellulose. A conversion factor was applied in the calculation of the carbohydrate content to account for the hydration of the cellulose during cleavage (Allen, et al., 2001).

Fermentation-Background

Mixed sugars derived from mixture of hardwoods and softwoods are potential substrates for fermentation to a variety of valuable products, including ethanol, vitamins, amino acids and many others. The microorganism most widely used in the fermentation to ethanol process is *Saccharomyces cerevisiae*. However, this yeast is unable to ferment pentose sugars, which can comprise an appreciable fraction of mixture of hardwoods and softwoods hydrolysates. There are essentially no commercially suitable wild types or naturally occurring bacteria or yeast for fermenting xylose and arabinose to coproducts. For example, naturally occurring yeast that do ferment xylose require aeration for growth, have low productivity, are very sensitive to inhibitors, especially acetate, and have a low ethanol tolerance (Bothast, et al., 1999; Dien, et al., 2002).

It is important that microorganisms selected for the conversion of hemicellulose hydrolysates have the ability to ferment the sugars rapidly in order to maximize conversion performance and to have an economically feasible process. In addition, the selected microorganisms should be robust growers, which would require an inexpensive medium formulation, and very resistant to inhibitors (generated in the pretreatment step) (Dien, et al., 2003).

Both yeast (such as *Saccharomyces* and *Pichia* species) and bacteria (such as *Escherichia coli*, *Klebsiella*, and *Zymonomas*) have been genetically engineered to ferment glucose and xylose (Bothast, et al., 1999; Dien, et al., 2003; McMillan, 1996). Xylose-fermenting yeast such as *P. stipitis* has shown a great potential for achieving high conversion yields on detoxified hydrolysates. However, aeration is required and there is a significant performance tradeoff between yield and productivity (often 0.3-0.4 g L^{-1} h^{-1}) Nevertheless, inhibitor tolerance remains a concern for all of these strains. For example, *Z. mobilis* is extremely sensitive to acetic acid (Dien, et al., 2003).

So far, there is no reported naturally occurring microorganism that is capable of utilizing concurrently, hexose and pentose sugars, without being genetically modified. Only recently, Dr. S. L. Doty at the University of Washington discovered a strain from hybrid poplar trees and was given name PTD3. The yeast strain selected from the tissue of poplar trees has the ability to grow on five carbon sugars, including xylose and arabinose and ferment hexoses to ethanol, xylose to xylitol and arabinose to arabitol.

Fermentation-Methods

The PTD3 strain was maintained on YPG solid medium (10 g L^{-1} yeast extract, 20 g L^{-1} peptone, 20 g L^{-1} glucose, and 18gL^{-1} agar, Difco, Becton Dickinson, MD) at 4°C and transferred to fresh plates on a bimonthly basis. Cells were grown to high cell density (culminating in average 600 nm absorbance values of approximately 10) in foam-plugged 1L Erlenmeyer flasks containing 500ml YP-sugar liquid media (10 g L^{-1} yeast extract and 10 g L^{-1} peptone, supplemented with 10 g L^{-1} glucose) in an orbital shaker for 2 days at 30°C and 150 rpm, with concurrent transfer to fresh medium performed every 24 h.

During the SO_2-catalysed steam explosion of yard waste and acid hydrolysis of paper and municipal solids waste, the water soluble fractions obtained from each of the pretreatment and enzymatic hydrolysis steps were assessed for their efficiency during fermentation to ethanol, without employing any detoxification steps.

Fermentation of the liquid sugar fractions (water soluble) was conducted in 125 mL flasks containing 50 mL medium pre-adjusted to pH 6.0 with 0.5 M sodium hydroxide. Control fermentations were run in parallel using glucose-based media. The fermentation vessels were maintained at 30°C with continuous agitation (150 rpm). Samples (0.5 mL) were withdrawn aseptically by syringe, centrifuged for 5 min at 15000 ´ g and 4°C and the supernatant was filtered by using a 0.45 mm syringe filter (Restek Corp., Bellefonte, PA, U.S.) and then stored at -20°C until analysis. Sugars, ethanol, 5-

HMF and furfurals were determined periodically from the aliquot culture samples during the course of the fermentation. The relative ethanol yield, Y_{EtOH} $(Y^{ref}_{EtOH})^{-1}$ was defined as the ratio of the ethanol yield of the filtrate and the theoretical fermentation. The theoretical yield for ethanol production from glucose is 0.51 g ethanol g^{-1} glucose (Olsson and Hahn-Hägerdal, 1996). Each experiment was run in duplicate and the range value reported.

Methods for analytic procedures

Analysis of solids

The chemical composition of the original starting material and pretreated solids were determined using a modified Klason lignin method derived from the TAPPI Standard method T222 om-88 (TAPPI, 1998a). Briefly, 0.2 g of sample (ground to pass through a 40-mesh screen) was incubated at 20°C with 3 mL of 72% H_2SO_4 for 2 hours with mixing every 10 minutes. The reaction was then diluted with 112 mL of deionized water (final acid concentration 4% H_2SO_4) and then transferred to a serum bottle. The solution was then subject to autoclaving at 121°C for 1 hour and, when cold, filtered through a medium coarseness sintered glass filter for the gravimetric determination of the acid insoluble lignin content. Klason lignin (acid insoluble lignin) was determined gravimetrically after rinsing the solids in the crucibles with 200 mL nanopure water, and overnight drying at 105°C. The concentration of sugars in the filtrate was measured by HPLC and the acid soluble lignin was quantified by measuring the absorbance at 205 nm according to the TAPPI Useful Method UM250 (TAPPI, 1998b). Each experiment was run in triplicate.

Post-hydrolysis

Post-hydrolysis experiments were performed according to (Shevchenko, et al., 2000). Duplicate samples containing 27 mL of the water soluble fraction were post-hydrolysed after adding concentrated sulphuric acid to achieve a final concentration of 3% acid. The post-hydrolysis was performed by heating the solution at 121°C for 1 hour in an autoclave. A batch of sugar standards was also autoclaved under the same conditions, to estimate any hydrolysis loss. The sugar concentrations were quantified by HPLC.

Analysis of the water soluble fraction - Monomeric sugars

The concentration of monomeric sugars (arabinose, galactose, glucose, xylose and mannose) was measured on a Dionex (Sunnyvale, CA) HPLC (ICS-3000) system equipped with an AS autosampler, ED electrochemical detector, dual pumps, and anion exchange column (Dionex, CarboPac PA1) across a gold electrode. Deionized water at 1 ml min^{-1} was used as an eluent, and postcolumn addition of 0.2 M NaOH at a flow rate of 0.5 ml/min ensured optimization of baseline stability and detector sensitivity. After each analysis, the column was reconditioned with 0.25 M NaOH. Twenty microliters of each sample were injected after filtration through a 0.45 mm syringe filter (Restek Corp., Bellefonte, PA, U.S.). Standards were prepared containing sufficient arabinose, galactose, glucose, xylose, and mannose to encompass the same range of concentrations as the samples. Fucose (0.2 g L^{-1}) was added to all samples and standards as an internal standard.

Analysis of the water soluble fraction - Ethanol, Furfurals and HMFs

Ethanol, glucose and xylose concentrations, and concentrations of sugar degradation products such as 5-hydroxymethylfurfural (5-HMF) and furfural were determined using Shimadzu Prominence HPLC chromatograph (Shimadzu Corporation, Columbia, MD). Separation of ethanol, xylitol, glucose, and xylose was achieved by an anion exchange column (REZEX RHM-Mono saccharide H^+(8%), Phenomenex, Inc., and Torrance, CA, U.S.) with isocratic mobile phase that consisted of 5µM H_2SO_4 at a flow rate of 0.6ml min^{-1}. The column oven temperature was maintained at 63°C constantly. Twenty microliters of each sample were injected after being appropriately diluted in deionized water and filtered through a 0.45 mm syringe filter (Restek Corp., Bellefonte, PA, U.S.). Standards were prepared containing sufficient concentration of a desired compound to encompass the same range of concentrations as the samples. Each experiment was run in duplicate and the range value reported.

The relative ethanol yield, YEtOH $(\text{Yref EtOH})^{-1}$ was defined as the ratio of the ethanol yield of the filtrate and the theoretical fermentation. The theoretical yield for ethanol production from glucose is 0.51 g ethanol g^{-1} glucose (Olsson and Hahn-Hägerdal, 1996). Ethanol yields and percent theoretical yields were calculated using the following equations, respectively:

$$YP/S = \frac{[EtOH]_{max}}{[Sugar]_{ini}}$$

$$Y\%T = \frac{YP/S}{0.51} \times 100$$

where YP/S = ethanol yield (g g^{-1}), $[EtOH]_{max}$ = maximum ethanol concentration achieved during fermentation (g L^{-1}), $[Sugar]_{ini}$ = total initial sugar concentration at onset of fermentation (g L^{-1}), $Y\%T$ = percent theoretical yield (%), and 0.51 = theoretical maximum ethanol yield per unit of hexose sugar from glycolytic fermentation (g/g).

Results and Discussion

Lignocellulosic rich urban waste composition

We initially determined the carbohydrates and Klason lignin of the original untreated yard, municipal solid and paper waste (Table 1-1). The total polysaccharides content for yard, municipal and paper waste proved to be very high 66, 88 and 79% respectively, making this lignocellulosic rich urban waste an attractive material for saccharification and fermentation processes. Glucose, followed by mannose and xylose were shown to be the most abundant components of yard, municipal and paper waste as determined by secondary acid hydrolysis of constituent polysaccharides. The total lignin (Klason lignin) content was determined to be highest for yard waste, 39% and the lowest for municipal solid waste 7.5% (Table 1-1). The total lignin content of paper waste was 21% (Table 1-1). The yard waste contained high lignin content since lots of branches and bark (both of which are lignin rich) were visually present in the samples.

Monomeric and oligomeric sugars

One of the requirements for an economical viable biomass to ethanol process is maximum hemicellulose recovery in monomeric form for ethanol production. Therefore, the concentration of water soluble monomeric and oligomeric sugars was measured for all streams tested by using dilute acid hydrolysis previously described by Bura *et al.* (2003). The concentration of monomeric sugars was determined by high pressure liquid chromatography (HPLC-Dionex 3000) analysis previously described by Bura *et al.* (2003).

The concentration of monomeric and oligomeric sugars in the liquid fraction after acid hydrolysis of pretreated yard, municipal solid and paper waste is shown in Table 1-2. The total amount of sugars released during acid hydrolysis of municipal solid waste and yard waste were very high 25.4 g/L and 18.2 g/L respectively which makes these fractions very attractive for fermentation processes. The low sugar content in the water soluble stream of paper waste (3.5 g/L) is a result of some of these sugars being removed in the pulping process and the difficulty to fractionate the main polymers in the lowest grade paper waste due to the physio-chemical modification of pulp for paper production (ink, coating, drying etc.) .

Recovery of sugars after pretreatment

The production cost for biomass-to-ethanol must be competitive with that of fossil fuels such as oil and gasoline. As previously shown, the highest costs in the bioconversion of biomass to ethanol are those of raw material and enzymes (Boussaid, et al., 1999; Galbe and Zacchi, 2002; Gregg, et al., 1998). Consequently, it is important to ensure a high degree of utilization of all carbohydrate components in the feedstock (Wu, et al., 1999). In addition, overall yield has been found to be the most important parameter when evaluating the production cost of bioethanol (von Sivers and Zacchi, 1995). During pretreatment of yard, municipal solid and paper waste we recovered majority of glucose and xylose 99-100% (Table 1-3). Not surprisingly, the greatest losses were of arabinose, followed by galactose, which concurs with previous findings (Grohmann and Bothast, 1997). It has been suggested that the high susceptibility of arabinosyl linkages to hydrolysis may be in part responsible for fragmentation and solubilisation of cell wall components in the lignocellulosic biomass, and thus formation of degradation products at elevated temperatures (BeMilller, 1967). However, arabionse and galactose were minor sugars in original lignocellulosic rich urban biomass, thus the incomplete recovery does not greatly influence overall biomass to ethanol yield. In addition, based on the almost complete glucose and xylose recoveries it can be concluded that the conditions for pretreatment of yard, municipal solid and paper waste were not too severe.

Enzymatic hydrolysis

Next we assessed whether the resulting water insoluble, cellulosic fractions of acid pretreated municipal solid waste and paper waste and steam pretreated yard waste were readily hydrolysable. The recovered, pretreated and water-washed solids (2% consistency) were subjected to enzymatic hydrolysis for 72 hours with cellulases supplemented with an excess of b-glucosidase in the hydrolysis buffer (50mM, pH 5) (Figure 1-1 and Table 1-4).

The cellulose to glucose and xylan to xylose conversions of municipal solid waste and paper waste were very high of 89 and 87%, respectively making this material excellent source for bioethanol production. We have shown that dilute acid pretreatment is an excellent fractionation method for paper waste compared to previously tested methods in our lab (deinking). Therefore, we could obtain very high cellulose to glucose conversion of 86% and moderate xylan to xylose conversion of 62% proving that the lowest grade paper waste could be utilized for bioethanol production.

The sequential steam explosion pretreatment of SO_2 soaked yard waste followed by enzymatic hydrolysis in the current study showed a 41% conversion of all original cellulose to monomeric glucose and 33% of xylan to xylose. The low conversions of sugars during enzymatic hydrolysis were not surprising since the original yard waste contained ~40% of lignin and the heterogeneous material contained softwood branches with bark and needles. Previous work has shown that SO_2-catalysed steam explosion can successfully pretreat softwood (Boussaid, et al., 2000; Clark, et al., 1989; Clark and Mackie, 1987); and hardwood residues (Mackie, et al., 1985; Schwald, 1988) during the bioconversion process. However, due to their chemical characteristics (high guaiacyl lignin content), softwood residues have proven to be more recalcitrant toward enzymatic hydrolysis when using the optimum pretreatment conditions, allowing for maximum hemicellulose and cellulose recovery in a fermentable form (Boussaid, et al., 2000; Robinson, 2003; Yang, et al., 2002). Therefore, an additional delignification process is required in the bioconversion of softwood to ethanol prior to enzymatic hydrolysis, and consequently increasing the overall cost of the process.

It has been suggested that during hydrolysis of steam-treated substrates, lignin acts as a physical barrier that hinders contact between the substrate and enzymes. The need for lignin removal during the bioconversion of softwood to ethanol makes this process economically challenging, by increasing process complexity, decreasing overall hemicellulose recovery (as it requires a water-wash step after delignification) and increasing the problems associated with dilute sugar stream. It has been reported that the recalcitrant lignin remaining after Douglas-fir wood had been steam exploded at medium severity was significantly reduced by post-treatment with 1% hydrogen peroxide at pH 11 and 80°C for 45 minutes. Eighty-two percent cellulose conversion at 10 FPU g^{-1} cellulose was achieved after 48 hours of reaction (Yang, et al., 2002) compared to 40% cellulose to glucose conversion for not delignified biomass. Additional delignification of pretreated yard waste might be required to improve the hydrolyzablity of solids.

Fermentation

The water-soluble fractions obtained after pretreatment of municipal solid, yard and paper waste and after hydrolysis of municipal solid, yard and paper waste were assessed for its feasibility as a medium for effective fermentation to ethanol (Figure 1-2 and Table 1-5). As expected, all the hexose sugars glucose, galactose and mannose, liberated in the yard waste hydrolyzate were effectively used by PTD3 during the fermentation process. The yeast grew well in the presence of a low concentration of mixed inhibitors (data not shown) and showed similarity in growth and fermentative pattern with controls Figure 1-2. Ethanol yields from hexoses (glucose, mannose and galactose) for all the sugar streams tested were close to 100% of theoretical ethanol (Table 1-5). Low concentration of inhibitors produced during the pretreatment, and very high conversion rates of sugars to ethanol suggest that conditions of 210°C, 10 minutes and 3% SO_2 and 60°C, 2.5% H_2SO_4 treatment for municipal solid and paper waste were optimal pretreatment condition for fermentation process.

Conclusion

- The paper, yard and municipal solid waste are sugar rich lignocellulosic feedstocks.
- Dilute acid hydrolysis is an effective pretreatment method for paper and municipal solid waste. Steam pretreatment (210°C, 10 min and 3% SO_2) is a good pretreatment method for fractionation of yard waste into hemicellulose, cellulose and lignin rich fractions.
- The water insoluble fractions of municipal solid and paper waste are easily hydrolysable by enzymes. Almost theoretical cellulose to glucose conversion was achieved.
- The water insoluble fraction of yard waste is difficult to hydrolyze by enzymes (41% cellulose to glucose conversion). However, the low cellulose to glucose conversion yields were expected since the biomass was composed of mixture of branches, wood chips, bark, and needles.
- The results obtained during this study also demonstrate that PTD*3* was able to very efficiently convert yard waste hydrolysate to ethanol with a yield 100% of theoretical during the fermentation process. Pretreated and hydrolyzed sugars of municipal solid, paper and yard waste are readily fermentable by yeast. High ethanol yields were obtained (100% of theoretical). Overall ethanol yields of 110 gallons/ton, 90 gallons/ton, and 40 gallons/ton are estimated for municipal solid waste, paper waste, and yard waste respectively.

Tables and Figures

Table 1-1. Chemical composition of lignocellulosic feedstock (paper waste, municipal solid waste and yard waste) (carbohydrates and lignin) (% weight).

	Paper waste (%)	Municipal solid waste (%)	Yard waste (%)
Arabinose	0.9	0.8	3.8
Galactose	0.3	0.5	5.2
Glucose	**65.1**	**72.1**	**39.6**
Xylose	**7.9**	**7.1**	**6.7**
Mannose	4.5	7.0	7.1
Total Lignin	21.4	7.5	39.1

Table 1-2. Concentration of total, monomeric and oligomeric sugars in the liquid streams after dilute acid pretreatment of: municipal solid waste and paper waste and steam explosion of yard waste.

	Total sugar conc (g/l)					Mono sugar conc (g/l)					Oligomer sugar conc (g/l)				
	Ara	Gal	Glu	Xyl	Man	Ara	Gal	Glu	Xyl	Man	Ara	Gal	Glu	Xyl	Man
MSW	0.76	0.91	22.27	1.08	0.44	0.74	0.17	5.92	0.60	0.07	0.02	0.74	16.35	0.48	0.37
Paper waste	0.30	0.22	1.48	1.12	0.38	0.26	0.10	0.50	0.95	0.12	0.04	0.12	0.99	0.17	0.27
Yard waste	1.76	3.48	4.41	3.23	5.37	1.37	2.38	2.76	2.36	2.68	0.39	1.10	1.65	0.87	2.69

Table 1-3. Recovery of sugars after pretreatment for paper waste, municipal solid waste and yard waste expressed as g per 100g of sugars in the biomass.

	Paper waste (%)	Municipal solid waste (%)	Yard waste (%)
Arabinose	83.6	61.1	73.4
Galactose	72.0	62.3	57.7
Glucose	**100.0**	**100.0**	**99.6**
Xylose	**99.3**	**98.1**	**97.9**
Mannose	81.7	83.2	66.8

Table 1-4. Hydrolysability of pretreated, water-washed municipal solid waste, paper waste and yard waste solids with 2% w/v at 20 FPU g cellulose^{-1} loadings and IU:FPU ratio 2:1.

	Cellulose to glucose conversion (%)	Xylan to xylose conversion (%)
Municipal solid waste	89	87
Paper waste	86	62
Yard waste	41	33

Figure 1-1. Hydrolysability of pretreated paper, municipal solid and yard waste over the course of 72 hours of enzymatic hydrolysis.

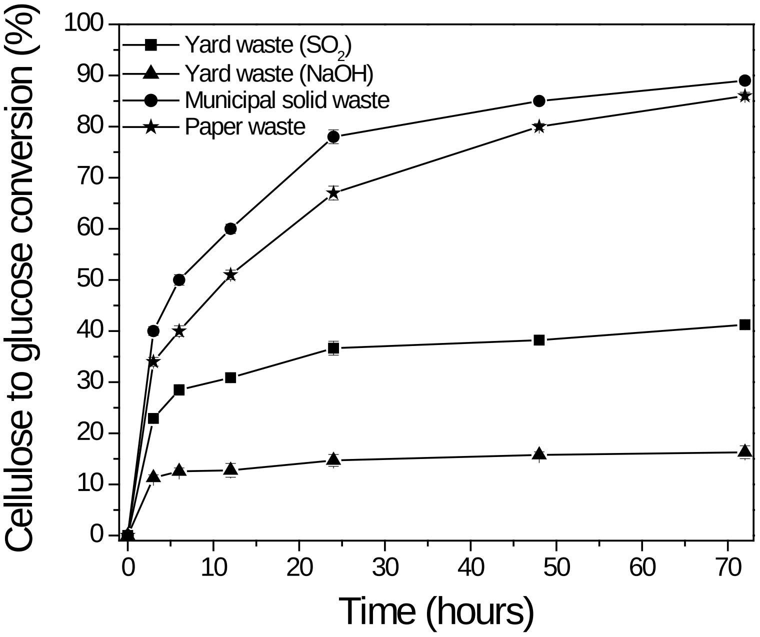

Figure 1-2. Hexose consumption, ethanol production and yeast growth during fermentation of steam pretreated yard waste by yeast with MS and yeast extract.

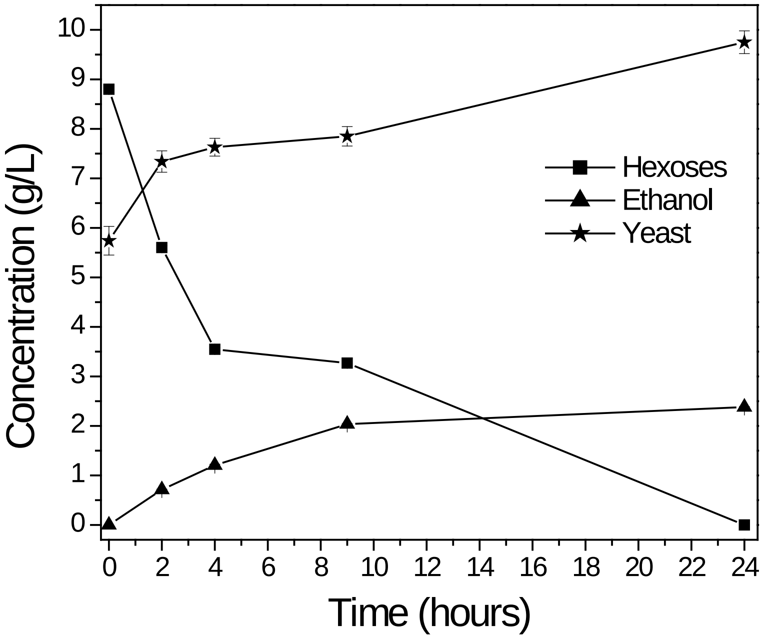

Table 1-5. Relative ethanol yield for the liquid fractions obtained after pretreatment (water soluble fraction) and enzymatic hydrolysis (water insoluble fraction) $Y_{EtOH} (Y^{ref}_{EtOH})^{-1}$ (%) for paper waste, municipal solid waste and yard waste.

	Hexosoe to ethanol conversion after pretreatment (%)	**Hexosoe to ethanol conversion after hydrolysis (%)**
Municipal solid waste	100	100
Paper waste	99	100
Yard waste	99	100

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Converting Washington Lignocellulosic Rich Urban Waste to Ethanol: Part 2, Process modeling and life cycle assessment

Introduction

ISO Standards

LCA is a protocol standardized by the International Standards Organization (ISO) [(ISO, 2006), (Organization, 2006)] to quantify the life cycle impacts of energy and materials use and waste by an industrial system. The life cycle extends from materials and energy acquisition and processing, through system manufacturing/ construction, use/maintenance, and the ultimate retirement of materials and equipment (reuse, remanufacturing, recycling, disposal). LCA can be used to quantify not only environmental impacts (e.g., life cycle energy consumption, contribution to climate change, acidification, toxic impacts, land use, etc.), but also the economic and social impacts of emerging technology/product development, selection and implementation (during R&D), design and other decisions [(Fava & Smith, 1998), (Cooper J. , 2003)]. When used during technology research and development, LCA can be a powerful tool to ensure technology development for systems-level improvement (Klöpffer & Hutzinger, 1997).

As defined by the ISO, LCA is a 4 phase process. The first phase of the process is the *goal and scope definition*, which outlines the objectives of the study, the intended audience, the systems and subsystems boundaries, a data collection and quality plan, and critical review. The second phase is the *life cycle inventory* (LCI) analysis, where a system model is built according to the goal and scope definition. The inventory analysis includes: the construction of a flow model, data collection, and calculations of resource use and pollutant emissions. The next phase is the *life cycle impact assessment* (LCIA), which is used to characterize the impacts of the environmental loads quantified in the inventory analysis. Finally, the *interpretation* phase assesses the overall context of the LCA and is used to provide recommendations.

Goal & Scope

The goal of the LCA is to identify potential environmental consequences associated with the conversion of three lignocellulosic rich solid waste streams to ethanol for the State of Washington. Additionally, it seeks to identify major contributing processes that may significantly influence results. The three waste streams considered are Municipal Solid Waste (MSW), Mixed Waste Paper (MWP), and urban Yard Waste (YW). The *intended audience* for this study is State officials at the Washington Department of Ecology, and associates of the Washington Beyond Waste Initiative. It is our hope that the results from this study will provide decision makers and scientist additional information towards developing future policy and implementation strategies for environmentally preferable waste management options.

The LCIA includes global warming potential (greenhouse gases), acidification, photochemical smog formation, total particulate matter emissions, and total energy consumption. The environmental flows tracked within the LCI include greenhouse gases (CO2, CH4, N2O), criteria pollutants (CO, NOx, PM10, PM2.5, and SOx), non-methane volatile organic carbons (NMVOC), and total energy consumption (fossil and renewable). All LCI data used were gathered from public sources allowing for complete transparency in the results. The computational structure for LCI calculations follows the framework developed by Heijungs and Suh (Heijungs & Suh, 2002). Results from the LCI were used to calculate the LCIA parameters as described in Table 2- 1. Global warming potential characterization factors are estimates from IPCC (Intergovernmental Panel on Climate Change, 2001), while acidification, and eutrophication characterization factors are from U.S. EPA TRACI (Bare, Norris, Pennington, & McKone, 2003). Total energy consumption and total particulate matter (PM10 and PM2.5) are not impact categories, rather summations of inventory flows.

Decision Category	Impacts Category	Impact Category Description
Infrastructure and human use impacts	Total energy consumption	Sum of total energy consumption for the life cycle (BTU)
Air emission impacts	Contribution to climate change	Total carbon dioxide equivalents from life cycle air emissions of CO2, N2O, & CH4 (as g CO2 equiv.)
	Contribution to acidification	Total hydrogen ion equivalents from life cycle air emissions of SOx & NOx (as g H+ equiv)
	Contribution to photochemical smog	Total nitrogen oxides equivalents from life cycle air emissions of CH4, NOx, CO, & NMVOCs (as g NOx equiv)
	PM emissions	Sum of particulate matter emissions (as g PM)

Table 2- 1: Decision and impact categories for LCA.

The LCIA results are normalized by total impacts for the State of Washington per capita. Normalized impact categories are reported as person equivalents. Total energy consumption for the State of Washington was reported by the EIA based on 2006 data[5]. Climate change data are given by the Washington State Greenhouse Gas Inventory released in 2007, based off data reported for 2005 (WA-DOE, 2007). Values for acidification, photochemical smog, and particulate matter are from air emissions data reported by the Washington Department of Ecology from a three year study of 2005 data[6], and then applying TRACI characterization factors for acidification and photochemical smog as described in Table 2- 1 above. The normalization values for the LCIA are all assumed to be valid estimates for 2007 and are given below in Table 2-2.

Impact Category	Value
Energy Consumption	328 MMBTU/capita
Global Warming	15.2 MT-CO2e/capita
Acidification	2.3 MT-H+ equiv/capita
Photochemical Smog	0.2 MT-NOx-e/capita
Particulate Matter	0.0 MT-PM/capita

Table 2- 2: Normalization factors for Washington State.

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[5] See US EIA, 2006 State Data, accessed at: http://tonto.eia.doe.gov/state/state_energy_profiles.cfm?sid=WA

[6] See WA State air emissions inventory summary, accessed at: http://www.ecy.wa.gov/programs/air/EmissionInventory/AirEmissionInventory.htm

Functional Unit

The functional unit as defined by ISO14040 (ISO, 2006), is a measure of the performance of the functional outputs of a product system. For our analysis we compare different strategies for managing three solid waste streams and the consequences of implementing those strategies. The functional unit for this study is the combined total of waste generated for the three waste streams of interest; ***5,763,904 metric tons of lignocellulosic rich solid waste generated within Washington State in 2007, which is 84% MSW, 6% MWP, and 10% YW.*** This follows from previous work performed that recommends using a functional unit that reflects the total quantity of waste generated within a given year for a region to better understand the difference between waste management strategies (Ekvall, Assefa, Bjorklund, Eriksson, & Finnveden, 2007).

System Boundaries

The system boundaries for the LCA includes unit processes for waste collection, intermediate waste processing, recycling, composting, landfill, ethanol production, chemicals/materials production, and energy/fuel production. Selected unit processes are assumed to be an approximated representation of solid waste management practices within the State of Washington. System level unit processes were broken up into modules and LCIs were calculated for each module. A diagram of the system level modules is shown in Figure 2- 1 below.

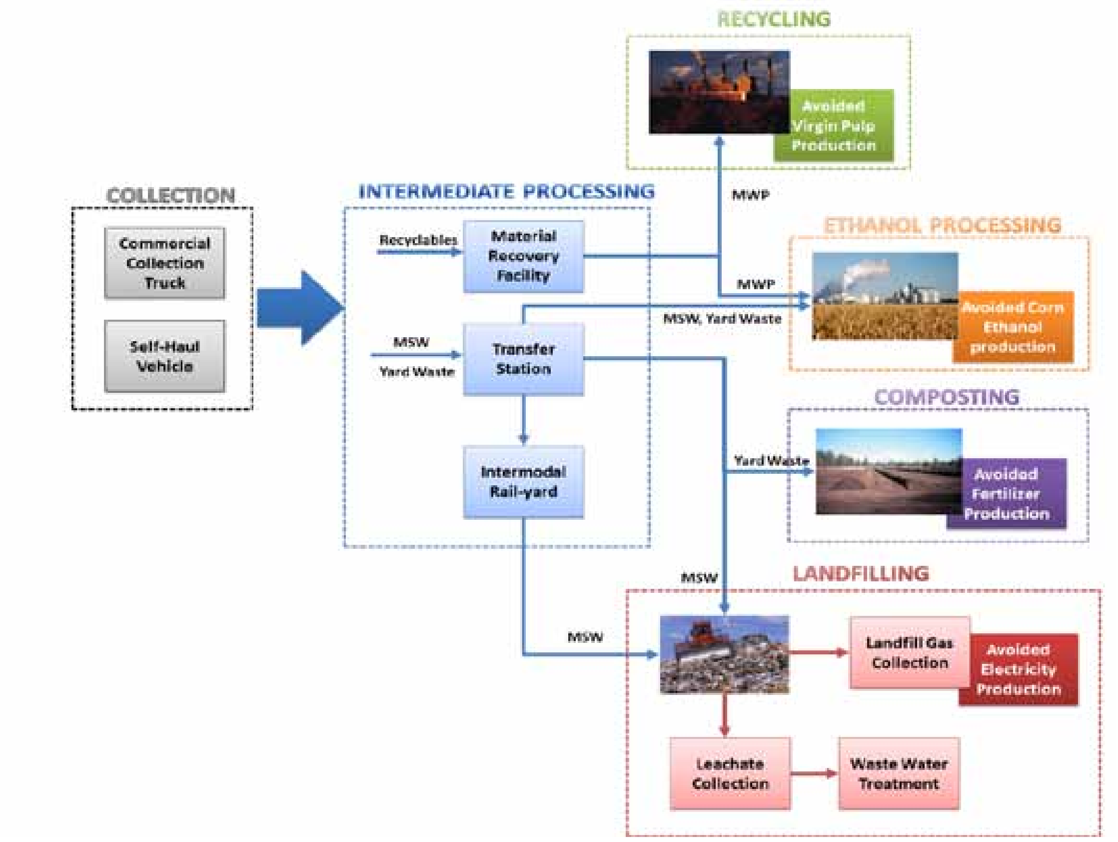

Figure 2- 1: Conceptual system level flow diagram

The LCA does not include the production and use of materials before they are considered “waste.” This is often the case in waste management LCAs to begin with the collection of the material, often regarded as the “zero-burden” assumption (Ekvall, Assefa, Bjorklund, Eriksson, & Finnveden, 2007). The three solid waste streams investigated are assumed to be collected separately. Recyclables are collected commingled and sent to a Material Recovery Facility (MRF), where product MWP is separated from the rest of the recyclables, bailed, and transported to recyclers. It is assumed that MWP is converted into a specific pulp grade for paper production, and replaces virgin pulp of the same grade. Yard waste is collected and sent to the transfer station, where it is compacted and transported to a commercial compost facility. The yard waste is then converted into commercial grade compost and assumed to replace commercial fertilizer production based on average nutrient equivalency. Solid waste in the form of MSW is collected and sent to a transfer station, where it is compacted and transported either by heavy-duty vehicles or train, to a landfill site. As the MSW decomposes, landfill gas is collected and combusted in an IC-engine to produce electricity. The electricity produced by landfill gas is assumed to offset electricity produced by the utility grid. A base case system was assumed and several scenario alternatives were projected to compare the gross LCA results. The base case and five scenarios are shown in Table 2- 3 below. The first scenario looks at a base case, where all MSW is sent to a landfill, all MWP is sent to a recycler, and all collected yard waste is sent to a compost facility. Scenario 2, we consider sending all lignocellulosic rich waste to a biorefinery for ethanol production, avoiding corn ethanol production. While in Scenario 3, we consider sending all MSW to a biorefinery for ethanol production, eliminating the need for a landfill. Similarly, for scenarios 4 and 5, recycling and composting are replaced with ethanol production. Finally in scenario 6, we consider the unlikely situation of sending all waste to a landfill.

Scenario	Functional Unit	Landfill	Recycle	Compost	Ethanol
Base Case	5,763,904 MT	84%	6%	11%	0%
Scenario 1; All waste to ethanol	5,763,904 MT	0%	0%	0%	100%
Scenario 2; All MSW to ethanol	5,763,904 MT	0%	6%	11%	84%
Scenario 3; All MWP to ethanol	5,763,904 MT	84%	0%	11%	6%
Scenario 4; All YW to ethanol	5,763,904 MT	84%	6%	0%	11%
Scenario 5; All waste to landfill	5,763,904 MT	100%	0%	0%	0%

Table 2- 3: LCA scenarios

Life Cycle Inventory

The following section gives a brief explanation of how the LCI data modules were formulated. For more information the authors refer to the associated document. Calculated LCI data for major unit process modules is given in appendix A.

Collection Module

Waste generation and collection is dependent upon a number of regional variables. Solid waste can either be collected commercially or self-hauled to an intermediate processing facility. A number of transfer stations or drop-boxes, are setup throughout the State for generators to deposit their waste, whereas in some regions self-haul is the only option for recyclables and yard waste. The LCI module includes both commercial collection from a solid waste truck and self-hauling by a passenger vehicle.

Commercial Collection

Commercial waste collection varies from region to region and even from route to route. This is a result of customer behavior, waste demand, policy, and availability of final processing facilities. The collection model developed includes several important parameters, such as distance between collection stops, amount of waste generated at each stop, set-out rate, loading time per stop, travel distance to intermediate facility, unloading time, and physical characteristics of collection vehicles.

The diversity in collection methods throughout the State makes system level modeling extremely complex. Figure 2- 2 shows the amount of MSW landfilled in 2005 for each county. The majority of the waste generated in Washington is from the western portion of the State, where majority of the population is located in dense urban areas. In order to simplify the model, average regional classifications were developed for the State. The first step was to separate each county into one of three regional classifications based on waste generation. The counties having an annual MSW generation rate of 100,000 MT or more, 10,000 to 100,000 MT, and less than 10,000 MT, were classified as a high, medium, or low generation area, respectively. Annual MSW, MWP, and yard waste generated for each county were calculated based on annual data for MSW sent to landfills[7] and biomass inventory data for the State (Frear, Zhao, Fu, Richardson, & Fuchs, 2005). Assuming weekly collection, the average amount of waste collected per single-family household per week is calculated. A linear probability model developed by Wilson and Baetz (Wilson & Baetz, 2001), is used to determine the total fleet route size when it is limited by collection volume constraints. The model calculates the size of the route, the number of vehicles required per fleet, the total time and distance traveled by the entire fleet, and the emissions for the entire fleet per metric ton of waste collected.

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[7] Data accessed at: http://www.ecy.wa.gov/programs/swfa/solidwastedata/

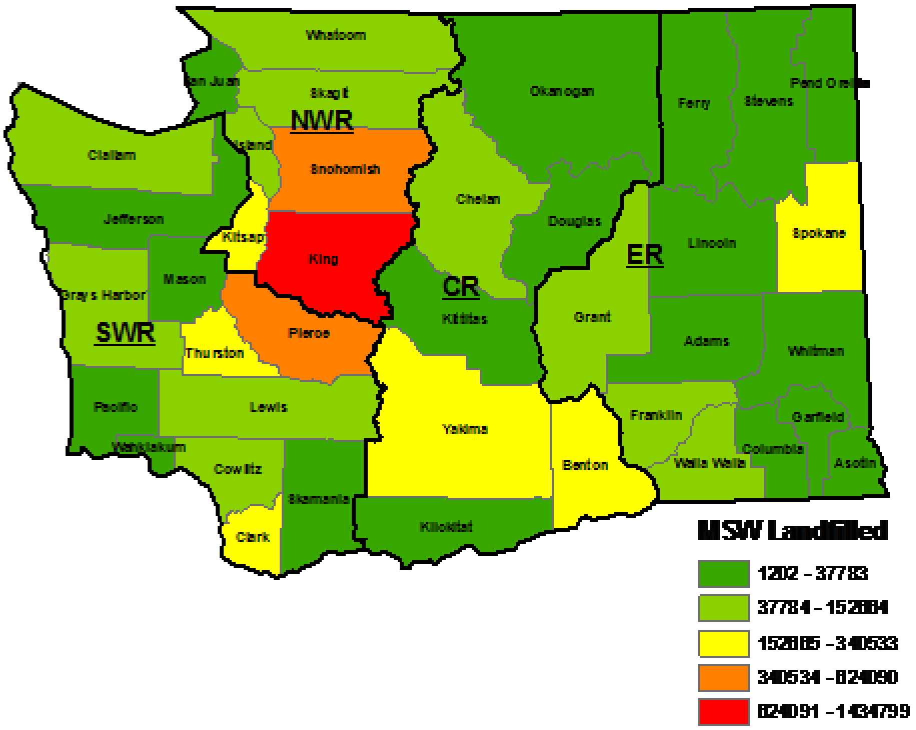

Figure 2- 2: MSW sent to landfills in 2006 for Washington Counties[8]

Calculations and assumptions for modeling total time and distance traveled by the collection fleet for each region is shown in Table 2- 4. The emissions are based on the amount of time the collection vehicle spends driving and time spent idling and emission factors developed by Agar et al are presented in Table 2- 5 (Agar, Baetz, & Wilson, 2007).

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[8] Data accessed at: http://www.ecy.wa.gov/programs/swfa/solidwastedata/

Calculations	**Unit**	**MSW High**	**Recycle High**	**YW High**	**MSW Medium**	**Recycle Medium**	**YW Medium**	**MSW Low**	**Recycle Low**	**YW Low**
Avg. Waste Collected annually	MT/year	400,000	90,000	120,000	45,000	10,000	15,000	3,000	750	1,000
Avg. Housing	households	200,000	200,000	200,000	25,000	25,000	25,000	4,000	4,000	4,000
Vehicle Capacity, (k)	m3	32.7	19.6	6.54	32.7	19.6	6.54	32.7	19.6	6.54
Compaction ratio, (p)		3	3	3	3	3	3	3	3	3
Set out rate, (φ)		0.9	0.4	0.3	0.9	0.4	0.2	0.9	0.4	0.1
Stops made, (Xf)	stops/route	757	2,270	582	454	1,816	454	908	3,632	908
No. of residences past, (Nf)	house/route	841	5,674	1,940	504	4,539	2,270	1,009	9,079	9,079
Distance btwn houses, (S)	m	5	5	5	15	15	15	30	30	30
Maximum Velocity, (V)	m/s	4	4	4	4	4	4	4	4	4
Acceleration, (a)	m/s2	1	1	1	1	1	1	1	1	1
Stop spacing Condition		4	4	4	2	2	2	1	1	1
Mean stop-to-stop travel time	sec	5	7	7	8	9	8	12	23	79
Avg. Loading time per stop, lt	sec.	20	20	20	20	20	20	20	20	20
Total Route time	hrs/route	5.2	16.7	4.4	3.5	14.4	3.6	8.2	43.1	25.0
Vehicles required per route	Veh./route	1	3	1	1	3	1	2	8	5
Number of routes per week	Routes/week	297	44	129	59	7	13	6	1	1
Total Route time for fleet	hrs/week	1,541	2,212	572	211	286	47	97	228	83
Total Distance traveled for fleet	km/week	22,190	31,849	8,235	3,033	4,125	680	1,397	3,283	1,188
Environmental Flows										
Diesel Fuel Consumption	BTU	54,043	387,842	77,142	36,935	334,913	41,427	170,096	2,665,425	723,347
CO2	g	4,065	29,175	5,803	2,778	25,193	3,116	12,795	200,502	54,413
CH4	g	0.19	1.39	0.28	0.13	1.20	0.15	0.61	9.55	2.59
N20	g	0.12	0.85	0.17	0.08	0.74	0.09	0.37	5.88	1.59
NMVOC	g	0	0	0	0	0	0	0	0	0
CO	g	202	1,451	289	138	1,253	155	637	9,975	2,707
NOX	g	230	1,650	328	157	1,424	176	723	11,336	3,076
PM10	g	4.2	30.3	6.0	2.9	26.1	3.2	13.3	208.1	56.5
PM2.5	g	0	0	0	0	0	0	0	0	0
SOx	g	0	0	0	0	0	0	0	0	0

Table 2- 4: Collection LCI inputs (Environmental flows are all based on 1 MT of waste hauled)

Activity	Unit	Idling	Driving
Percent of time spent per activity		52%	48%
Proportion of fuel consumed		16%	84%
Avg. Rate of Fuel Consumption	L/hr & km/L	3.1	0.9
Emission Factors			
CO2	g/L	2,730	2,730
CH4	g/L	0.13	0.13
N20	g/L	0.08	0.08
CO	g/L & g/km	94.6	26.6
NOX	g/L & g/km	144	6.68
PM10	g/L & g/km	2.57	0.17

Table 2- 5: Commercial waste vehicle collection emission factors.

Self-haul

Self-haul is based on the assumption that passenger or light-duty vehicles are used to transport waste to an intermediate processing facility. It is assumed that the maximum waste that can be hauled per trip is roughly 400 lbs [king county]. The average distance a self-haul vehicle travels is assumed to vary by the regional population density. The distance generators are willing to travel, for high, medium, and low generation regions, is assumed to be 5, 7.5, and 10 miles, respectively. The average fuel efficiency is 24.8 miles per gallon based on the GREET model (USDOE, 2006). Emissions for passenger vehicles are based upon a GM study released in 2005 (Brinkman, Wang, Weber, & Darlington, 2005). Table 2- 6 summarizes the major LCI inputs for self-haul.

	Units	High	Medium	Low
Vehicle Type		Passenger	Passenger	Passenger
Maximum Waste hauled per trip	kg/trip	175.5	175.5	175.5
Distance traveled to facility	km/MT	45.8	68.7	91.7
Average Fuel efficiency	mpg	24.8	24.8	24.8
Fuel Type		Conventional RFG	Conventional RFG	Conventional RFG
RFG Fuel Lower Heating Value	BTU/gal	115,500	115,500	115,500
Environmental Flows				
CO2	kg/km	19.56	19.56	19.56
CH4	kg/km	0.108	0.108	0.108
N2O	kg/km	0.00033	0.00033	0.00033
NMVOC	kg/km	0.0235	0.0235	0.0235
CO	kg/km	0.0117	0.0117	0.0117
NOx	kg/km	0.0441	0.0441	0.0441
PM10	kg/km	0.00934	0.00934	0.00934
PM2.5	kg/km	0	0	0
SOx	kg/km	0.0270	0.0270	0.0270

Table 2- 6: Summary of LCI inputs for Self-haul

Intermediate Waste Processing

Intermediate waste processing includes the handling of waste received at transfer stations, material recovery facilities (MRF), and intermodal rail-yard. An LCI model was created for these three facilities operations, including energy, fuel consumption and emissions from equipment. The module does not include facility construction or building operations, such as, lighting or heating/cooling loads.

Transfer Stations

Three designs were used for the transfer station, depending on the regional classification, as with the collection model. For larger areas, additional processing equipment is required for handling approximately 350 metric tons of waste per hour. For our model we assume that transfer stations are only used for MSW and yard waste. The general design for transfer stations is based on EPA recommendations (USEPA, 2002). The design for large transfer stations includes a tipping floor, where vehicles dump incoming waste, front-end loaders, to move waste from the tipping floor into compactors, and finally compacted waste is transferred to long-haul vehicles were it is sent to a final processing facility. The flow diagram for a large transfer station is shown in Figure 2- 3. Medium and small transfer stations are assumed to be designed so that waste collection vehicles can off-load incoming waste directly into compactors, so no front-end loader is required. The LCI module for transfer stations includes the equipment operations on-site and the production of fuel and energy. Operational emissions for diesel equipment were based on calculations from EPA emission factors for non-road CI spark ignition engines and the equations below (USEPA, Exhaust and crankcase emission factors for nonroad engine modeling - compression ignition, 2004). Fuel and electricity pre-combustion emissions are from GREET 1.7.

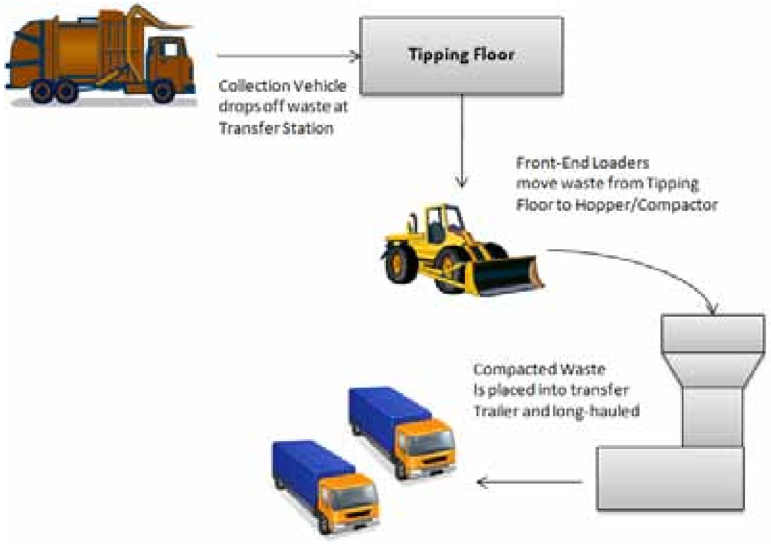

Figure 2- 3: Process flow diagram for large capacity transfer station.

The equation used to calculate fuel consumption in BTU per metric ton is,

$$Fuel\ Consumption = EF \times 453.6 \times \frac{LHV}{\rho} \times \frac{HP}{CF}$$

where: EF = the emission factor in (lb/hp-hr)
453.6 = the conversion from lb to grams
LHV = lower heating value of fuel (BTU/gal)
ρ = the density of fuel (grams/gal)
HP = horsepower of the engine
CF = capacity factor for equipment (MT/hr)

Similar, for the calculation for tailpipe emissions in grams per metric ton is,

$$Emission(CO, CO_2, SO_2, PM10, PM2.5) = EF \times \frac{HP}{CF}$$

where: EF = the emission factor in (g/hp-hr)
HP = horsepower of the engine
CF = capacity factor for equipment (MT/hr)

Sulfur dioxide emissions are used for SOx emissions.

	unit	Front-End Loader	Compactor (Small)	Compactor (Medium)	Compactor (Large)
Number of Units		7	4	2	1
Capacity	MT/hr	50	10	50	100
Engine/Motor Size	HP	250	82	140	213
Fuel Type		Diesel	Electricity	Electricity	Electricity
Environmental Flows					
Total Energy	BTU	36,106	23,188	15,836	24,093
CO2	g	2,653			
CO	g	0.40			
NOx	g	12.5			
PM10	g	0.36			
PM2.5	g	0.35			
SOx	g	0.003			

Table 2- 7: LCI inputs for transfer station equipment.

Intermodal rail-yard

A significant amount of waste is exported from Washington into neighboring States. This waste is commonly transported long distances by train. In order to transfer waste on and off a train, a staging area is required. The intermodal rail-yard serves as a staging point connecting the transfer station to the train. The LCI module is based off of the Seattle Rail-yard system, as described in an online article (Harder, 1994). The rail-yard LCI includes trucks dumping waste from transfer station to loading area, lift trucks than move waste containers on and off the train. At the landfill site yard-goats transport the containers from the receiving area to the landfill loading area. Two tippers are used to dump the waste onto the landfill site. Emissions include equipment use, fuel and energy production, and transportation emissions. Equipment inventory data is shown in Table 2- 8, while the process is shown in Figure 2- 4.

	unit	Yard Goat	Lift Truck	Tippers
Number of Units		2	2	2
Capacity	MT/hr	257	257	257
Engine/Motor Size	HP	220	250	210
Fuel Type		Diesel	Diesel	Diesel
Environmental Flows				
Fuel Consumption	BTU	6,182	7,025	5,901
CO2	g	454	516	434
CO	g	0.068	0.077	0.065
NOx	g	2.15	2.44	2.05
PM10	g	0.062	0.071	0.059
PM2.5	g	0.060	0.069	0.058
SOx	g	0.00045	0.00052	0.00043

Table 2- 8: LCI input data for intermodal rail-yard equipment.

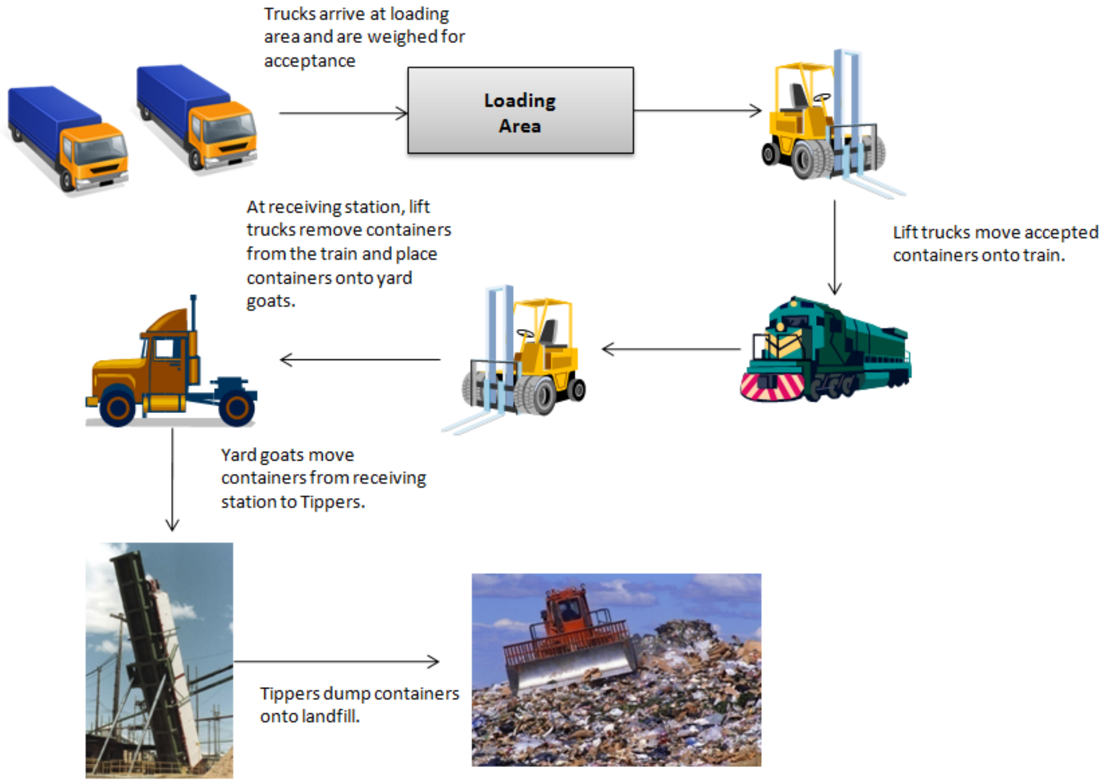

Figure 2- 4: Process flow diagram for intermodal rail-yard.

Material Recovery Facility

The model for a MRF was developed based upon the work of Tchobanoglous et al (Tchobanoglous, Theisen, & Vigil, 1993). The model includes typical unit processes of a MRF for the separation of recycled paper, plastic, glass, and metals. Figure 2- 5 shows a process diagram for the MRF, with processes shaded in gray specific to mixed waste paper operations. Recyclables are received in the tipping area, where front-end loaders move material onto the first picking conveyer. Bags are assumed to be opened automatically by a bag opener (modeled as a trommel screen). Large items and old corrugated cardboard (OCC) are first removed manually from the stream. The remaining waste passes through a trommel screen, where it is assumed that paper, plastics and metals, and glass are separated. The paper then goes through another round of manual picking to separate the paper by grade (Paperboard, High grade, newsprint, and mixed waste). The picking rate is 2.5 tons per person per hour and is assumed to have 80 percent recovery efficiency. Each product is then baled and sold off to final processors. Data from a King County2005 survey of MRFs (Cascadia Consulting Group, inc., 2006) was used to estimate the characteristics of recovered mixed waste paper. The survey estimated that 29 percent of the mass coming out of an MRF is attributed to mixed waste paper product. LCI data for the MRF was allocated for MWP based on the product output.

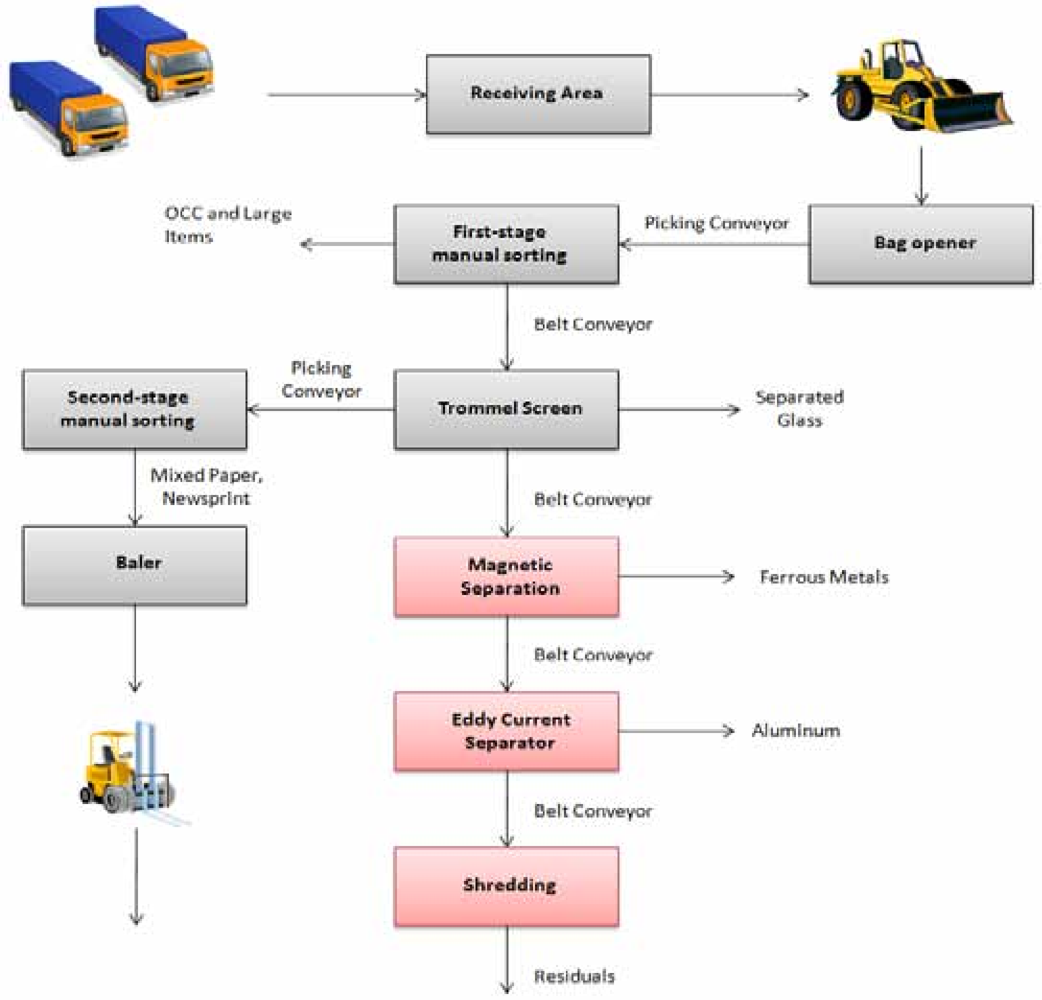

Figure 2- 5: Process flow diagram for Material Recovery Facility (MRF).

	unit	Front-End Loader	Forklift	Bag Breaker	Conveyor Belt	Picking Belt	Trommel Screen	Baler
Number of Units		4	2	1	1	2	1	1
Capacity	MT/hr	36.302121	108.7785	36.302121	36.302121	36.302121	37.4	108.7785
Engine/Motor Size	HP	95	50	0.03	0.03	0.03	30	55
Fuel Type		Diesel	Diesel	Electricity	Electricity	Electricity	Electricity	Electricity
Environmental Flows								
Fuel Consumption	BTU	21,009	3,690	2.34	2.34	2.34	2,268	1,429
CO2	g	1,544	271					
CO	g	0.66	0.75					
NOx	g	7.88	2.18					
PM10	g	0.22	0.091					
PM2.5	g	0.21	0.089					
SOx	g	0.00154	0.00027					

Table 2- 9: LCI input for select MRF equipment and operations for MWP processing.

Landfill

This section describes the module for waste sent to a landfill. The unit processes include: landfill daily operations, landfill gas generation/collection, leachate generation, and waste water treatment.

Daily Operations at Landfill

The daily operations of the landfill consist of receiving waste from long-haul vehicles, placement of waste in landfill cell, and applying a daily cover to the compacted waste. The model assumes a landfill capacity of 1800 metric tons of MSW per day. In comparison, the three largest landfills, Cedar Hills, Columbia Ridge, and Roosevelt, receive an estimated 2800, 2300, and 3300 tons of waste per day, respectively[9]. This corresponds to approximately 400 square meters per day or a tenth of an acre per day. The waste is received at the cell location, spread out, compacted, and covered in soil and a High Density Polyethylene (HDPE) liner. It was determined that each cell requires 328 grams of HDPE per metric ton of waste. Equipment operations include: scraper, compactor, motor grader, track loader, track tractor, articulated truck, rubber tire loader, and a water truck. The emissions from vehicle operations were based on EPA Tier-4 emissions data for crank-shaft engines used in the EPA NONROAD (data presented in **Appendix C**) and equations presented earlier. Table 2- 10 gives the LCI inputs and emissions associated with landfill equipment. LCI data for HDPE and non-road diesel consumption is from GREET 1.7.

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[9] Data accessed at: http://www.ecy.wa.gov/programs/swfa/solidwastedata/

	unit	Scraper	Compactor	Motor grader	Track Loader	Track Tractor	Articulated Truck	Rubber Tire Loader	Water Truck
Number of Units		1	1	1	1	1	1	1	1
Capacity	MT/hr	200	200	200	200	200	200	200	200
Engine/Motor Size	HP	462	354	297	239	310	317	180	180
Fuel Type		Diesel	Diesel	Diesel	Diesel	Diesel	Diesel	Diesel	Diesel
Environmental Flows									
Fuel Consumption:	BTU	16,681	12,782	10,724	8,629	11,193	11,446	6,499	6,499
CO2	g	1,226	939	788	634	822	841	478	478
CO	g	0.206	0.158	0.118	0.095	0.138	0.141	0.072	0.072
NOx	g	5.79	4.44	3.72	3.00	3.89	3.98	2.26	2.26
PM10	g	0.168	0.129	0.108	0.087	0.113	0.115	0.066	0.066
PM2.5	g	0.163	0.163	0.105	0.084	0.109	0.112	0.064	0.064
SOx	g	0.00122	0.00122	0.00079	0.00063	0.00082	0.00084	0.00048	0.00048

Table 2- 10: LCI inputs for Landfill equipment (all fuel consumption and emissions per unit).

Landfill Gas Collection and Electricity Production

According to the U.S. EPA all landfills constructed in after 1991 with total capacities greater than 2.5 million cubic meters are required to install landfill gas collection systems (USEPA, 1999). Therefore, landfill gas generation and collection was included, and modeled based on work developed for the MSW-DST model [(Sich & Barlaz, 2000), (Thorneloe, Weitz, & Jambeck, 2007)]. The general equation for landfill gas generation per metric ton of waste placed is given as,

$$Landfill\ Gas = \left[\left(-(k+s)e^{-k(t2-t1)} + k\left(e^{-(k+s)(t2-t1)}\right) + s\right) \times \frac{L_o}{s}\right]$$

Where: k = first order decay rate,
t2 = time when model stops,
t1 = time when model begins,
s = first order phase constant,
Lo = the landfill gas potential.

A first order decay rate of 0.04/yr was assumed based on EPA AP-42 recommendation for areas with rainfall greater than 25 inches per year (USEPA, 1995). The first order phase constant of 1, with landfill gas collection occurring in three periods is assumed. Period 1 is the first five years from the initial placement of waste, the second from 5 – 40 years, and the third collection from 40 – 80 years. The overall modeling period for landfill gas generation is 100 years. The landfill gas potential is calculated based on decomposition factors published (Barlaz, 2006) and an MSW composition from a King County characterization study (Cascadia Consulting Group, Inc., 2004). Material decomposition factors and MSW composition for degradable components are shown in Table 2- 11. Total landfill gas potential is estimated as 83.1 cubic meters per metric ton.

EPA estimates average landfill gas potential is approximately 100 cubic meters per metric ton (USEPA, 1999). Furthermore it was assumed that landfill gas is 55% methane, and 45% carbon dioxide.

MSW Components	Decomp. Factor	MSW Composition	WA-MSW
	g-CH4/Kg	%	g-CH4/Kg
Grass	96	2.5%	2.4
Leaves	45	2.5%	1.1
Branches	40	1.8%	0.7
Food Waste	197	20.0%	39.4
Coated Paper	56	14.1%	7.9
Newsprint	50	2.7%	1.4
OCC	100	4.6%	4.6
Office Paper	142	1.6%	2.3

Table 2- 11: Decomposition factors, MSW composition, and decomposition emissions for Washington MSW components.

Based on an estimated efficiency of landfill gas collection (assumed 75% for all periods), the total landfill gas collected is calculated. It is assumed that during the first and last period the gas was collected and flared, while in the second period the gas is combusted for electricity production. This is in line with work presented by Obersteiner et al, that assumes the second period of landfill gas generation is the most useful for electricity production (Obersteiner, Binner, Mostbauer, & Salhofer, 2007). Total emissions from the landfill for all three periods including losses from inefficiencies were calculated and electricity generation was estimated based on an assumed ICE efficiency of 33%. Total electricity production from landfill gas is estimated as 251,800 BTU per metric ton of MSW. The amount of landfill gas generated and collected is shown below in Figure 2- 6.

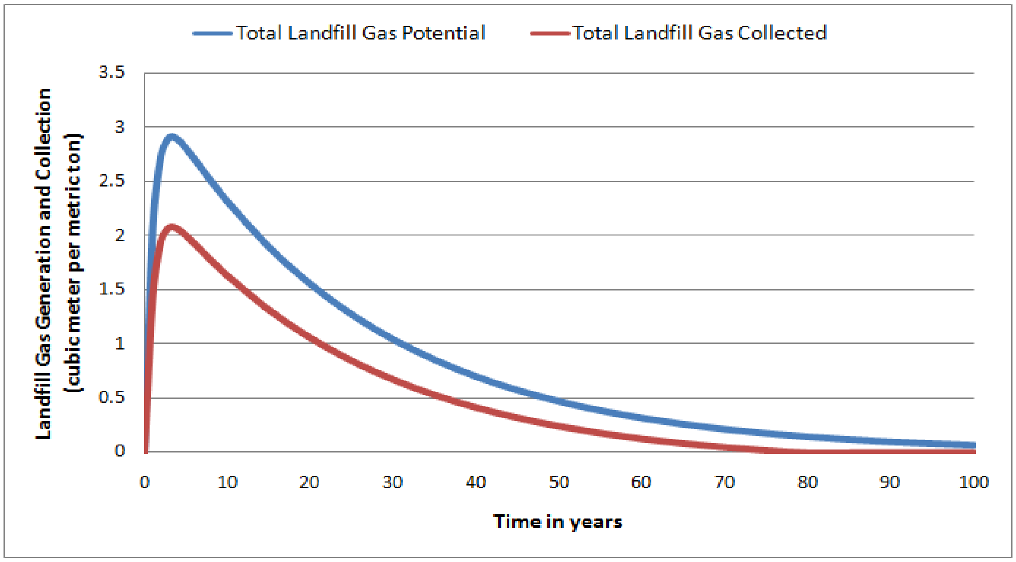

Figure 2- 6: Model for landfill gas generation and collection.

Leachate Generation and Waste Water Treatment

Landfill leachate is generated by rainwater that infiltrates waste layers in landfills. It poses the potential risk of carrying pollutants, such as, dissolved organic matter, inorganic matter, heavy metals, and xenobiotic organic compounds, into local groundwater and surface water. Average leachate composition was obtained from (Kjeldsen, Barlaz, Rooker, Baun, Ledin, & Christensen, 2002), leachate generation was calculated based on work performed by (Sich & Barlaz, 2000) and (Obersteiner, Binner, Mostbauer, & Salhofer, 2007). The average annual rainfall in Washington is 45.7 inches[10] or 1.14 cubic meters per square meters. Assuming that during the first period 20 percent of the precipitation is converted into leachate, 7 percent during the second period, and no leachate is generated for waste during the third period, a total leachate generation of 859 liters per metric ton of waste deposited. The leachate is then characterized in terms of the COD content, which are 12,500, 3,333, and 100 mg per liter of leachate for periods one, two, and three, respectively. All leachate is collected and sent to a waste water treatment plant.

An LCI module of an industrial waste water treatment facility was developed based on the functional unit of 1 kg of COD. The model developed by Jimenez-Gonzalez et al (Jimenez-Gonzalez, Overcash, & Curzons, 2001), is based off design equations and average data from literature and industrial sources. The model includes energy consumption, ancillary substances, and fuel consumption. It is a partial LCI and does not include all possible unit processes and emissions. Table 2- 12 gives the inputs used for both landfill gas generation/collection and leachate waste water treatment. Data for sodium hydroxide production was based on U.S. LCI Database (NREL, 2008), while ammonia, phosphoric acid, electricity, and fuel data was based on data from GREET 1.7. Polymer production was ignored for lack of availability in clarifier polymer production.

	Units	**Landfill Gas**	**WWTP**
Leachate Treated	kg - COD		5.2
NaOH production	kg		0.0136
Polymers production	kg		0.0013
Ammonia production	kg		0.0326
Phosphoric acid production	kg		0.0167
Conventional gasoline and RFG, at POU	BTU		156
Residual Oil, at POU	BTU		52
WA state electricity mix, at POU*	BTU	251,799	3,753
Environmental Flows			
Energy Consumption	BTU		3,962
CO2 (biogenic)**	g	103,805	870
CH4	g	16,505	
CO	g	536	
NOx	g	173	
PM10	g	36	
SOx	g	10	

Table 2- 12: LCI input data for landfill gas and WWTP.

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[10] See http://www.weather.gov/view/states.php?state=wa&map=on

Recycling Mixed Waste Paper

For this analysis, it is assumed that mixed waste paper is collected from generators, sorted by an MRF, and then sent to pulp recyclers to convert the waste into pulp for newsprint production. This recycled pulp is assumed to replace virgin thermo-mechanical pulp (TMP) that would otherwise be used for newsprint. Furthermore, it avoids the need for an associated amount of forestry operations including: logging operations, transportation to mills, and a mix of operations from saw mills, veneer mills, and chipping mills in the Pacific Northwest that produce virgin pulp chips for the pulp and paper industry in Washington. A brief description of the recycling, pulp production, and forestry operations are given for a more detailed discussion refer to the associated report.

Recycled Pulp Operations

Recycled pulp is a complex market, where demand and supply fluctuates constantly. MWP can be used in several recycled paper and paperboard processes, from tissues to linerboard. Due to lack of data it was difficult to determine what specific processes utilize MWP the most in the State of Washington. In fact, it is most likely that majority of the MWP is purchased by China as discussed in related King County reports (Cascadia Consulting Group, inc., 2006). For this analysis, it is assumed that Washington recyclers purchases the MWP and use it for newsprint production.

The transport distance from the MRF to pulp mill, is assumed to be 100 km by heavy duty truck. The energy and fuel consumption data for the recycling deinking processes was taken from a report, which surveyed the energy bandwidth of the US pulp and paper board industry (Jacobs, 2006). The recycled pulp is assumed to replace virgin TMP at a ratio of 1.25:1. The overall deinking process is assumed to be 80% efficient. A summary of LCI inputs are given in Table 2- 13.

Category	Unit	ONP, deinked	TMP
Total process efficiency		80%	96%
Energy Requirements			
Electricity	BTU/admt	1,451,496	8,527,537
Steam	BTU/admt	1,333,562	671,317
Fuel Requirements for steam production			
Natural Gas required	BTU	1,568,896	
Wood residue Combusted	BTU		972,923
Input Materials			
Waste Paper required	MT	1.25	
Pulp chips required	MT		1.04
Pulp chips, from Lumber, US PNW	MT		0.68
Pulp chips, from veneer, US PNW	MT		0.26
Pulp chips, from chip mill, US PNW	MT		0.10

Table 2- 13: LCI inputs for recycled newsprint (deinked) and TMP.

Virgin Pulp Production

Virgin paper production begins with forestry operations. In the United States, majority of the virgin pulp fibers come from the Pacific Northwest or the Southeastern region of the country. In the Pacific Northwest, majority of the wood is used for forestry products, such as, lumber, plywood, chips, etc. Pulp mills purchase pulp chips from saw and chip mills. The LCI data presented includes forestry operations, sawmill, chip mills, and pulp mills.

Thermo-mechanical Pulping

TMP is the most common mechanical pulping process used to produce virgin newsprint. It produces the highest grade of pulp from mechanical pulping without additional bleaching. The TMP process uses steam to soften wood chips before using a mechanical pulper. The process is the most energy intensive of the mechanical pulps, requiring intensive electricity consumption. LCI data for thermo-mechanical pulping comes from the industrial survey (Jacobs, 2006).

Forestry Operations

Forestry LCI data was from US LCI database for average intensity softwood logging in the Pacific Northwest. US LCI database inventory data was also used for saw mill operations for lumber production, veneer production, and chipping and debarking.

	Units	Lumber Operations	Plywood Operations	Chipping Operatons
Product Outputs				
Pulp chips, from rough green Lumber, US PNW	kg	384		
Pulp chips, at plywood plant, US PNW	kg		0.34	
Pulp chips, from Chipping Mill, US PNW	kg			1
Inputs				
Softwood logs	m3	0.81	0.0025	0.0025
Conditioned log, at plywood plant, US PNW	kg		6	
WA state electricity mix, at POU	BTU	79,101	933	176
US non-road diesel, at POU	BTU	16,657	206	62.6
LPG, at POU	BTU	3.07	85.5	
Gasoline (combusted in equipment)	BTU	1,564		
Air Emissions				
PM10 (Dust)	g	0.56	0.044	
VOC	g	1.55		

Composting

Commercial compost facilities in Washington, such as Cedar Groves, process collected yard waste. In our assessment we assume that a compost facility creates commercial compost from yard waste that competes with commercial fertilizer production as a soil amendment.

Windrow Turning Facility

Composting is the biological decomposition of organic matter into nutrients, which can be used as a soil nutrient or amendment. An LCI model for a yard waste compost facility was developed for the US EPA (Komilis & Ham, 2000), and adapted for our purposes. The model includes equipment operations for a commercial windrow facility and decomposition emissions from converting yard waste into commercial compost. The facility modeled in this study is assumed to operate at a capacity of 130,000 MT per year. Yard waste is transported from a transfer station to the compost facility. It is assumed that on average a compost facility will accept materials within 50 kilometers from its facility in order for it to operate cost efficiently. The yard waste is moved from the tipping floor into a tub grinder where oversized material is shredded. It is then placed in windrow piles where it has a residence time of 16 weeks. No water or nutrients are added to the compost piles, since the yard waste is assumed to have a moisture content of 60 percent. The piles are turned monthly with a front-end loader. Finally the compost is passed through a trommel screen to capture the fine fraction product compost. It is estimated that 46 percent of incoming yard waste is converted into compost, while 4 percent is sent to landfill as waste. Emissions from the biological decomposition of waste material into product compost, and equipment energy consumption and emissions were included in the assessment.

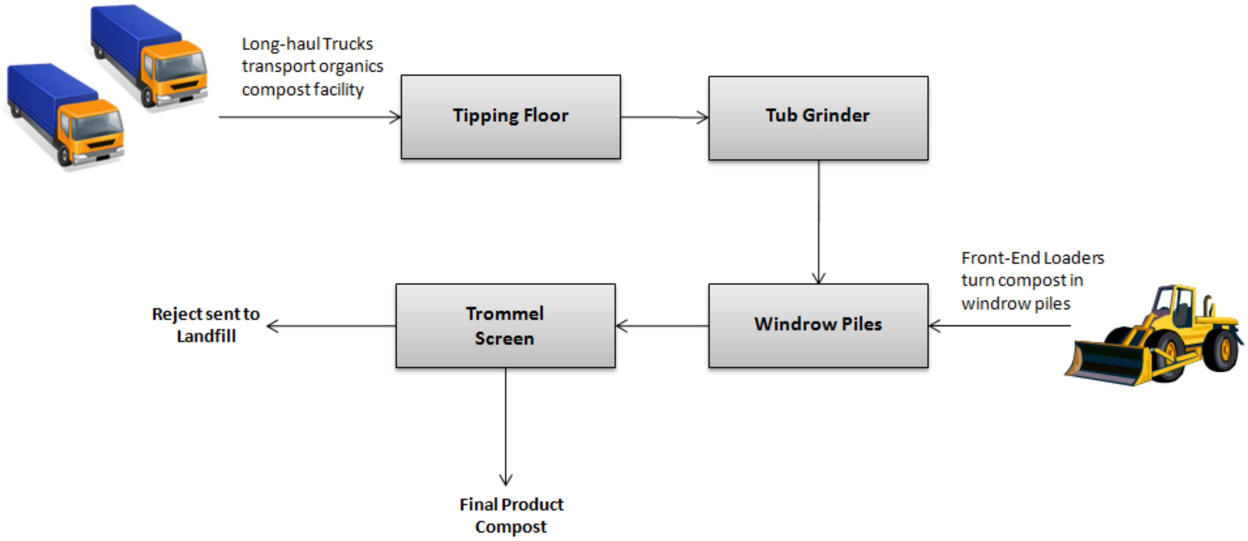


Figure 2- 7: Process flow diagram for windrow compost facility

	unit	Front-End Loader	Trommel Screen	Tub-grinder	Compost Emissions
Number of Units		2	2	2	
Capacity	MT/hr	25	100	25	
Engine/Motor Size	HP	110	25	378	
Fuel Type		Diesel	Electric	Diesel	
Environmental Flows					
Fuel Consumption	BTU	11,327	6,002	38,796	
CO2 (Biogenic)	g				237,300
CO2	g	936		3,205	
NMVOC	g				0.83
CO	g	0.16		0.54	
NOx	g	4.42		15.2	
PM10	g	0.13		0.44	
PM2.5	g	0.12		0.43	
SOx	g	0.00093		0.0032	

Table 2- 14: LCI inputs for compost facility operations.

Commercial Fertilizer Production

Commercial fertilizer production LCI data was taken from GREET 1.7 for nitrogen, phosphate, and potassium nutrients. It was assumed that yard waste compost has an average nutrient content of 6.2 kg, 2 kg, and 4.5 kg per kg of compost for N-, P-, and K-nutrient, respectively (Smith, Brown, Ogilvie, Rushton, & Bates, 2001). An equivalent amount of nutrients are avoided in the production of commercial fertilizer.

Biorefinery

A model for a lignocellulosic biorefinery was created using ASPEN ™ Plus software. The model is based off previous work performed by researchers at NREL for the conversion of corn stover to ethanol (Aden, et al., 2002), model version bw0401a_simp.bkp. It includes major unit processes for lignocellulosic ethanol prodution, such as, feedstock handling, pretreatment, saccharification and fermentation, ethanol recovery, and facility utilities (electricity, heat, waste treatment). A conceptual flow diagram for the biorefinery processing areas with major inputs and outputs is shown in **Figure 2- 7**.

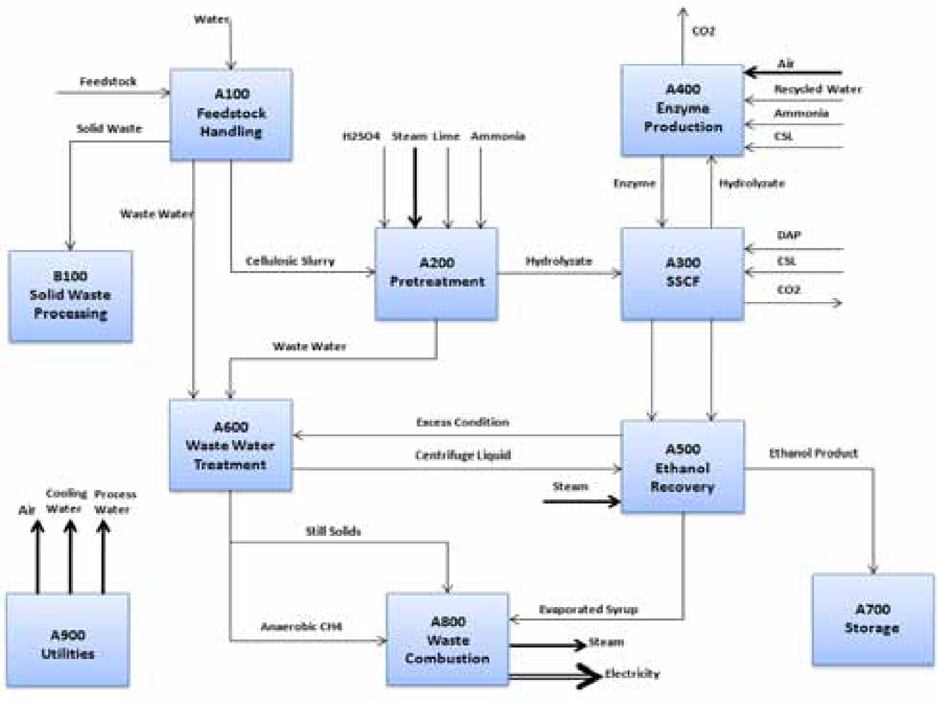


Figure 2- 8: Major process flow diagram for biorefinery model.

Lignocellulosic composition for the three feedstock materials is shown in Table 2- 15. The composition for MSW, and MWP were determined experimentally by researchers at the University of Washington College of Forest Resources, while the composition for yard waste is based off of literature values. The theoretical yields for MSW, MWP, and YW are calculated as 151, 118, and 70 gals per ton, respectively. It is assumed that the farthest distance feedstock can be transported and still remain economical is 50 miles this is assumed to be the same here. The capacity for lignocellulosic ethanol production is 98,040 kg/hr, however, the capacity for the feedstock handling area is actually larger to include removal of contaminants from the feed stream.

Lignocellulosic Components	**MSW**	**Waste Paper**	
Cellulose	74.0%	64.3%	44.7%
Xylan	7.3%	7.8%	14.6%
Arabinan	0.8%	0.9%	0.8%
Mannan	7.9%	4.4%	2.2%
Galactan	0.5%	0.3%	1.0%
Lignin	7.7%	21.1%	26.4%
Ash	1.8%	1.1%	1.7%
Moisture	0.0%	5.0%	0.0%
Other	0.0%	0.0%	8.6%
Theoretical Yield (gal/ton)	156.7	134.6	110

Table 2- 15: Lignocellulosic composition and theoretical yield for ethanol feedstocks.

Feedstock Handling & Pretreatment

Each solid waste stream requires different feedstock handling to remove various contaminants (metals, plastics, oversized waste) before it can continue through the ethanol conversion process.

MSW

MSW from transfer stations is transported to the biorefinery by heavy-duty trucks. Lignocellulosic portions of incoming MSW material makes up approximately 53 percent of total waste (Cascadia Consulting Group, Inc., 2004). To achieve 98,040 kg/hr of lignocellulosic feedstock approximately 184,286 kg/hr of MSW must be received. This is equivalent to approximately 2,200 MT per day of MSW. Trucks unload waste onto the tipping floor where front-end loaders then transfer the feedstock from the tipping floor to feed conveyors. The waste is conveyed through a bag breaker (modeled as a trommel screen), which tears open plastic bags containing waste and separates the oversized waste from the feedstock. Unprocessed waste is sent to solid waste processing (B100), where it is baled and sent to a landfill. Usable feedstock is dumped onto a drag conveyor belt and passed through a ferrous magnet and eddy current separator to remove ferrous and nonferrous metals. It then passes through a second trommel screen to remove plastics and glass contaminants. The remaining feedstock is sent through the wash table to remove excess dirt and grit. Finally it is passed into two shredders to reduce waste to under 1.5 inches. Shredded feedstock is then sent to pretreatment.

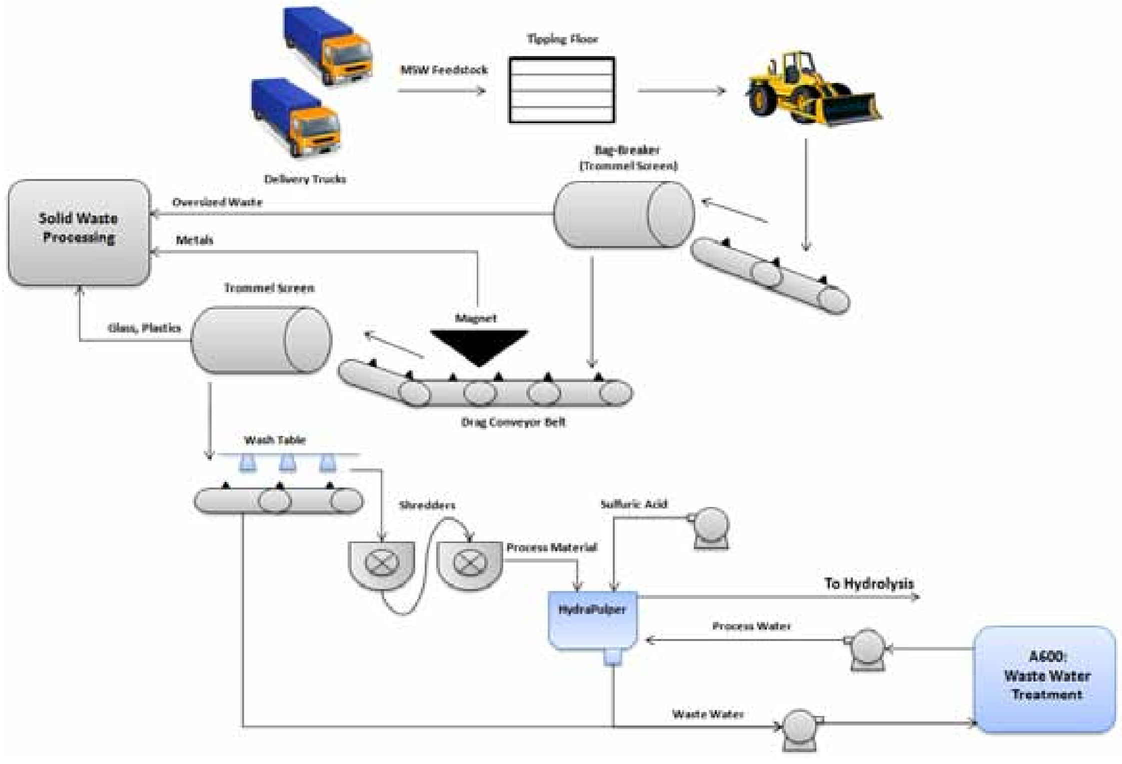


Figure 2- 9: Process diagram for MSW feedstock handling.

Paper

Paper processing is similar to MSW processing. Baled mixed waste paper is delivered in heavy duty trucks transporting mixed waste paper from an MRF to the biorefinery. Forklifts unload bales from the trucks and transfer to the storage area. Another set of forklifts move the baled mixed paper waste from storage area to the bale unwrapper (modeled as conveyor belt). The loose paper is passed onto a second conveyor which travels through a ferrous magnet. The remaining material is passed into a shredder to reduce size of feedstock. The shredded material is sent to the hydrapulper for pretreatment. Waste water from pretreatment is sent to A600 waste water treatment, while solid wastes are processed in a separate area.

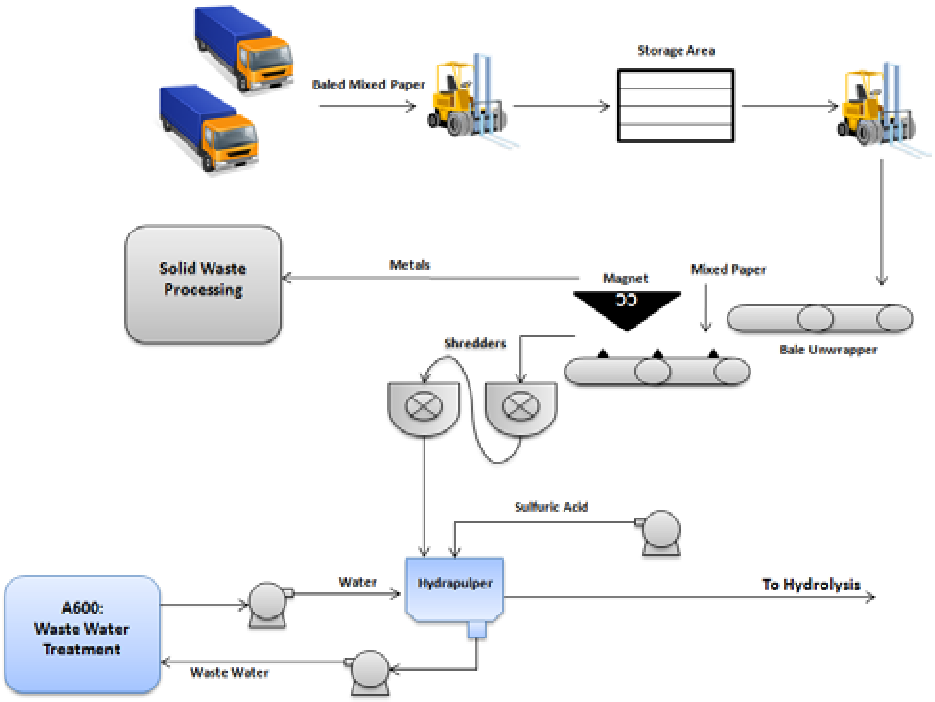
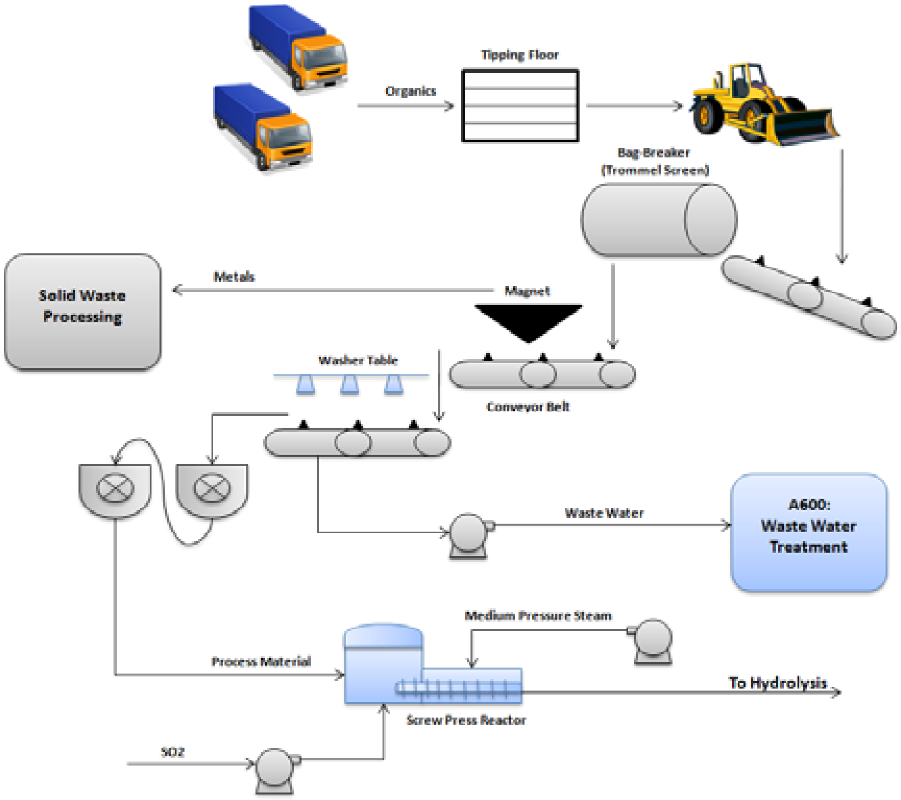


Figure 2- 10: Process flow diagram for MWP feedstock handling.

Yard Waste

Yard waste is shipped from transfer station to biorefinery in heavy duty truck and dumped onto the tipping floor. A front-end loader is used to move the organics from the tipping floor to feed conveyor. The organics are conveyed through a bag breaker to free up any bagged yard waste. The loose feedstock passes through magnetic separation to remove any metals and then goes through a wash table. The washed feedstock passes through primary and secondary shredders to reduce the size to less than 1.5 inches. The shredded feed is sent to steam explosion pretreatment.



ASPEN Model Development

Feedstock handling was modeled outside the ASPEN model in an associated spreadsheet; this section describes the inputs for the NREL model bw0401a_simp.bkp[11].

The models for MSW and MWP are essentially the same, in terms of physical treatments. The reactor for pretreatment was modeled as a hydrapulper, instead of a screw press reactor. Sulfuric acid is added to the hydrapulper at a concentration of 3 percent to induce acid hydrolysis and separation of lignin at a temperature of 60°C. The pretreated slurry is sent to saccharification and fermentation. The adjustment to a low pressure hot water system eliminated the use of a distillation economizer, and this process and associated equipment were removed from the analysis. While for yard waste, a steam explosion pretreatment process was modeled and temperatures in the pretreatment reactor were changed to 215°C and 13 atm. In addition, SO_2 at a 3 percent concentration was used instead of H_2SO_4. The remainder of the physical processing is outlined in the NREL model description and is essentially unchanged (Aden, et al., 2002). Changes in conversion rates and chemical loadings are described in Tables 2-14 and 2-15, while model outputs are given in Table 2- 16.

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[11] Accessed at: http://devafdc.nrel.gov/biogeneral/Aspen_Models/

Feedstock Type	**MSW**	**Waste Paper**	**Yard Waste**
Moisture Content	20%	5%	60%
Pretreatment Conditions			
Type	Acid Hydrolysis in Hydrapulper	Acid Hydrolysis in Hydrapulper	Steam Explosion
Catalyst	H_2SO4	H_2SO4	SO_2
Concentration	4%	4%	3%
Residence Time	6 hrs	6 hrs	5 mins
Temperature (deg C)	60	60	215
Pressure (atm)	1	1	12.1
SSF Conditions			
Saccharification Type	Enzymatic	Enzymatic	Enzymatic
Enyzme Organism	T. Reesei	T. Reesei	T. Reesei
Enzyme Loading (FPU/g)	20	20	20
Fermentation Bacteria	Z. Mobilis	Z. Mobilis	Z. Mobilis
Residence Time (days)	1	1.5	1.5
Temperature (deg C)			
Hydrolysis	65	65	65
Fermentation	41	41	41
Pressure (atm)	1	1	1

Table 2- 16: ASPEN model inputs.

Pretreatment Conversions	**MSW**	**Waste Paper**	**Yard Waste**
Cellulose -> C6 sugars	0%	0%	0%
Cellulose -> glucose	0%	0%	0%
xylan -> xylose	84%	62%	75%
C5solid -> C5sugar	59%	72%	75%
C6solid -> C6sugar	12%	27%	0%
SSF Conversions			
Cellulose --> Glucose	89%	86%	75%
Hexose --> EtOH	95%	95%	95%
Pentose --> EtOH	85%	85%	85%
Seed Train			
Hexose --> EtOH	90%	90%	90%
Pentose --> EtOH	80%	80%	80%
Final Yields			
Model yield (gal/ton)	115.8	98.2	72.4
Theoretical Yield (gal/ton)	156.7	134.6	110
Percent of theoretical	74%	73%	66%

Table 2- 17: Conversion rates for different stages of processing.

	units	MSW	Waste Paper	Yard Waste
Ethanol Produced	kg/hr	29,987	30,218	9,375
Incoming Feedstock	kg/hr	184,286	120,590	98,040
Cellulosic Feedstock	kg/hr	98,040	98,040	98,040
Transportation Distance	km	80	80	80
Chemicals/Fuel Consumption				
Sulfuric Acid	kg/hr	8,444	10,090	3,325
Hydrated Lime	kg/hr	6,095	7,283	358
Corn Steep Liquor	kg/hr	1,216	1,445	564
Enzyme	kg/hr	23,113	14,108	6,886
Ammonium Phosphate	kg/hr	151	180	70
Denaturant	kg/hr	1,237	1,247	387
Solid waste	kg/hr	86,246	22,550	0
Electricity Consumption/Production				
Electricity Produced	kW	11,934	34,323	19,731
Electricity Consumed	kW	14,656	16,914	9,905
Net Electricity	kW	-2,722	17,409	9,827
Emissions				
CO2	kg/hr	103,514	74,704	48,017
N2	kg/hr	261,249	113,050	118,351
CH4	kg/hr	0.64	0.42	0.17

Table 2- 18: LCI inputs for lignocellulosic ethanol production

U.S. Corn Ethanol Production

It is assumed that for every liter of cellulosic ethanol produced, and equal amount of corn ethanol is displaced. For the analysis dry-mill ethanol LCI data from GREET 1.7 is used to represent ethanol. Since majority of the ethanol produced in the U.S. is from this process.

Chemicals Production

The life cycle of cellulosic ethanol production requires the use of several chemical inputs. This includes the production of sulfuric acid, lime production, enzyme production, corn steep liquor production, ammonium phosphate, and ethanol denaturant. All chemical LCI input data are given in the associated report.

Sulfuric Acid Production

Sulfuric acid is used during the pretreatment of MSW and MWP to weaken the bond between cellulosic material and the lignin structure. It is also used in the overliming process of the biorefinery to remove lime from the product stream and convert it into gypsum. LCI data for sulfuric acid production was taken from GREET 1.7 based on US average electricity grid.

Lime Production

Hydrated lime [$Ca(OH)_2$] is used to neutralize the acidity of the liquid waste coming out of the pretreatment process. Residual lime is separated from the solid stream by mixing with sulfuric acid to form gypsum. The co-product gypsum is ignored from the analysis as the model cannot assess the level of quality of the product or the potential demand in industry. LCI data for lime production comes from U.S. EPA AP-42 (USEPA, 1995) and data from the US LCI database for quicklime (NREL, 2008).

Ammonia Phosphate Production

Ammonium phosphate is a commercial fertilizer used within the production of ethanol as a nutrient for the fermentation process. It is produced by reacting phosphorous acid (H_3PO_4) and anhydrous ammonia (NH_3) (USEPA, 1995). LCI data for ammonia phosphate production is based off US DOE Fertilizer industry survey (Energetics, 2000).

Enzyme Production

Cellulase enzymes are used during the enzymatic hydrolysis converting cellulose to glucose. Enzyme production is based off literature data presented by Sheenhan et al, for the conversion of corn stover to ethanol (Sheehan, et al., 2004). It is assumed that enzymes are produced at a nearby facility and electricity and heat demands are met by excess energy produced from the biorefinery.

Corn Steep Liquor Production

Corn steep liquor is a byproduct of the initial stages of wet milling of corn. The primary use of CSL is as a nutrient for ruminant animals. The majority of CSL produced is immediately added to corn gluten and fibrous materials for use as animal feed. The remaining CSL has several uses, including as a liquid feed supplement for animals, in chemicals production such as acetic acid and food acids, and in the fermentation process. CSL is used in during the fermentation process as a nutrient, and LCI data comes from a corn wet-mill facility energy report (Galitsky, Worrell, & Ruth, 2003) and GREET 1.7 data for corn farming.

Energy & Fuel Production

GREET Data

The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model (Versions 1.7) (USDOE, 2006) was used to estimate the life cycle of grid electricity, fuel production, heating fuel combustion, transportation (heavy-duty truck, diesel train, cargo ship), and select chemical's. The data used is presented in **Appendix B**.

Life Cycle Impact Assessment

The results for both the total life cycle inventory and life cycle impact assessment are presented for all scenarios (see Table 2- 3 for a description of the scenarios). LCIA results are given in both normalized results (person equivalents) and without normalization. In many cases, inventory or impact values may be reported as negative values. This because system expansion is used in all scenarios, thus avoiding unit processes. For example, production of lignocellulosic ethanol is assumed to avoid corn ethanol production. This product substitution is necessary to have the same comparable basis for all scenarios. Even though the negative impacts may suggest that waste management decreases environmental interventions, this does not mean that we should seek waste maximization strategies. Rather, negative impacts should suggest a possible benefit to the overall system by comparison, and not as a decrease in net impacts. The inverse is true for total energy consumption, where negative implies consumption and a positive value implies a benefit. Unit processes were aggregated for the contribution analysis to come up with five major categories: collection and transportation, landfilling, composting, recycling, and ethanol production. The excel model includes further contribution analysis for each unit process. Also it should be noted that the environmental flow "CO2 (biogenic)" represents biological decomposition of organic material into carbon dioxide, and is tracked from landfill and compost emissions, and forestry emissions. It is only tracked to offer the possibility of taking credit for non-fossil based CO2, which could possibly considered carbon neutral. However, global warming potential includes both forms of CO2 in the calculation.

LCIA Results		**Base Case**	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**
Energy Consumption	trillion-BTUs	0.4	9.7	10.3	-1.8	1.9	-3.2
Global Warming	Gg-CO2e	569	-910	-2,909	2,836	301	3,291
Acidification	Gg-H+ equiv	138	213	181	164	144	152
Photochemical Smog	Gg-NOx-e	4.0	-1.2	-0.7	3.7	3.6	4.1
Particulate Matter	Gg PM	0.1	3.1	2.6	0.6	0.0	0.3
Normalized Results							
Energy Consumption	Person Equiv.	-1,226	-29,434	-31,449	5,498	-5,936	9,803
Global Warming	Person Equiv.	37,521	-60,059	-192,007	187,133	19,857	217,182
Acidification	Person Equiv.	61,147	94,378	80,116	72,884	63,673	67,561
Photochemical Smog	Person Equiv.	22,829	-7,034	-3,978	21,554	21,048	23,809
Particulate Matter	Person Equiv.	2,180	76,498	65,838	14,301	719	6,349

Table 2- 19: LCIA and normalized LCIA results.

Environmental Flow	**Units**	**Base Case**	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**
Total Energy*	trillion-BTUs	0.40	9.66	10.32	-1.80	1.95	-3.22
CO2 (biogenic)**	Gg	-1,610	10.5	-2,121	669	-1,757	624
CO2	Gg	185	-417	-361	216	98	279
CH4	Gg	79.8	-1.75	-1.44	79.6	79.6	95.5
N2O	Gg	-0.0037	-1.5397	-1.3101	-0.1366	-0.1004	0.0031
NMVOC	Gg	0.05	-1.09	-0.93	-0.04	-0.01	0.08
CO	Gg	4.30	0.49	0.64	4.24	4.21	4.66
NOx	Gg	3.62	-0.37	0.03	3.47	3.36	3.72
PM10	Gg	0.09	3.31	2.86	0.57	0.06	0.23
PM2.5	Gg	-0.006	-0.248	-0.226	-0.001	-0.033	0.025
SOx	Gg	-0.14	4.48	3.53	0.50	0.18	0.07

Table 2- 20: Total life cycle inventory results.

***a positive energy value indicates a reduction in energy consumption.**

****CO2 (biogenic) represents biological decomposition emissions from landfill, and compost activities.**

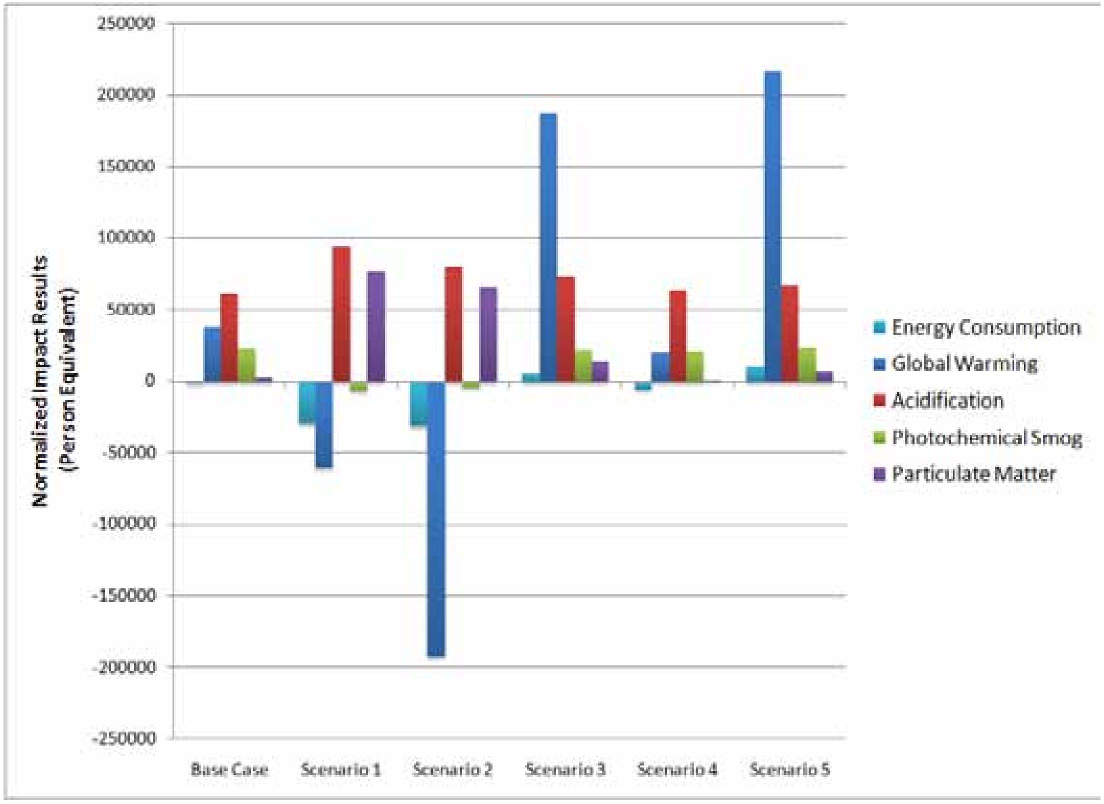

Figure 2- 11: Normalized LCIA results for all impact categories, showing how impacts deviate for each scenario

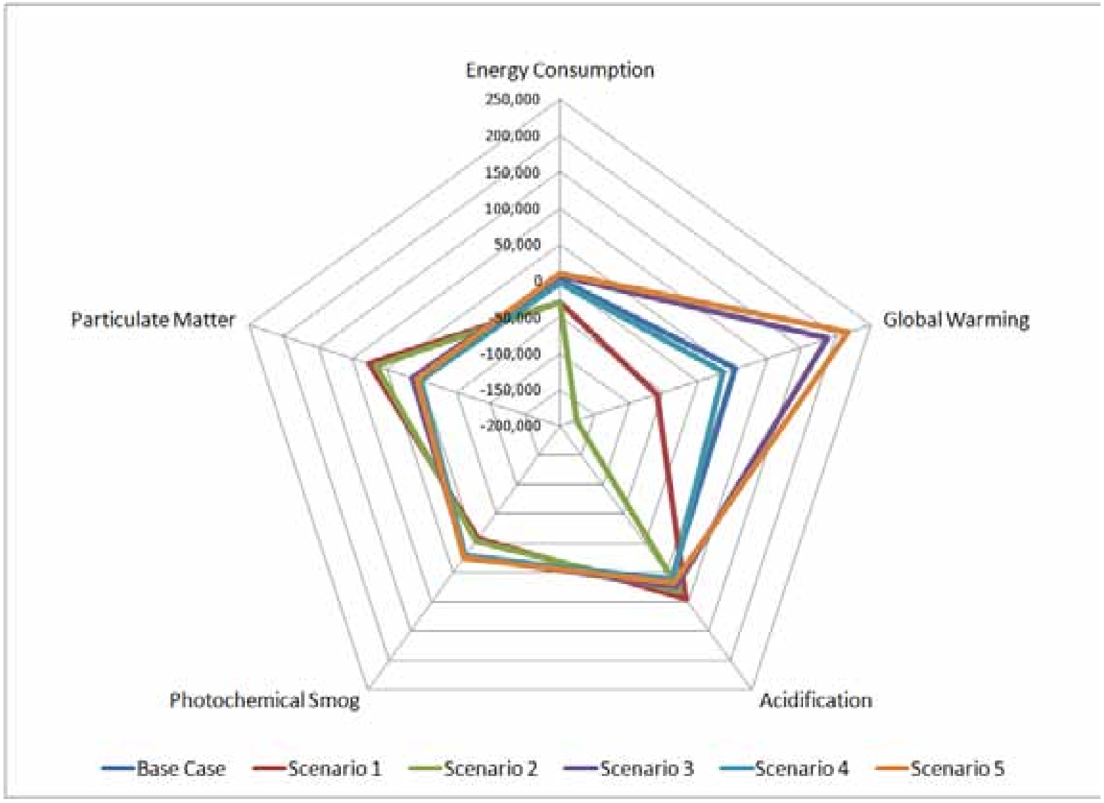

Figure 2- 12: Normalized LCIA results, showing how scenarios compare in each impact category.

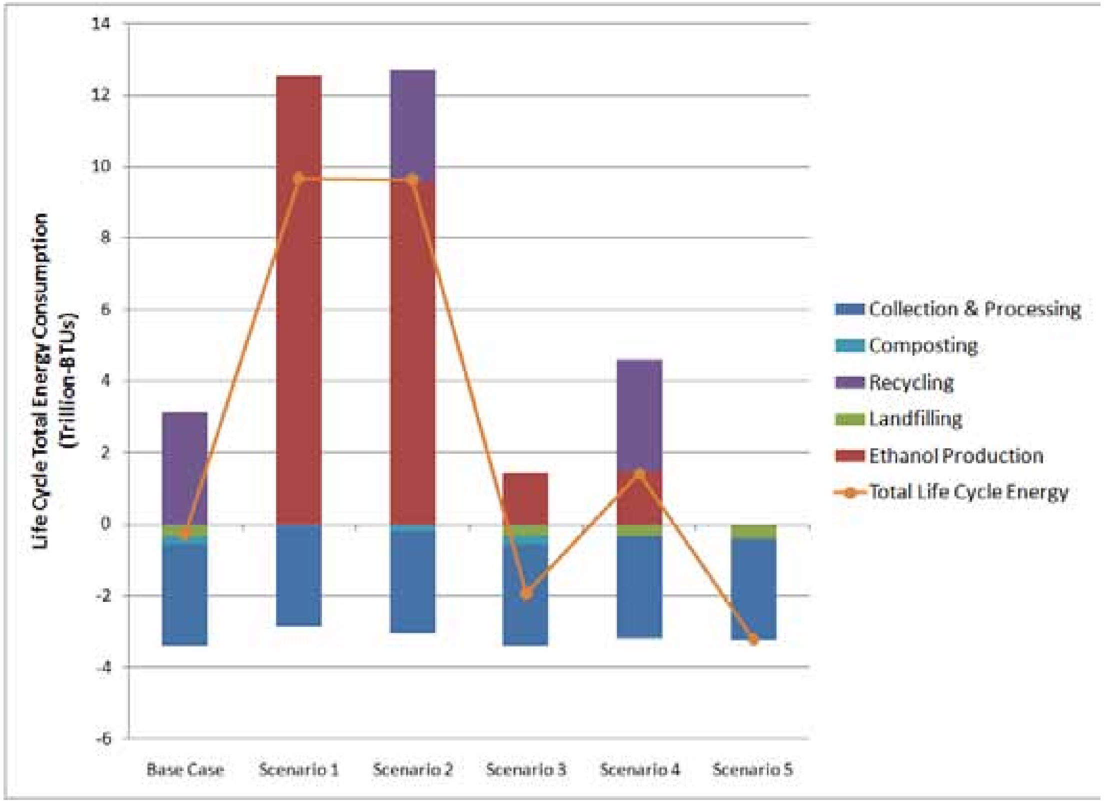

Figure 2- 13: LCIA contribution analysis for Total Energy Consumption

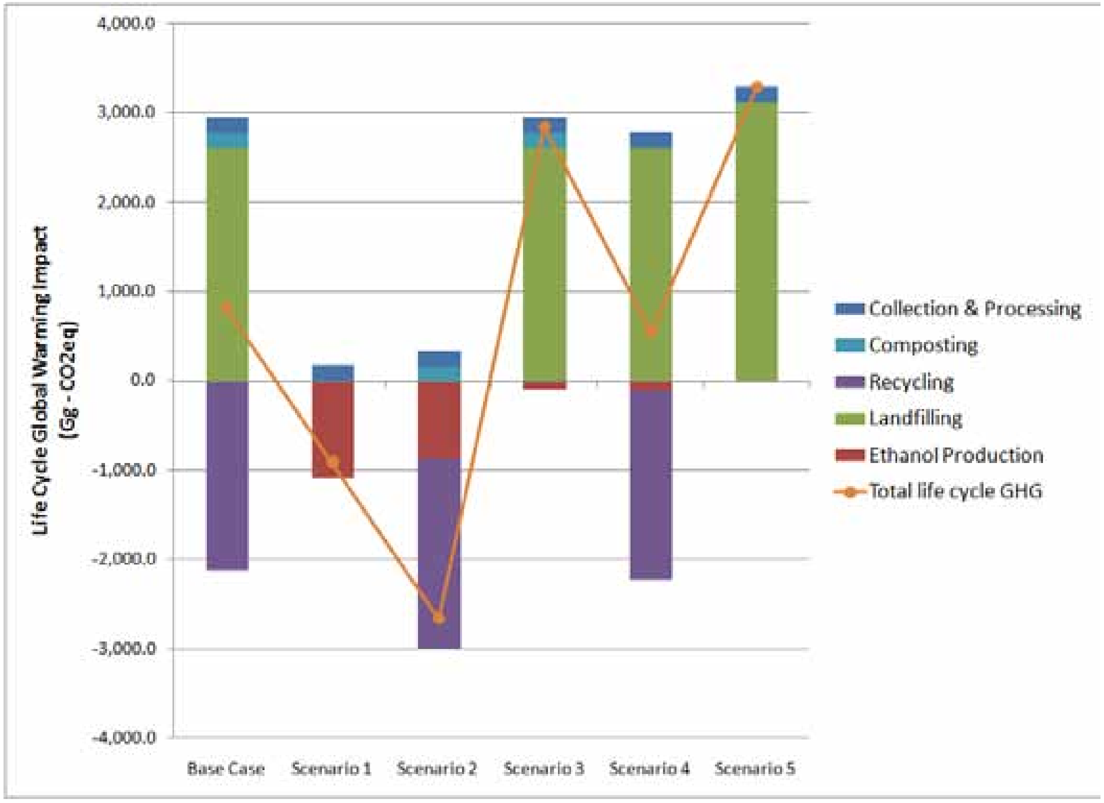

Figure 2- 14: LCIA contribution analysis for Global Warming Potential.

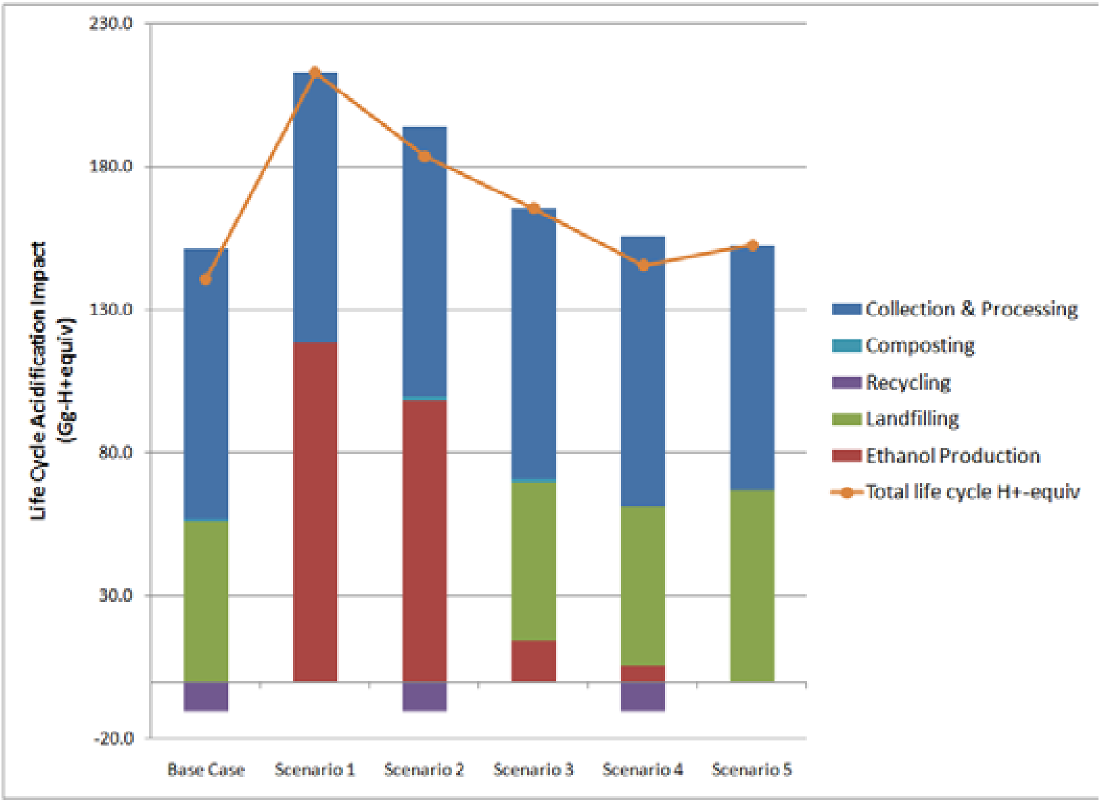

Figure 2- 15: LCIA contribution analysis for acidification potential.

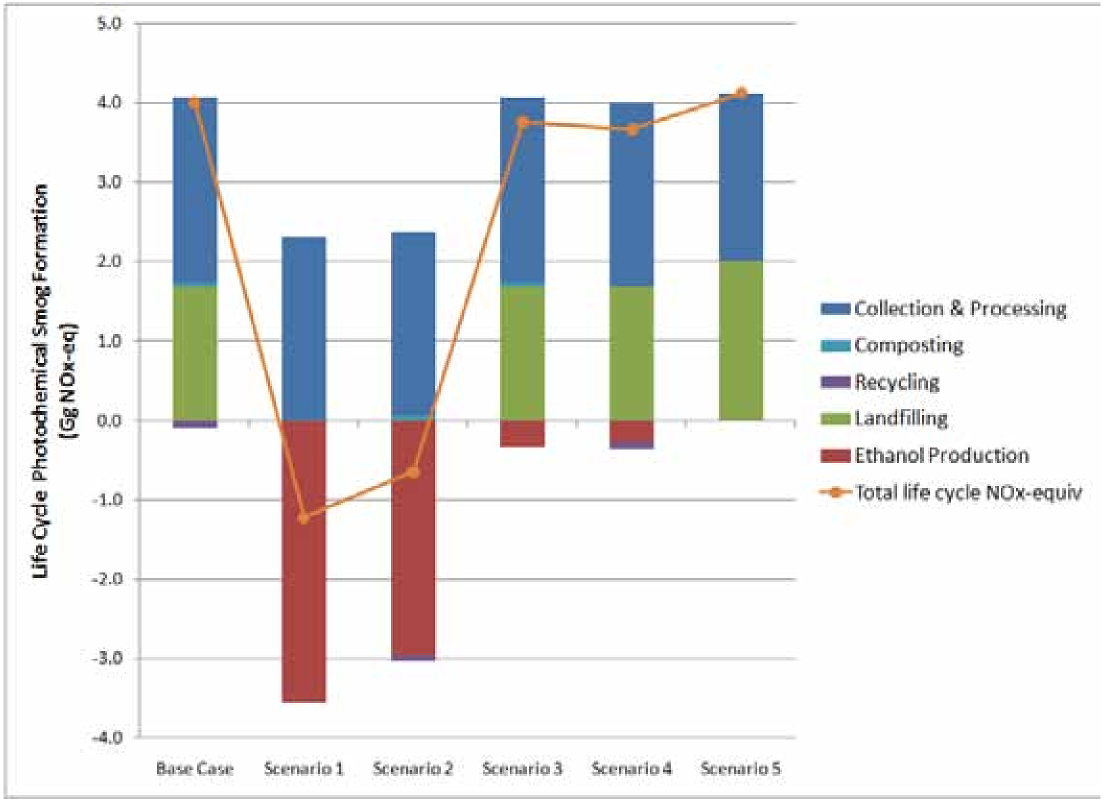

Figure 2- 16: LCIA contribution analysis for Photochemical Smog formation.

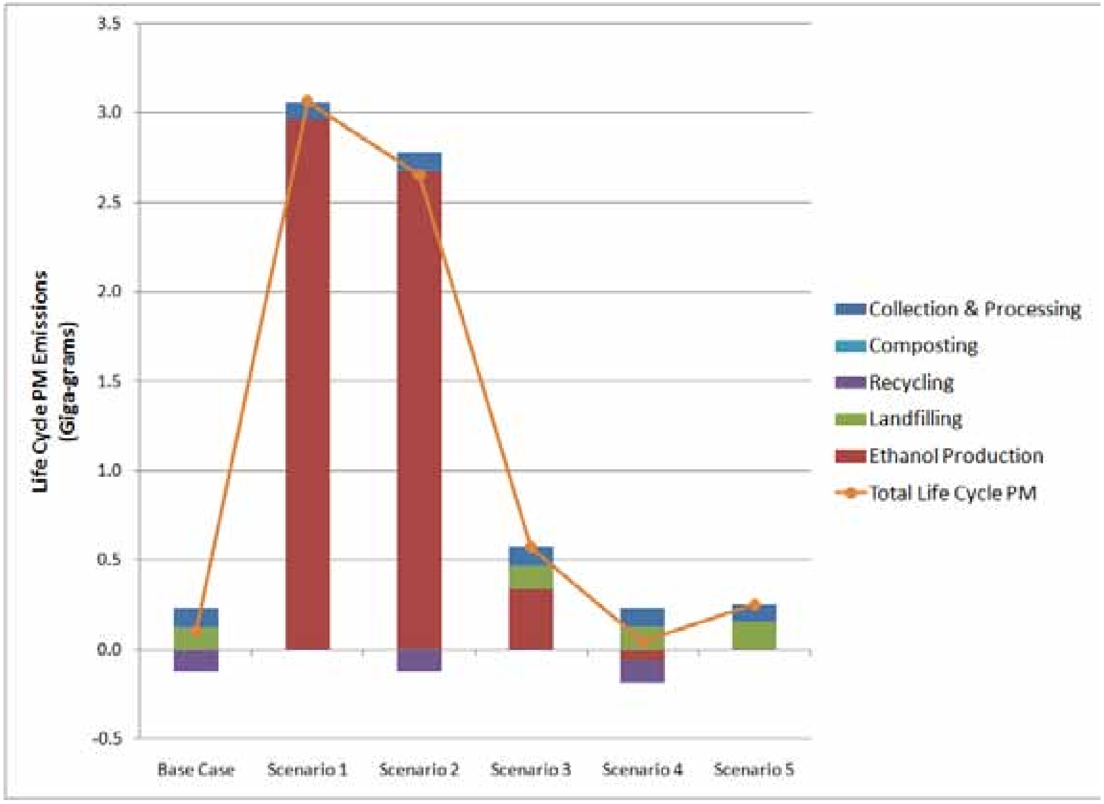

Figure 2- 17: LCIA contribution analysis for total life cycle PM emissions

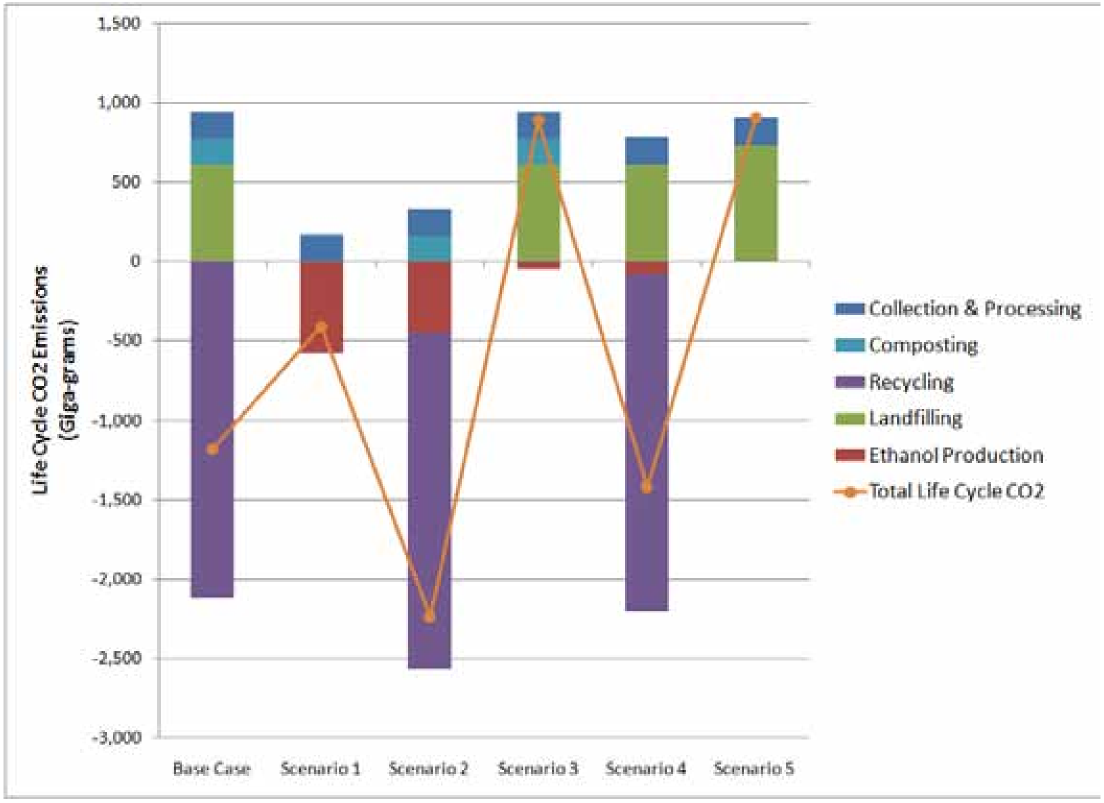

Figure 2- 18: LCI contribution analysis for total CO2 emissions.

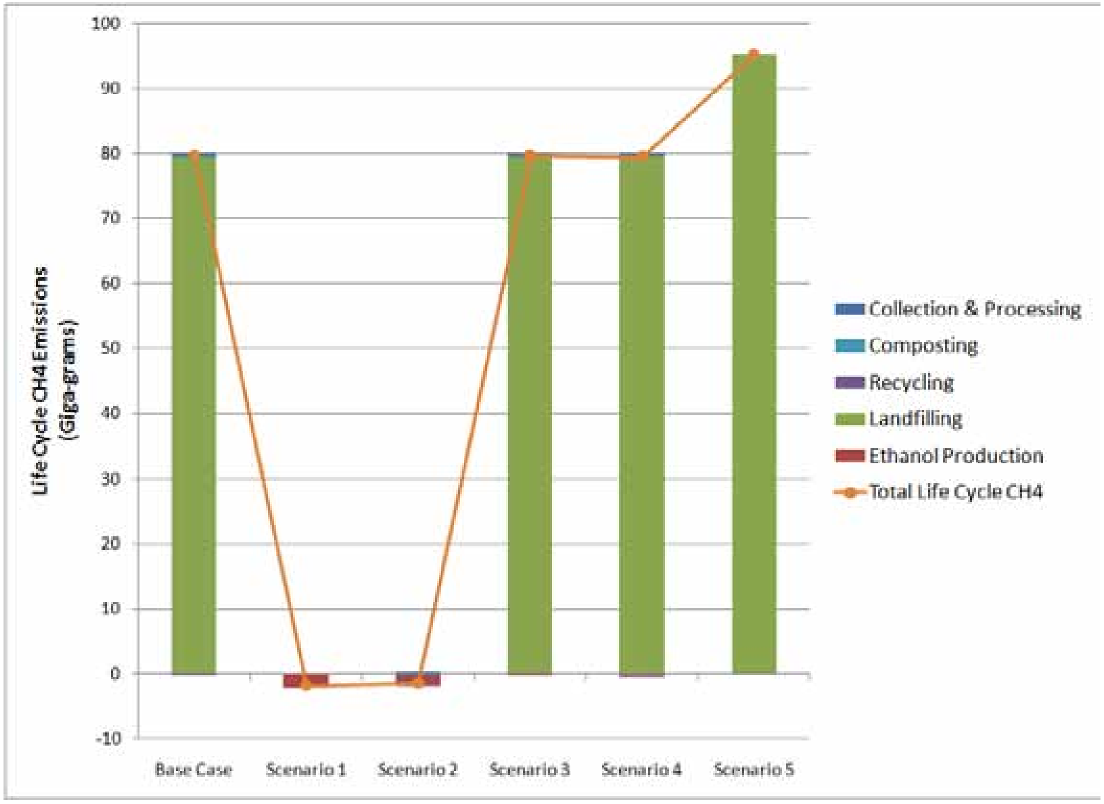

Figure 2- 19: LCI contribution analysis for total CH4 emissions.

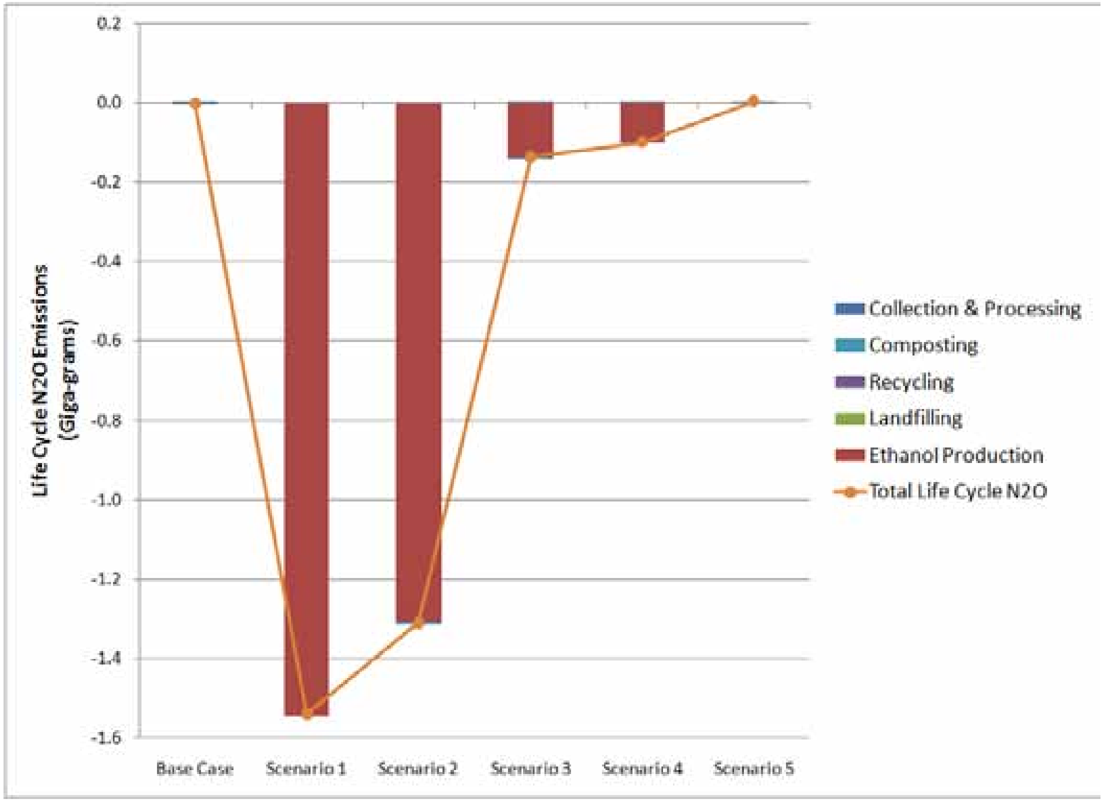

Figure 2- 20: LCI contribution analysis for total N2O emissions.

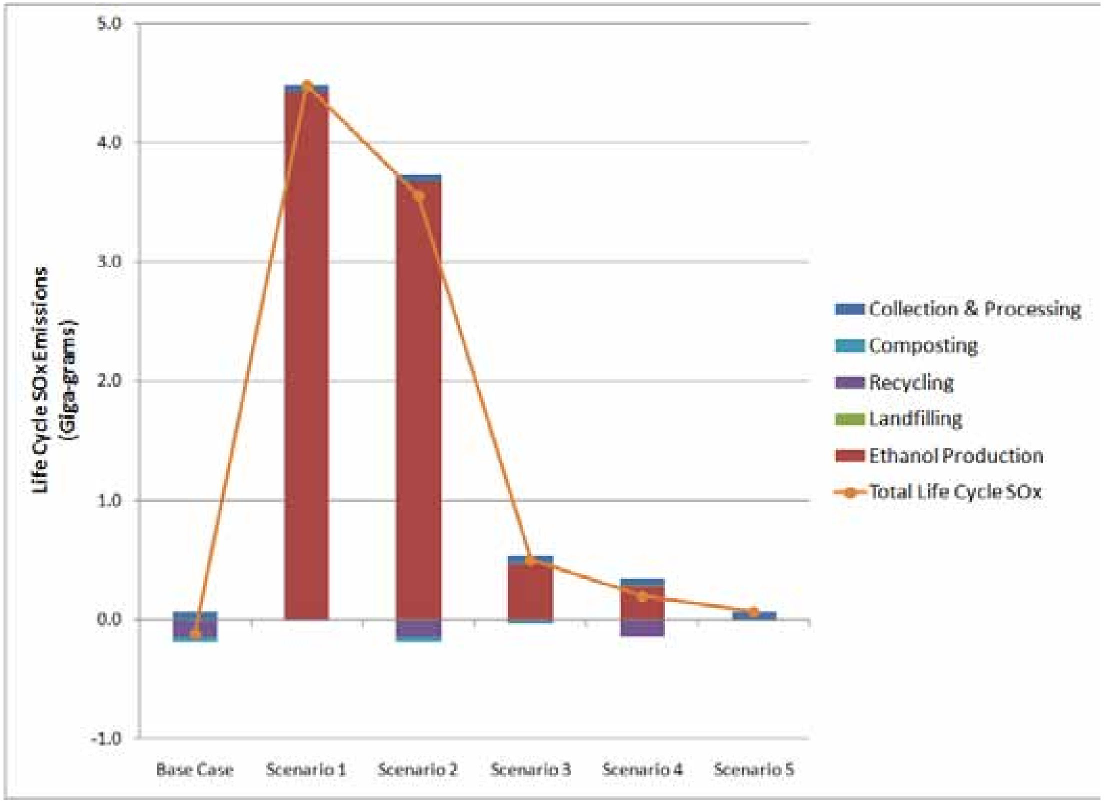

Figure 2- 21: LCI contribution analysis for total SOx emissions.

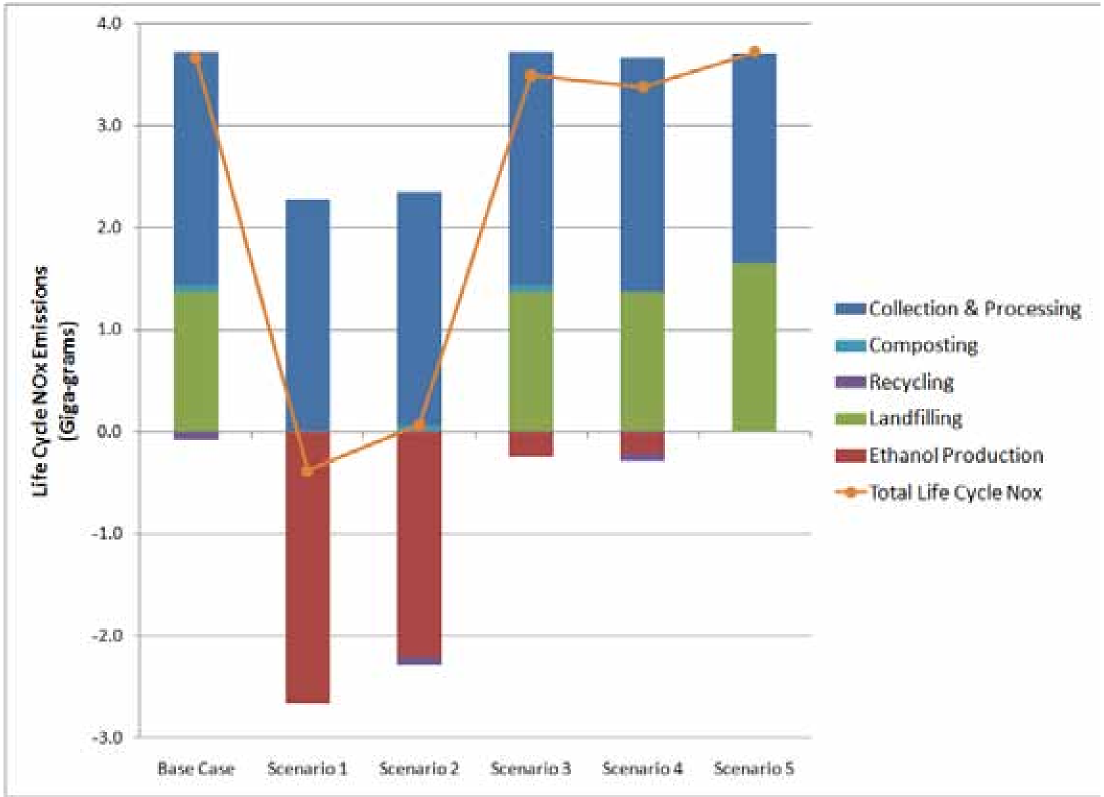

Figure 2- 22: LCI contribution analysis for total NOx emissions.

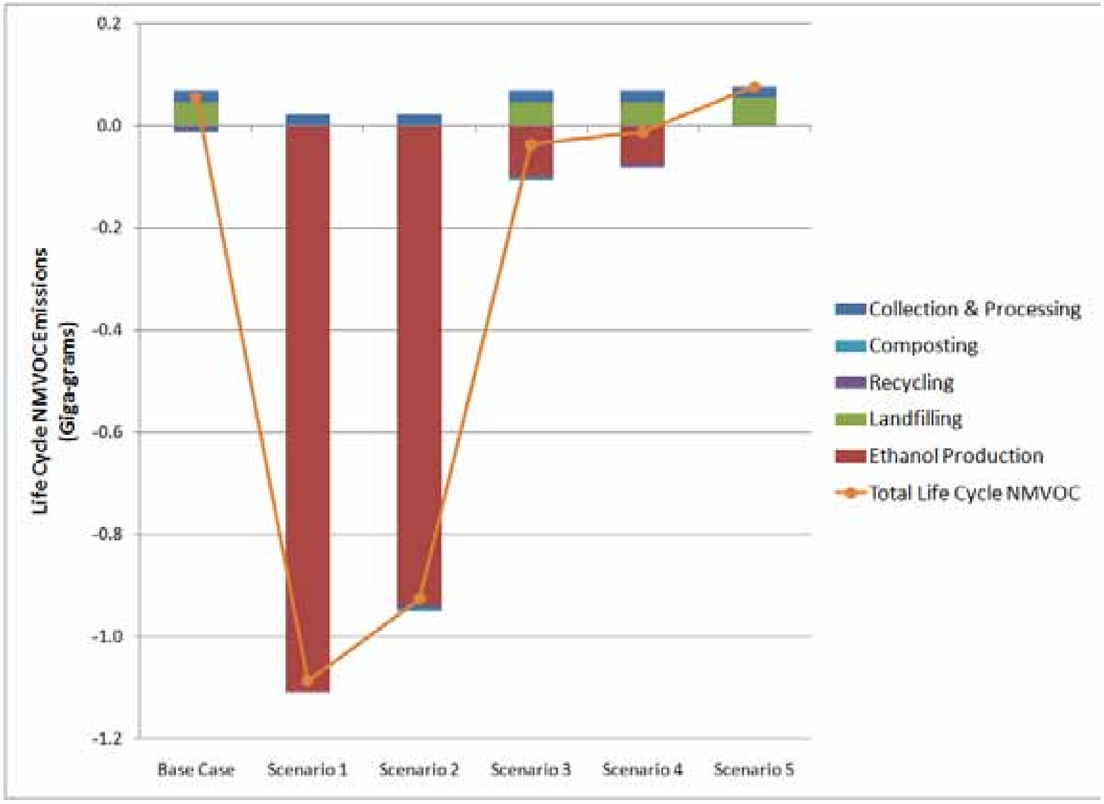

Figure 2- 23: LCI contribution analysis for total NMVOC emissions.

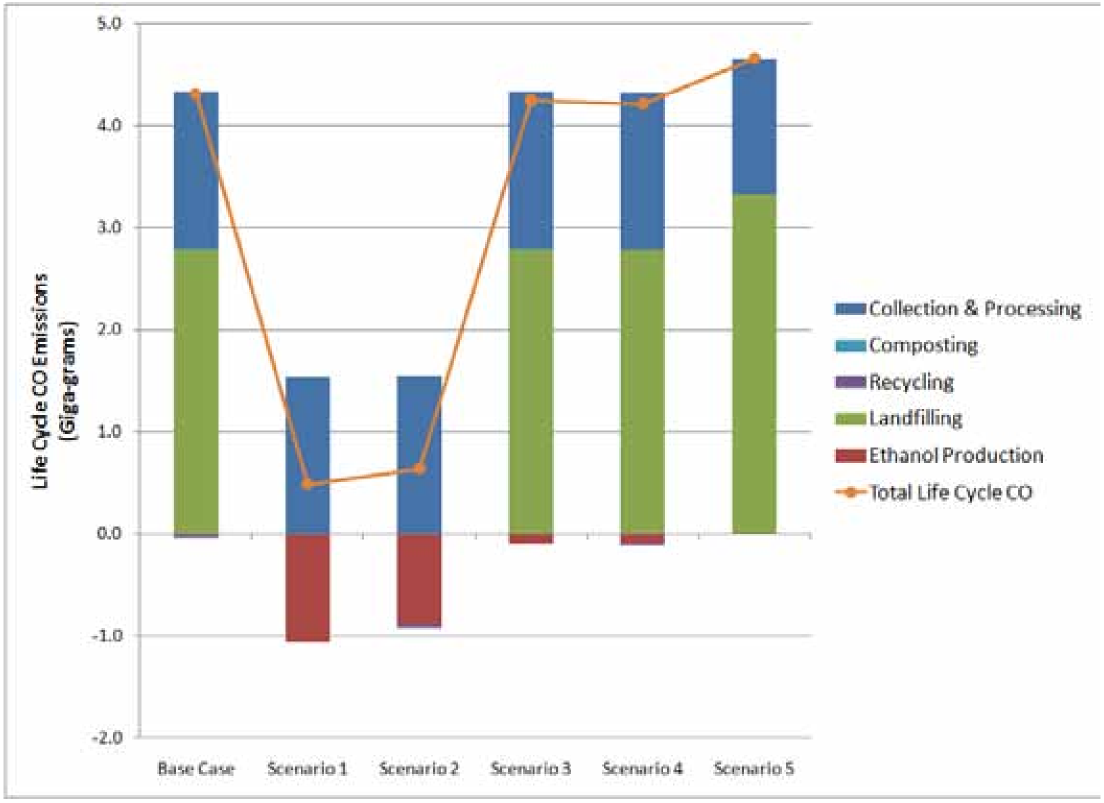

Figure 2- 24: LCI contribution analysis for total CO emissions.

Process Economics

The process modeling that was done for the LCA research was also used to make estimates of the economic viability of converting the three waste streams to ethanol. In this economic analysis we assumed construction of biorefineries that consume about 800,000 tons per year of biomass (either municipal solid waste, paper waste, or yard waste). The cost analysis includes a total project investment based on installed capital cost, variable operating costs, and fixed operating costs for each plant design. From these three factors, a discounted cash flow analysis is performed and the breakeven selling price of ethanol determined.

Methods

Total Project Investment

The capital cost was determined by estimating the individual equipment costs associated with ethanol production. The cost estimate is classified as class 30 (roughly 30% accuracy) and is to be used for feasibility purposes. Installation factors are used to determine installed costs from purchased equipment costs. The majority of the installation factors were obtained from CHEMSYSTEMS[12] or from equipment vendors.

Once capital costs were determined for the base year, they were indexed to 2009 using the Chemical Engineering Plant Cost Index. Additional costs are included as fractions of the total capital cost. These costs include warehouse costs, site development, prorateable costs, field expenses, construction, contingency, and a few others. A detailed list of these costs and methods for calculating them can be found in NREL report (Aden, et al., 2002) assessing a biorefinery using cornstover feedstock.

Variable Operating Costs

The variable operating costs are calculated based on the material and energy balance provided by the Aspen models. The costs include raw materials, waste handling charges, and by-product credits as provided by the corn in the ethanol NREL report.

Fixed Operating Costs

Fixed operating costs include labor and overhead. Fixed operating costs came from Aden (Aden, et al., 2002) or from Peters (Peters, Timmerhaus, & West, 2003). General overhead is estimated as 60% of the total salaries and covers items such as safety, general engineering, general plant maintenance, payroll overhead (including benefits), plant security, janitorial and similar services, phone, light, heat, and plant communications. Additional maintenance materials were estimated at 2% of total installed cost. Insurance and taxes were estimated at 1.5% of total installed cost.

Discounted Cash Flow Analysis

The discounted cash flow analysis is used to find the price of ethanol required for a net present value of $0 after a 20 year plant life and at a discounted cash flow rate of return of 15%. The analysis assumes a federal tax rate of 39%. .

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[12] http://www.chemsystems.com/

Results

For each feedstock option, an economic analysis was performed for processes using one of two fermentation organisms; conventional Brewer's yeast (*Saccharomyces cerevisiae)* and Zymomonas mobilis. The Brewer's yeast was assumed to ferment only hexose sugars while Zymomonas was assumed to ferment hexose and pentose sugars according to the yields given by Aden (Aden, et al., 2002). The discounted cash flow analysis for the Brewer's case resulted in a minimum selling price for ethanol of approximately $1.49 per gallon in the municipal solids waste case. For the case of waste paper and Brewer's yeast, the minimum selling price is slightly higher at $2.34 per gallon. Lastly, the yard waste feedstock analysis yielded a selling price of $2.92 per gallon. The considerably lower minimum selling price for the municipal solid waste reflects this raw materials ease of conversion and relatively low pentose sugar content.

In the Zymomonas case, the minimum selling prices are $1.36, $2.15, and $2.25 for solids waste, waste paper, and yard waste respectively. The lower minimum selling prices for Zymomonas reflect its ability to convert both hexose and pentose sugars.

The results for the municipal solids waste process economic analysis in the Brewer's yeast case are shown in Table 2-21. The feedstock rates for each of the three processes are equal. However, the different yields and compositions will change the economics from case to case.

Table 2-21. Summary of Production Rates, Yields, and Converting Costs forMSW Process using Brewer's Yeast

Feedstock Rate (metric ton/day)	2256
Ethanol Production (MM Gal. / Year)	76.8
Ethanol Yield (Gal / Dry US Ton Feedstock)	105.6
Total Equipment Cost (2009 $)	$97,000,000
Total Project Investment (2009 $)	$168,800,000
Waste Disposal ($/yr)	$3,600,000
Fixed Costs ($/yr)	$7,600,000
Minimum Ethanol Selling Price ($/gal)	$1.49

Similarly, the results for the waste paper process design using Brewer's yeast are below in Table 2-22.

Table 2-22. Summary of Production Rates, Yields, and Converting Costs for Waste Paper Process using Brewer's Yeast

Feedstock Rate (metric ton/day)	2256
Ethanol Production (MM Gal. / Year)	77.4
Ethanol Yield (Gal / Dry US Ton Feedstock)	89.7
Total Equipment Cost (2009 $)	$124,500,000
Total Project Investment (2009 $)	$215,200,000
Waste Disposal ($/yr)	$4,200,000
Fixed Costs ($/yr)	$8,700,000
Minimum Ethanol Selling Price ($/gal)	$2.34

Lastly, the economic results for the yard waste process design are listed in Table 2-23. The total equipment cost and total project investment for yard waste are somewhat higher due to the addition of a steam gun.

Table 2-23. Summary of Production Rates, Yields, and Converting Costs for Yard waste Process using Brewer's Yeast

Feedstock Rate (metric ton/day)	2256
Ethanol Production (MM Gal. / Year)	20.0
Ethanol Yield (Gal / Dry US Ton Feedstock)	55.0
Total Equipment Cost (2009 $)	$123,500,000
Total Project Investment (2009 $)	$217,000,000
Waste Disposal ($/yr)	$400,000
Fixed Costs ($/yr)	$8,000,000
Minimum Ethanol Selling Price ($/gal)	$2.92

The three results summary tables for the Zymomonas case are shown in Table 2-24 through Table 2-26 . The yields tend to be slightly higher than in Tables 2-21 – 2-23 due to higher conversions in the fermentation process.

Table 2-24. Summary of Production Rates, Yields, and Converting Costs for MSW Process using Zymomonas

Feedstock Rate (metric ton/day)	2256
Ethanol Production (MM Gal. / Year)	84.1
Ethanol Yield (Gal / Dry US Ton Feedstock)	115.8
Total Equipment Cost (2009 $)	$93,700,000
Total Project Investment (2009 $)	$163,300,000
Waste Disposal ($/yr)	$3,600,000
Fixed Costs ($/yr)	$7,500,000
Minimum Ethanol Selling Price ($/gal)	$1.36

Table 2-25. Summary of Production Rates, Yields, and Converting Costs for Waste Paper Process using Zymomonas

Feedstock Rate (metric ton/day)	2256
Ethanol Production (MM Gal. / Year)	84.8
Ethanol Yield (Gal / Dry US Ton Feedstock)	98.2
Total Equipment Cost (2009 $)	$121,100,000
Total Project Investment (2009 $)	$209,700,000
Waste Disposal ($/yr)	$4,200,000
Fixed Costs ($/yr)	$8,600,000
Minimum Ethanol Selling Price ($/gal)	$2.15

Table 2-26. Summary of Production Rates, Yields, and Converting Costs for Yard waste Process using Zymomonas

Feedstock Rate (metric ton/day)	2256
Ethanol Production (MM Gal. / Year)	26.3
Ethanol Yield (Gal / Dry US Ton Feedstock)	72.4
Total Equipment Cost (2009 $)	$120,600,000
Total Project Investment (2009 $)	$212,200,000
Waste Disposal ($/yr)	$400,000
Fixed Costs ($/yr)	$7,900,000
Minimum Ethanol Selling Price ($/gal)	$2.25

Discussion

The lowest yield and highest minimum selling price in both the Brewer's yeast and Zymomonas cases are for the yard waste case. This is largely due to the low 41% conversion of glucose to ethanol in the fermentation step. The high lignin content and relatively low cellulose content make the sugars less accessible for fermentation and therefore the process has lower yields. It is possible that once the process is optimized that these yields may be improved drastically.

In contrast, the highest yields and lowest minimum selling price is associated with the solids waste in each case. The sugars in this case are easily accessible and lignin content is low resulting in higher overall yields.

Overall, the use of Zymomonas bacteria will result in slightly higher yields and lower prices. This is due to the fermentation of sugars otherwise inaccessible by Brewer's yeast. It is unclear if Zymomonas would perform as well as the time tested Brewer's yeast in a commercial operation.

Overall the economic analysis suggests that conversion of municipal waste is economically viable. Further economic analysis would be required, however, for a more definitive conclusion. For example, more accurate capital cost estimates can be made especially in the case of the steam gun in the yard waste case. Also, the cost of raw materials could be more accurately estimated by factoring in transportation costs. It is recommended that these details be well established to improve the accuracy of the economic results.

Recommendations & Conclusion

The LCA modeled is presented as a "what-if" scenario. It looks retrospectively at Washington's waste management strategies and analyses what would happen if the waste was treated by sending it to a lignocellulosic biorefinery. Each waste management strategy, including landfill, has the potential to create a product that could avoid the production of another similar product. Compost can replace fertilizer, recycle waste paper can replace virgin pulp and forestry operations, landfilled waste can generate landfill gas, which can be combusted for electricity production. The question is whether, avoiding corn ethanol production with lignocellulosic ethanol has a greater benefit than the others. From our analysis we can make several conclusions and recommendations:

1. Municipal solid waste seems to offer the greatest potential as both a waste management strategy and for bio-fuel production. With over 4 million metric tons of MSW generated in 2007, there is enough lignocellulosic material available to meet the demands of a large capacity biorefinery within the State.
2. The greatest contributor to ethanol production environmental flows is chemicals production, specifically lime production. On the other hand, avoidance of dry-mill corn ethanol greatly reduces the environmental flows for ethanol production.
3. Landfilled waste offers the least benefit overall, even with production of electricity and avoidance of Washington electric grid. This is related to the fact that the Washington electric grid is largely dominated by clean hydropower and offers little benefit from avoidance.

Based on these conclusions and the findings from the LCA it is recommended that bio-fuel production from lignocellulosic rich MSW should be pursued over the other waste streams. Mixed waste paper, although has benefits for ethanol production, seems to have greater benefits for replacing virgin pulp. Likewise yard waste seems to offer greatest benefits as a compost than as solely as an ethanol fuel source. It is also possible that some combination of the waste streams be used.

The LCA is incomplete as it does not include all possible environmental flows and is only restricted to nine air emissions and total energy. Furthermore, it does not include all possible technology for ethanol production, composting, and especially for recycling.

The process economic analysis suggests that the conversion of MSW to ethanol is economically viable. The ease of conversion and good process yields for this raw material results in reasonable minimum ethanol selling prices even when using conventional Brewer’s yeast as a fermentation organism.

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Appendix A: LCI data results

		High Generation Region			Medium Generation Region			Low Generation Region		
	Units	MSW Collection	Recycle Collection	Yard Waste Collection	MSW Collection	Recycle Collection	Yard Waste Collection	MSW Collection	Recycle Collection	Yard Waste Collection
Total Energy	BTU	-95,235	-354,220	-156,402	-190,082	-568,617	-228,035	-739,526	-4,115,966	-436,730
CO2	g	4,171	24,329	2,701	9,839	39,323	3,554	49,999	307,191	14,805
CH4	g	8.47	31.8	13.8	17.0	51.1	20.0	66.4	370.4	38.7
N2O	g	0.15	0.68	0.17	0.32	1.10	0.25	1.42	8.34	0.60
NMVOC	g	1.37	2.93	3.28	2.37	4.63	4.88	6.31	27.9	7.37
CO	g	143	972	27	361	1,573	20	1,989	12,515	438
NOx	g	165	1,113	35	415	1,802	29	2,279	14,325	509
PM10	g	3.8	23.2	2.0	9.1	37.5	2.6	47.6	294	13.1
PM2.5	g	0.33	1.16	0.57	0.65	1.87	0.84	2.44	13.3	1.55
SOx	g	1.86	6.67	3.17	3.67	10.7	4.63	14.0	76.9	8.64

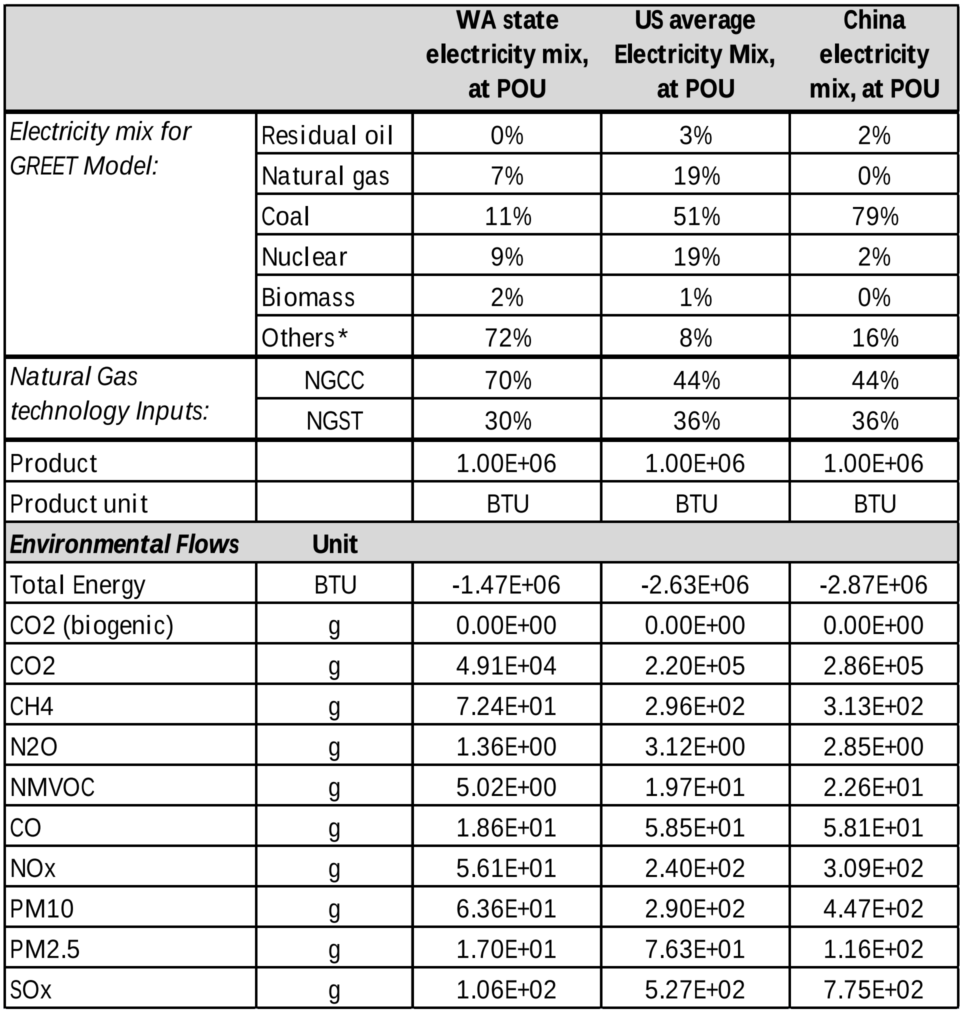
	Units	Large Transfer Station	Medium Transfer Station	Small Transfer Station	Large Trasnfer Station w/ Rail-yard	Material Recovery Facility
Total Energy	BTU	-358,267	-39,140	-57,312	-403,432	-31,388
CO2	g	23,426	778	1,139	26,788	913
CH4	g	27.8	1.15	1.68	31.7	2.74
N2O	g	0.094	0.021	0.031	0.103	0.006
NMVOC	g	2.06	0.08	0.12	2.35	0.20
CO	g	6.43	0.29	0.43	7.33	0.74
NOx	g	100	0.89	1.30	115	4.06
PM10	g	6.27	1.01	1.47	6.99	0.32
PM2.5	g	3.75	0.27	0.39	4.25	0.18
SOx	g	7.88	1.68	2.46	8.68	0.56

		Landfilling			Composting	Ethanol Production		
	Units	Landfill Daily Operatons	Landfill Gas Generation/ Collection	Waste Water Treatment	Compost Operations	MSW Conversion to Ethanol	MWP Conversion to Ethanol	Yard Waste Conversion to Ethanol
Total Energy*	BTU	-116,443	251,799	-10,981	-495,512	-1,427,126	-802,027	369,128
CO2 (Bio)**	g	0	103,805	870	237,483	2,117	847	2.0
CO2	g	8,711	0	280	29,634	157,386	231,308	19,454
CH4	g	10.8	16,505	0.41	42.5	165	226	24.5
N2O	g	0.036	0	0.01	0.43	1.91	2.28	0.31
NMVOC	g	0.83	0	0.17	9.40	26.0	34.7	11.8
CO	g	2.45	536	0.23	35.6	87.6	124	30.6
NOx	g	34.7	173	0.40	125	254	361	77.8
PM10	g	2.53	36	0.29	5.96	817	1,448	73.4
PM2.5	g	1.50	0	0.089	3.27	28.1	38.5	-0.25
SOx	g	4.14	9.9	1.43	11.3	1,174	2,067	685

	Units	ONP Recycling, in WA	Softwood Logs Production, in PNW	Pulp Chips from Green Lumber, in PNW	Pulp Chips from dry veneer, in PNW	Pulp chips from chip mill, in PNW	TMP Production, in WA
Total Energy	BTU	-5,393,538	-18,021	-603,542	-12,303,319	-554,993	-25,906,215
CO2 (Bio)*	g	0	829,263	1,758,745	36,347,306	2,056,240	10,870,453
CO2	g	182,389	1,318	13,615	406,510	17,838	676,759
CH4	g	426	8.71	38.3	840	40.9	886
N2O	g	4.06	0.084	0.47	11.1	0.49	25.9
NMVOC	g	23.0	0.89	7.39	74.0	3.65	79.1
CO	g	84.8	1.28	7.16	179	8.34	315
NOx	g	249	3.76	21.6	598	27.2	822
PM10	g	100	0.78	16.6	488	16.4	697
PM2.5	g	31.6	0.31	4.34	143	6.39	194
SOx	g	176	2.26	27.7	540	25.7	1,077

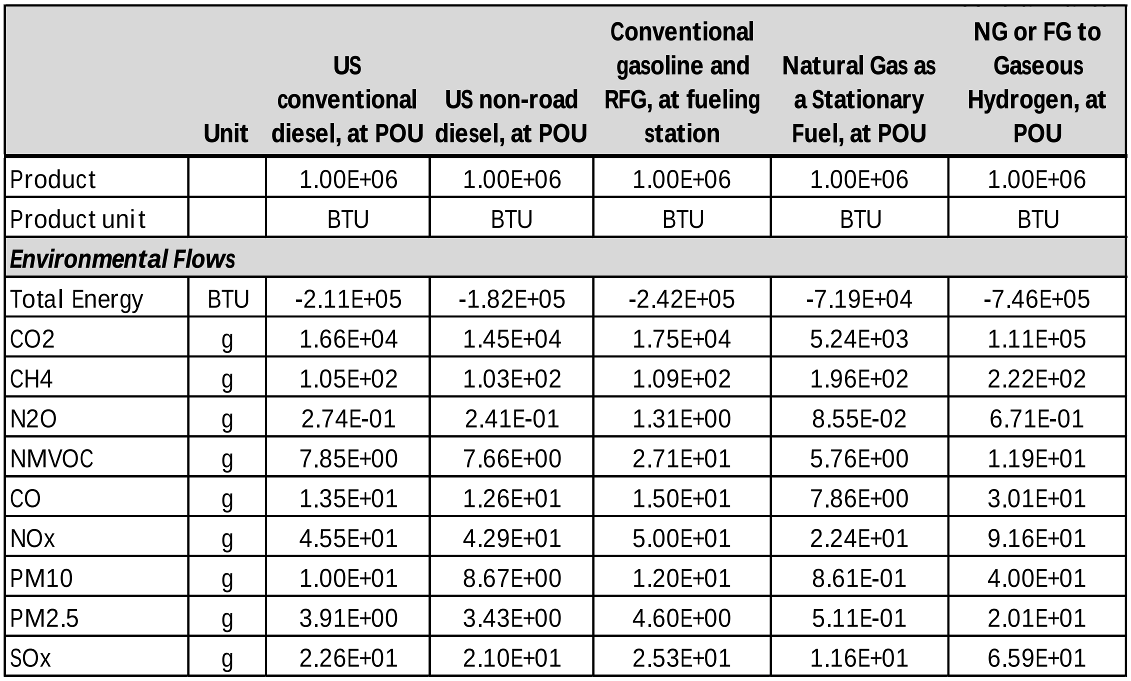
	Units	Soda Ash Production, US average	NaOH production, US Average*	Peroxide production, US average	Lime production, US average	CSL production, US average*	Ammonia Phosphate production, US average	Enzyme production, in WA
Total Energy	BTU	-8,092,566	-15,418,359	-13,273,126	-19,531,601	-1,972,770	-1,498,244	-175,153
CO2	g	796,561	1,140,530	845,454	3,607,881	168,879	79,485	88,044
CH4	g	1,362	1,914	1,684	3,028	286	180	13.0
N2O	g	13.4	16.8	5.14	28.4	18.9	1.39	0.35
NMVOC	g	154	103	90.3	223	107	18.4	21.6
CO	g	594	390	229	1,483	265	69.6	22.3
NOx	g	1,587	1,289	698	4,179	563	179	15.9
PM10	g	802	1,013	307	24,273	142	74.8	4.01
PM2.5	g	226	290	153	675	55.0	21.0	1.46
SOx	g	1,479	2,008	507	6,675	447	137	11.5

Appendix B: GREET LCI Data



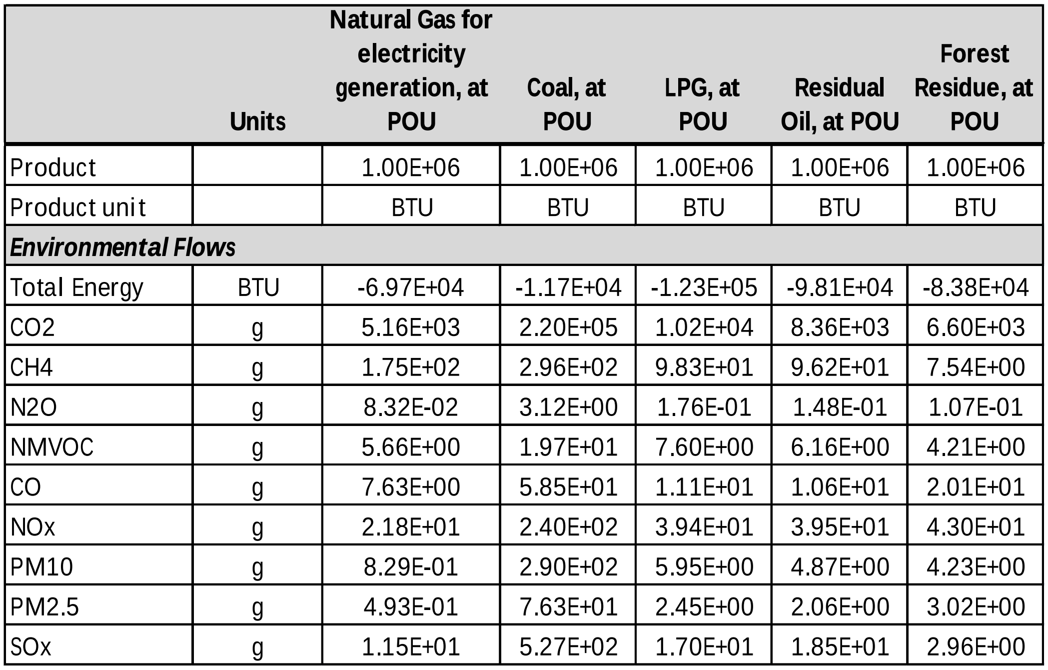
		WA state electricity mix, at POU	US average Electricity Mix, at POU	China electricity mix, at POU
Electricity mix for GREET Model:	Residual oil	0%	3%	2%
	Natural gas	7%	19%	0%
	Coal	11%	51%	79%
	Nuclear	9%	19%	2%
	Biomass	2%	1%	0%
	Others*	72%	8%	16%
Natural Gas technology Inputs:	NGCC	70%	44%	44%
	NGST	30%	36%	36%
Product		1.00E+06	1.00E+06	1.00E+06
Product unit		BTU	BTU	BTU
Environmental Flows	**Unit**			
Total Energy	BTU	-1.47E+06	-2.63E+06	-2.87E+06
CO2 (biogenic)	g	0.00E+00	0.00E+00	0.00E+00
CO2	g	4.91E+04	2.20E+05	2.86E+05
CH4	g	7.24E+01	2.96E+02	3.13E+02
N2O	g	1.36E+00	3.12E+00	2.85E+00
NMVOC	g	5.02E+00	1.97E+01	2.26E+01
CO	g	1.86E+01	5.85E+01	5.81E+01
NOx	g	5.61E+01	2.40E+02	3.09E+02
PM10	g	6.36E+01	2.90E+02	4.47E+02
PM2.5	g	1.70E+01	7.63E+01	1.16E+02
SOx	g	1.06E+02	5.27E+02	7.75E+02

Figure 2- 25: GREET LCI data for electricity production.



	Unit	US conventional diesel, at POU	US non-road diesel, at POU	Conventional gasoline and RFG, at fueling station	Natural Gas as a Stationary Fuel, at POU	NG or FG to Gaseous Hydrogen, at POU
Product		1.00E+06	1.00E+06	1.00E+06	1.00E+06	1.00E+06
Product unit		BTU	BTU	BTU	BTU	BTU
Environmental Flows						
Total Energy	BTU	-2.11E+05	-1.82E+05	-2.42E+05	-7.19E+04	-7.46E+05
CO2	g	1.66E+04	1.45E+04	1.75E+04	5.24E+03	1.11E+05
CH4	g	1.05E+02	1.03E+02	1.09E+02	1.96E+02	2.22E+02
N2O	g	2.74E-01	2.41E-01	1.31E+00	8.55E-02	6.71E-01
NMVOC	g	7.85E+00	7.66E+00	2.71E+01	5.76E+00	1.19E+01
CO	g	1.35E+01	1.26E+01	1.50E+01	7.86E+00	3.01E+01
NOx	g	4.55E+01	4.29E+01	5.00E+01	2.24E+01	9.16E+01
PM10	g	1.00E+01	8.67E+00	1.20E+01	8.61E-01	4.00E+01
PM2.5	g	3.91E+00	3.43E+00	4.60E+00	5.11E-01	2.01E+01
SOx	g	2.26E+01	2.10E+01	2.53E+01	1.16E+01	6.59E+01

Figure 2- 26: GREET LCI data for fuel production.



	Units	Natural Gas for electricity generation, at POU	Coal, at POU	LPG, at POU	Residual Oil, at POU	Forest Residue, at POU
Product		1.00E+06	1.00E+06	1.00E+06	1.00E+06	1.00E+06
Product unit		BTU	BTU	BTU	BTU	BTU
Environmental Flows						
Total Energy	BTU	-6.97E+04	-1.17E+04	-1.23E+05	-9.81E+04	-8.38E+04
CO2	g	5.16E+03	2.20E+05	1.02E+04	8.36E+03	6.60E+03
CH4	g	1.75E+02	2.96E+02	9.83E+01	9.62E+01	7.54E+00
N2O	g	8.32E-02	3.12E+00	1.76E-01	1.48E-01	1.07E-01
NMVOC	g	5.66E+00	1.97E+01	7.60E+00	6.16E+00	4.21E+00
CO	g	7.63E+00	5.85E+01	1.11E+01	1.06E+01	2.01E+01
NOx	g	2.18E+01	2.40E+02	3.94E+01	3.95E+01	4.30E+01
PM10	g	8.29E-01	2.90E+02	5.95E+00	4.87E+00	4.23E+00
PM2.5	g	4.93E-01	7.63E+01	2.45E+00	2.06E+00	3.02E+00
SOx	g	1.15E+01	5.27E+02	1.70E+01	1.85E+01	2.96E+00

Figure 2- 27: GREET LCI data for fuel Production.

	Units	Life Cycle of HDPE Production	Life Cycle of CaCO3 Production	Life Cycle of Sulfuric Acid Production	Life Cycle of Ammonia Production	Life Cycle of Urea	Life Cycle of Ammonium Nitrate	Life Cycle of Phosphoric Acid Production	Life Cycle of Potash Production	Life Cycle of CaCO3	Life Cycle of Herbicide for corn	Life Cycle of Insecticide for corn
Product		1	1	1	1	1	1	1	1	1	1	1
Product unit		ton	ton	ton	ton	ton	ton	ton	ton	g	g	g
Electricity Mix		US Average	US Average	US Average	US Average	US Average	US Average	US Average	US Average	US Average	US Average	US Average
Environmental Flows												
Total Energy	BTU	-4.60E+07	-7.00E+06	-5.57E+05	-3.19E+07	-2.14E+07	-1.96E+07	-1.21E+07	-7.65E+06	-7.71E+00	-2.64E+02	-3.14E+02
CO2	g	3.54E+06	5.50E+05	4.47E+04	1.91E+06	6.40E+05	1.21E+06	8.94E+05	6.02E+05	6.06E-01	2.07E+01	2.42E+01
CH4	g	5.87E+03	8.31E+02	5.86E+01	1.87E+03	1.58E+03	1.33E+03	1.61E+03	8.89E+02	9.15E-04	3.00E-02	3.55E-02
N2O	g	4.29E+01	7.76E+00	9.10E-01	1.38E+01	1.22E+01	6.25E+03	1.67E+01	9.12E+00	8.55E-06	2.39E-04	3.10E-04
NMVOC	g	5.01E+02	6.80E+01	2.47E+01	4.41E+03	2.57E+03	2.43E+03	3.36E+02	1.10E+02	7.48E-05	2.54E-03	3.75E-03
CO	g	1.05E+03	2.44E+02	8.16E+01	4.04E+03	2.54E+03	2.47E+03	1.15E+03	3.95E+02	2.69E-04	9.56E-03	1.46E-02
NOx	g	4.81E+03	7.82E+02	5.28E+02	1.60E+03	2.15E+03	3.24E+03	6.54E+03	1.68E+03	8.61E-04	3.37E-02	4.25E-02
PM10	g	2.63E+03	5.44E+02	3.36E+01	3.80E+02	3.94E+02	1.39E+03	1.56E+03	5.72E+02	6.00E-04	1.64E-02	1.87E-02
PM2.5	g	9.66E+02	1.82E+02	1.58E+01	1.31E+02	1.95E+02	9.75E+02	9.57E+02	2.02E+02	2.00E-04	7.47E-03	8.86E-03
SOx	g	6.55E+03	9.05E+02	1.83E+04	9.85E+02	1.11E+03	1.36E+03	5.79E+04	1.26E+03	9.96E-04	3.19E-02	2.46E-02

	Units	Diesel Fuel burned in a Industrial Boiler: urban facility, at POU	Natural Gas burned in a Utility/Industrial Boiler (>100 mmBtu/hr input): urban facility	Natural Gas burned in a CC Gas Turbine: urban facility, at POU	Coal burned in a Utility Boiler: urban facility, at POU	LPG burned in a Industrial Boiler: urban facility	Residual Oil burned in a Industrial Boiler: urban facility, at POU	Forest Residue burned in a Large Industrial Boiler: urban facility, at POU
Product		1.00E+06	1.00E+06	1.00E+06	1.00E+06	1.00E+06	1.00E+06	-1.00E+06
Product unit		BTU	BTU	BTU	BTU	BTU	BTU	BTU
US conventional diesel, at POU	BTU	-1.00E+06						
Natural Gas as a Stationary Fuel, at POU	BTU		-1.00E+06	-1.00E+06				
Coal, at POU	BTU				-1.00E+06			
LPG, at POU	BTU					-1.00E+06		
Residual Oil, at POU	BTU						-1.00E+06	
Forest Residue, at POU	BTU							-1.00E+06
Environmental Flows								
Total Energy	BTU	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
CO2	g	7.82E+04	5.94E+04	5.94E+04	1.08E+05	6.80E+04	8.50E+04	1.30E+05
CH4	g	1.80E-01	1.10E+00	4.26E+00	1.20E+00	1.08E+00	3.24E+00	3.83E+00
N2O	g	3.90E-01	1.10E+00	1.50E+00	1.06E+00	4.86E+00	3.60E-01	1.10E+01
NMVOC	g	1.17E+00	1.56E+00	3.43E+00	1.14E+00	1.89E+00	9.07E-01	5.34E+00
CO	g	1.67E+01	1.64E+01	2.40E+01	1.00E+02	1.84E+01	1.58E+01	7.68E+01
NOx	g	8.22E+01	5.76E+01	1.60E+01	1.06E+02	7.16E+01	1.25E+02	1.10E+02
PM10	g	4.25E+01	3.21E+00	2.00E+00	1.00E+01	3.24E+00	4.44E+01	1.27E+01
PM2.5	g	3.80E+01	3.21E+00	2.00E+00	5.00E+00	3.24E+00	2.89E+01	6.33E+00
SOx	g	0.00E+00	0.00E+00	0.00E+00	2.29E+02	0.00E+00	2.03E+02	4.10E+00

		Transport by Diesel Freight Train (US)	Cargo Ships, 45,000 dwt- 80% load	Transport by Medium-Heavy Truck- class 6 or 7 (8 ton cargo), 7.3mpg, 100% load, Fronthaul	Transport by Heavy-Heavy Truck- class 8a or 8b (20 ton cargo), 5.0mpg, 100% load, Fronthaul	Transport by Medium-Heavy Truck- class 6 or 7 (8 ton cargo), 7.3mpg, 0% load, Backhual	Transport by Heavy-Heavy Truck- class 8a or 8b (20 ton cargo), 5.0mpg, 0% load, Backhaul
Product		1	1	1	1	1	1
Product unit		kg-km	kg-km	kg-km	kg-km	kg-km	kg-km
US conventional diesel, at POU				-1.51E+00	-8.80E-01	-1.02E+00	-5.98E-01
US non-road diesel, at POU		-2.53E-01					
Residual Oil, at POU			-8.51E-02				
Environmental Flows							
Total Energy	BTU	-2.53E-01	-8.51E-02	-1.51E+00	-8.80E-01	-1.02E+00	-5.98E-01
CO2	g	1.97E-02	7.22E-03	1.17E-01	6.85E-02	7.98E-02	4.66E-02
CH4	g	9.99E-07	4.88E-08	2.31E-06	1.37E-06	1.57E-06	9.32E-07
N2O	g	5.07E-07	1.70E-07	4.37E-06	1.76E-06	2.97E-06	1.20E-06
NMVOC	g	1.87E-05	9.97E-07	4.84E-05	2.96E-05	3.29E-05	2.01E-05
CO	g	5.41E-05	1.07E-05	1.75E-04	1.57E-04	1.19E-04	1.07E-04
NOx	g	3.84E-04	1.08E-04	4.47E-04	3.23E-04	3.04E-04	2.20E-04
PM10	g	9.11E-06	2.68E-06	1.19E-05	6.63E-06	8.12E-06	4.51E-06
PM2.5	g	8.20E-06	1.34E-06	1.10E-05	6.10E-06	7.47E-06	4.15E-06
SOx	g	2.04E-06	1.27E-04	1.49E-05	8.68E-06	1.01E-05	5.90E-06

Appendix C: Equipment Emission Factors

			Emissions (g/hp-hr)						
Engine Power (hp)	**Technology Type**	**BSFC (lb/hp-hr)**	**HC**	**CO**	**NOX**	**PM10**	**PM2.5**	**SO2**	**CO2**
>0 to 11	Tier 4A	0.408	0.557	4.367	4.314	0.316	0.307	0.000588	588.6
	Tier 4B	0.408	0.557	4.367	4.314	0.316	0.307	0.000588	588.6
>11 to 16	Tier 4A	0.408	0.443	2.295	4.454	0.316	0.307	0.000588	589.0
	Tier 4B	0.408	0.443	2.295	4.454	0.316	0.307	0.000588	589.0
>16 to 25	Tier 4A	0.408	0.443	2.295	4.454	0.316	0.307	0.000588	589.0
	Tier 4B	0.408	0.443	2.295	4.454	0.316	0.307	0.000588	589.0
>25 to 50	Tier 4A	0.408	0.282	1.627	4.743	0.199	0.193	0.000589	589.5
	Tier 4	0.408	0.133	0.162	3.010	0.069	0.067	0.000589	589.9
>25 to 75	Tier 4A	0.408	0.186	2.512	3.010	0.199	0.193	0.000589	589.8
	Tier 4	0.408	0.133	0.252	3.010	0.069	0.067	0.000589	589.9
>75 to 100	Tier 4	0.408	0.133	0.252	3.010	0.082	0.080	0.000589	589.9
	Tier 4N	0.408	0.133	0.252	0.277	0.082	0.080	0.000589	589.9
>100 to 175	Tier 4	0.367	0.133	0.092	2.508	0.073	0.071	0.00053	530.6
	Tier 4N	0.367	0.133	0.092	0.277	0.073	0.071	0.00053	530.6
>175 to 300	Tier 4	0.367	0.133	0.080	2.508	0.073	0.071	0.00053	530.6
	Tier 4N	0.367	0.133	0.080	0.277	0.073	0.071	0.00053	530.6
>300 to 600	Tier 4	0.367	0.133	0.089	2.508	0.073	0.071	0.00053	530.6
	Tier 4N	0.367	0.133	0.089	0.277	0.073	0.071	0.00053	530.6
>600 to 750	Tier 4	0.367	0.133	0.141	2.508	0.073	0.071	0.00053	530.6
	Tier 4N	0.367	0.133	0.141	0.277	0.073	0.071	0.00053	530.6
>750	Tier 4	0.367	0.285	0.081	2.400	0.015	0.015	0.00053	530.1
except gen sets	Tier 4N	0.367	0.133	0.081	2.400	0.046	0.044	0.00053	530.6
>750 to 1200	Tier 4	0.367	0.285	0.081	2.400	0.015	0.015	0.00053	530.1
gen sets	Tier 4N	0.367	0.133	0.081	0.462	0.059	0.057	0.00053	530.6
>1200	Tier 4	0.367	0.285	0.081	0.462	0.015	0.015	0.00053	530.1
gen sets	Tier 4N	0.367	0.133	0.081	0.462	0.059	0.057	0.00053	530.6