Duke University Nicholas School of the Environment

Garbage to Gasoline: Converting Municipal Solid Waste to Liquid Fuels

Technologies, Commercialization, and Policy

Maura Farver and Christopher Frantz

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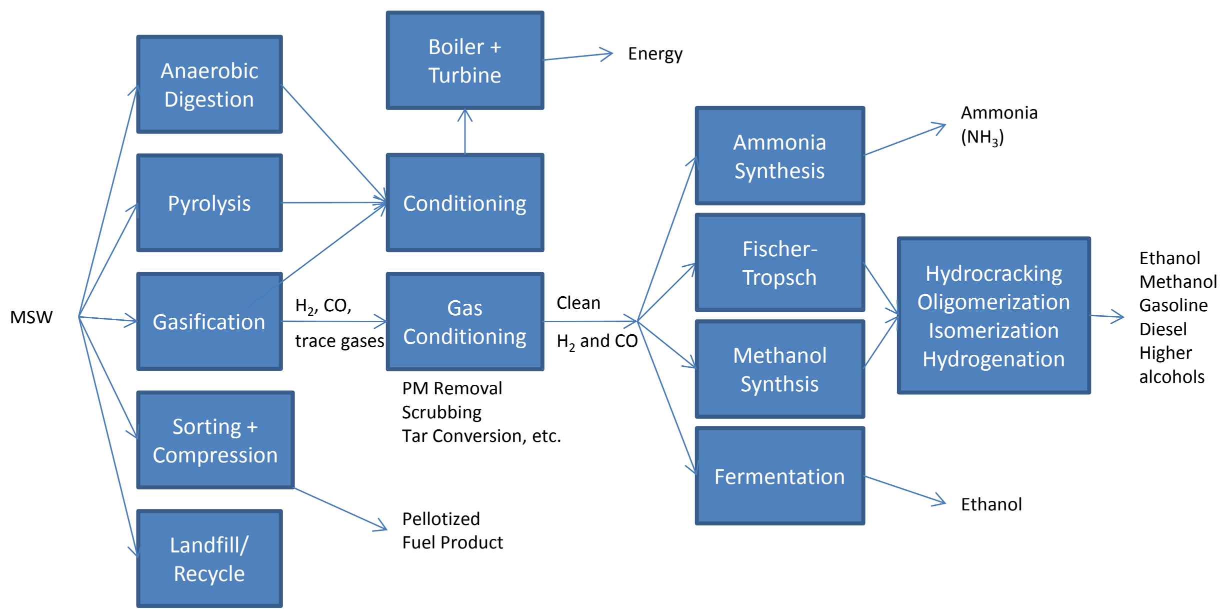
Abstract

Liquid fuels are in high demand throughout the United States and crude oil is a finite resource. With strain on conventional sources for liquid fuels, the unconventional sources and new technologies to create liquid fuels are becoming more attractive as alternative options. One such conversion technology uses municipal solid waste (MSW) as the feedstock, offering the additional benefit of relief on another constrained resource: landfills. This paper provides an overview of the principal technologies that are being used to convert MSW to salable products and delves deeply into the potential for facilities that gasify MSW and convert the synthetic gas (syngas) to ethanol, diesel, or gasoline. The analysis also includes a financial model that assesses the financial viability of such a project under many different conditions, including financing choices (debt to equity ratio, project location, and interest rates). The results of the financial model indicate that sorting costs, tipping fees, and fuel prices have the largest effect on the financial viability of the project. In order to make an adequate internal rate of return, fuel prices need to be high and the project needs to be located in a region with high tipping fees. Other factors not accounted for in the model can also significantly impact the viability of this technology, including how the fuels are regulated under the Clean Air Act and which category they fall under with the Renewable Fuels Standard. These fuels are still relatively new to the market and the United States Environmental Protection Agency must clarify how they are defined and which regulations they are subject to. Having regulatory certainty will eliminate some risk for investors and will therefore make investing in MSW to liquid fuels conversion projects more attractive in the future.

Introduction

Liquid fuels are in high demand throughout the United States for uses such as transportation, industrial processes, and electricity generation. Americans consumed around 134 billion gallons of gasoline alone in 2011.[1] Crude oil is a finite resource, though, and proven oil reserves are being depleted worldwide. With strain on conventional sources for liquid fuels, the unconventional sources and new conversion technologies to create liquid fuels are becoming more attractive as the next best option. One such conversion technology uses municipal solid waste (MSW) as the feedstock, offering the additional benefit of relief on another constrained resource: landfills. Several types of commercially viable technologies converting MSW into salable products are currently in various stages of testing and piloting. These technologies can be placed in two general categories: 1. advanced sorting that can be combined with thermal treatment to produce a customizable solid fuel product (e.g. pellet), or 2. conversion of components of MSW to a gas (e.g., anaerobic digestion, pyrolysis, and gasification) that can be burned or refined further.



This paper provides an overview of the principal technologies that are being used to convert MSW to salable products (see the figure above) and delves deeply into the potential for facilities that gasify MSW and convert the synthetic gas (syngas) to ethanol, diesel, or gasoline. The analysis also includes a financial model that assesses the financial viability of such a project under many different conditions, including financing choices (debt to equity ratio, project location, and interest rates).

This particular conversion process (gasification of MSW with conversion to liquid fuel) was chosen as a focus because it turns the typical model for alternative transportation fuels on its head. Most alternative fuel refineries incur large feedstock costs that greatly affect the finances of the project.[2] Refining liquid fuels from MSW feedstock, however, allows the project to generate revenue from accepting the

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[1] (EIA, 2013)
[2] (Swanson, 2010)

feedstock itself because companies pay “tipping fees” to get rid of their garbage. Secondly, the process converting the syngas to the liquid fuel (called Fischer-Tropsch synthesis) allows the refinery to alter the end products (typically gasoline, diesel, or ethanol) by altering the pressure and temperature of the operating conditions. This flexibility will allow refineries to make adjustments in their output based on fluctuations in the market price of these end products. Third, Fischer-Tropsch synthesis is a highly exothermic reaction and the excess heat it gives off can be used to generate the power necessary to perform gasification at the beginning of the process, thereby greatly improving the efficiency of the system. In fact, there is so much power produced from the excess heat that the model shows a small amount of electricity being sold back to the grid. Lastly, this process has been demonstrated at a laboratory, pilot, and semi-commercial scale and there are several such commercial scale projects in the planning or construction phases. Analysis of a commercial scale plant is therefore timely and pertinent to this technology’s development.

The paper concludes with an analysis of the environmental risks and opportunities associated with this technology as well as the existing government policies that are shaping the industry and could impact it in the future. Reducing the amount of waste going to landfills is an exceptional benefit but this unique feedstock and process need further regulatory clarification from the United States Environmental Protection Agency (EPA). This paper is intended to analyze one promising technology on the verge of commercial scale and the financial, economic, and political drivers that may affect its success.

Conversion of MSW to Useful Gas

MSW can be converted to economically useful gas through three general processes: anaerobic digestion, pyrolysis, or gasification. These processes can exist in many variations, but an overview of each is provided below. The “Primary” products are those that the process is intended to produce for use onsite or sale. The “Secondary” products are byproducts that in some cases can be sold, but generally must be removed and disposed.

Process	**Description**	**Products**
Anaerobic Digestion	• Slow biological decomposition (roughly 5 to 15 days) • Usually involves the application of moderate temperature (35°C to 63°C) to biomass in oxygen starved environment • Can involve proprietary strains of bacteria/microorganisms • Feedstock is limited to biologically active organic waste (e.g., food) • Low capital and operating costs • Relatively low efficiency of converting waste to fuel	*Primary* • Methane (CH_4) *Secondary* • CO_2 • Compost/undigested biomass
Pyrolysis	• Thermo-chemical reaction • Requires application of medium temperature (400°C-500°C) to biomass in oxygen starved environment • Higher capital and operating costs than anaerobic digestion • Viscous liquid product requires substantially more cleaning before use than gasification products • Due to the cleanup, process is less economical than gasification if MSW is the feedstock	*Primary* • Bio-oil (up to 300 different compounds consisting of carbon, hydrogen and oxygen) *Secondary* • Char (solid carbon) • Water • Gas • Acid gases • Toxic metals • Polycyclic aromatic hydrocarbons (PAHs)
Gasification	• Thermo-chemical reaction • Requires high temperature (750°C-1500°C) and pressure in an oxygen starved environment • High capital and operating costs • High efficiency of turning waste to fuel • Can convert carbon with up to 98% to 99% efficiency (i.e., char is minimized) • Fewer pollution problems than pyrolysis	*Primary* • Synthetic gas or “syngas” (a combination of CO and H_2 in varying proportions) *Secondary* • CO_2 • Water vapor • CH_4 • Char and slag • Particulates, tars, alkali compounds, sulfur compounds, nitrogen compounds, and other contaminants

The focus of this paper is the emerging industry that takes the syngas product from gasification and converts it to more economically valuable products that can be transported and sold offsite (e.g., ethanol, gasoline, and diesel). Below is a detailed description of the gasification process. Detailed descriptions of anaerobic digestion and pyrolysis can be found in the Appendix.

Gasification

Overview

Gasification is a thermo-chemical reaction that requires high temperature (750^oC-1500^oC) and high pressure. "[I]t can be defined as a partial oxidation of the waste in presence of an oxidant amount lower than that required for the stoichiometric combustion."[3] First, a feedstock rich in carbon (sometimes referred to as carbonaceous) must be reduced in size (often accomplished with a chipper and hammer mill) and dried to reduce the amount of energy used in the gasifier for further drying. The feedstock is then placed in a gasifier under high temperature and pressure in the presence of air, steam, or oxygen. The carbonaceous material oxidizes (combines with oxygen) to produce synthesis gas (also known as syngas or producer gas) along with CO_2, CH_4, water vapor, char, slag, and trace gases that depend on the composition of the feedstock. Gasifiers are capable of converting the carbon from the feedstock into products with up to 99% efficiency (i.e., the production of char is minimal). The syngas is composed primarily of CO and H_2, and thus is much more uniform than the products of anaerobic digestion or pyrolysis. The process consists of four steps:

1. Drying – The feedstock is chipped and/or milled and then heated to remove all moisture.
2. Devolatization – The dried feedstock is heated to remove volatile matter.
3. Combustion – CO_2 and CO are formed from carbon and oxygen. This process is exothermic, providing the heat for the last step.
4. Reduction Reactions – The energy from the combustion step provides the energy necessary for four reduction reactions: the water gas reaction, the Boudouard reaction, the water-gas-shift reaction, and the methanation reaction.[4]

$$C + H_2O \rightarrow CO + H_2\ (Water\ Gas)$$

$$C + CO_2 \rightarrow 2CO\ (Boudouard)$$

$$CO + H_2O \rightarrow CO_2 + H_2\ (Water - Gas - Shift)$$

$$CO + 3H_2 \rightarrow CH_4 + H_2O\ (Methanation)$$

The syngas that leaves the gasifier must go through a cleaning process because it contains particulates, tars, alkali compounds, sulfur compounds (e.g., hydrogen sulfide - H_2S), nitrogen compounds (e.g., ammonia – NH_3), and other contaminants, depending on the feedstock. These contaminants are of

[3] (Arena, 2012)
[4] (Swanson, 2010)

environmental concern and can damage catalysts that are used for further processes downstream. Typically, particulates are removed first using cyclones, in which larger particles fall to the bottom and gas rises to the top. Then the gas is cooled using either a heat exchanger or the injection of water. Tars can then be removed using scrubbing or catalytic conversion. Alkali compounds and ammonia can also be removed using wet-scrubbing. Sulfides are typically removed using chemical solvents, physical solvents, or catalytic sorbents.[5]

The different types of gasification are generally categorized "on the basis of oxidation medium."[6] Below are the mediums with which gasification can be accomplished. They are listed in the order of least to greatest energy content of the resulting syngas:

1. Partial oxidation with air
2. Oxygen enriched air or pure oxygen
3. Steam
4. Plasma gasification, which can control temperature regardless of whether oxygen is provided through air, pure oxygen, or steam. Plasma gasification has the added advantage of being able to accommodate varying feed rates, moisture content of feedstock, and size of feedstock.[7]

The main uses of syngas are direct burning on site to provide heat or energy, conversion to high value chemicals such as ammonia (NH_3), and conversion to liquid fuels such as gasoline or ethanol. For the production of energy, the syngas is burned in a gas turbine to power a generator. Additionally, the gas turbine can be coupled with a steam turbine to recover the excess heat. The combination of a gasifier, a gas turbine, and a steam turbine is referred to as integrated gasification combined cycle (IGCC) power generation.[8] The syngas is also suitable to be burned in a conventional burner or a more efficient reciprocating engine. The production of a uniform gas fuel as well as the potential to make further high value products makes gasification attractive for the treatment of unsorted downstream MSW as well as for more consistent waste streams.[9] The processes required for the liquid fuel conversions and the chemical conversions are described in detail in the following section.

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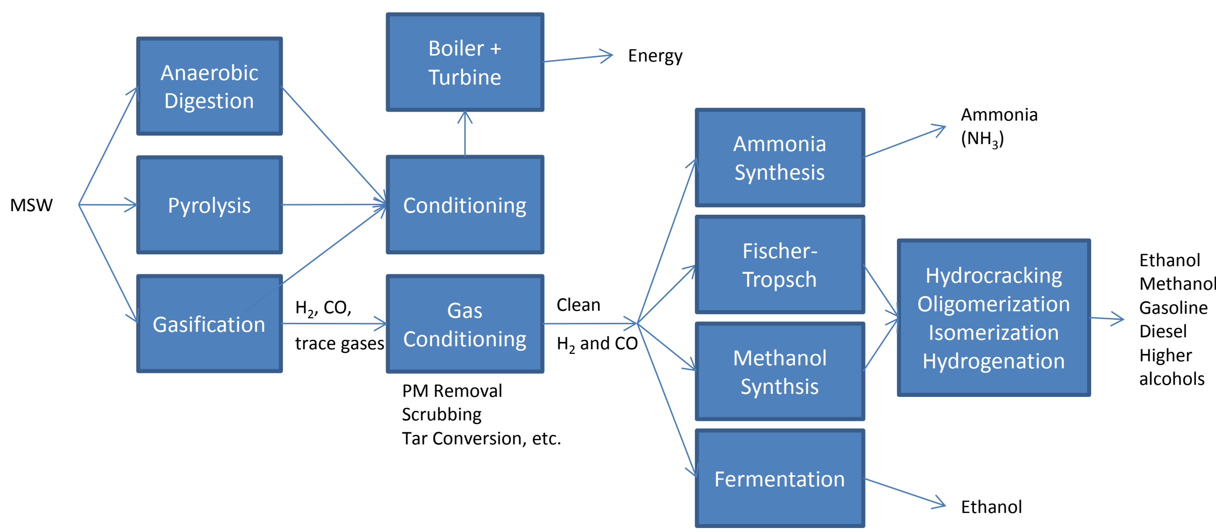
[5] (Swanson, 2010)
[6] (Arena, 2012)
[7] (Arena, 2012)
[8] (Swanson, 2010)
[9] (Arena, 2012)

Conversion of Syngas to Salable Products

Syngas, as described in the gasification section above, is composed primarily of CO and H_2. Syngas also contains trace gases and the amount of those trace gases depends on the composition of the gasification feedstock. This initial gasification step constitutes more than half the capital cost of a gas-to-liquids plant. In a conventional commercial plant that relies on syngas as a feedstock, the syngas is typically generated by steam-reforming natural gas, however, as discussed above, it can also be generated through the gasification of MSW.[10]

The syngas can be burned directly to generate energy or it can be refined into other, more valuable products such as ethanol or methanol. Additionally, the hydrogen could be separated out for use in a hydrogen turbine or fuel cell (but both of these technologies are not currently commercialized on a large scale). The most promising processes for the commercial scale conversion of syngas to products are ammonia synthesis, methanol synthesis, the Fischer-Tropsch process, and ethanol fermentation.[11] Ammonia synthesis, methanol synthesis, and the Fischer-Tropsch process have already been applied to syngas on a commercial scale (although not with MSW as a feedstock), and ethanol fermentation has been demonstrated on a pilot scale with commercial plants under development. The diagram below shows some of the common processes that can be applied to syngas in order to create salable products.



Note: There are other processes that can be applied to syngas to produce salable products. Those given above appear to be the most commercially viable at the current time.

Ammonia synthesis, methanol synthesis, and the Fischer-Tropsch Process are all synthesis reactions that occur under high temperatures and pressures in the presence of a catalyst. The reactants adsorb to the catalyst, rearrange themselves and combine in different ways, and then desorb from the catalyst. The catalyst plays a crucial role in the efficiency of these reactions and the optimization of product yields and, consequently, many companies have developed proprietary catalysts. These reactions also require

[10] (Spath, 2003)
[11] (Swanson, 2010)

a fairly pure syngas feedstock, which necessitates robust syngas conditioning prior to synthesis at a significant cost.[12]

Ethanol fermentation is fundamentally different from a catalytic synthesis reaction. Instead, the syngas is consumed by anaerobic bacteria to produce ethanol. The bacteria, like the catalyst in a synthesis reaction, is crucial to the efficiency of the process and thus has been a focus of research by the public and private sectors. Many private companies have developed proprietary strains of bacteria as well.

The primary products of these four processes are listed below. The Fischer-Tropsch process is discussed in detail in the following section, as it is the primary focus of this paper. Further detail on the alternative processes is given in the appendix.

Product	**Process**	**Primary Use**
Hydrogen	• Syngas conditioning	• Conversion to ammonia • Fuel cells and hydrogen engines (demand is small)
Ammonia	• Ammonia Synthesis	• Fertilizers
Methanol	• Methanol Synthesis • Fischer-Tropsch Process • Ethanol Fermentation (small amounts)	• One of the top chemicals produced in the world • Intermediate to fuels and chemicals (e.g., formaldehyde, dimethyl ether, and acetic acid) • Blended with gasoline (with cosolvent alcohol) • Transportation fuel (engine conversion necessary)
Ethanol	• Fischer-Tropsch Process • Ethanol Fermentation	• Blended with gasoline
Gasoline	• Fischer-Tropsch Process	• Transportation fuel
Diesel/Biodiesel	• Fischer-Tropsch Process	• Transportation fuel
Higher Alcohols	• Fischer-Tropsch Process • Oxosynthesis	• Blended to form gasoline with higher octane ratings • Solvents, detergents, flavorings, perfumes, and commodity chemicals
Waxes	• Fischer-Tropsch Process	• Broken down through hydrocracking into gasoline, diesel, ethanol, methanol, and higher alcohols

[12] (Swanson, 2010)

Fischer-Tropsch Process

Overview

The Fischer-Tropsch process synthesizes CO and H_2 into hydrocarbons by applying heat and pressure in the presence of a catalyst. Many companies have developed proprietary catalysts, however, transitional metals are commonly used (i.e., cobalt, iron, and ruthenium).

$$(2n+1)\,H_2 + nCO \rightarrow C_nH_{(2n+2)} + nH_2O\ (Paraffins)$$

$$2n\,H_2 + nCO \rightarrow C_nH_{2n} + nH_2O\ (Olefins)$$

$$2n\,H_2 + nCO \rightarrow C_nH_{(2n+1)}OH + (n-1)H_2O\ (Alcohols)$$

Modifications in heat, pressure and the catalyst allow companies to convert syngas into various liquid hydrocarbons, such as ethanol (C_2H_5OH), methanol (CH_3OH), jet fuel, wax, gasoline, diesel, and some higher alcohols.[13] Higher temperatures (300°C to 350°C) and an iron catalyst are used for the gasoline range products (shorter carbon chain). Lower temperatures (200°C to 240°C) and a cobalt catalyst are used for the diesel-wax range products (longer carbon chain). Both processes operate in the pressure range of 10 to 40 bar. The reaction is highly exothermic (produces heat), so heat removal is a crucial aspect of the reactor design.[14] The reacted gas is cooled and distilled in a process referred to as "upgrading" to separate these products. Hydrocracking, hydrotreating, and hydroisomerization can also be part of the "upgrading" process in order to maximize quantities of different products. Oxosynthesis can be used in combination with the Fischer-Tropsch process to combine CO and H_2 with olefins to form higher alcohols. It is catalyzed by cobalt or

Fischer-Tropsch Process

"The production of liquid hydrocarbons and oxygenates from syngas conversion over iron catalysts was discovered in 1923 by Fischer and Tropsch. Variations on this synthesis pathway were soon to follow for the selective production of methanol, mixed alcohols, and isosynthesis products. Another outgrowth of Fischer-Tropsch Synthesis (FTS) was the hydroformylation of olefins discovered in 1938. Many of the syngas conversion processes were developed in Germany during the first and second world wars at a time when natural resources were becoming scarce and alternative routes for hydrogen production, ammonia synthesis, and transportation fuels were a necessity." (Swanson, 2010)

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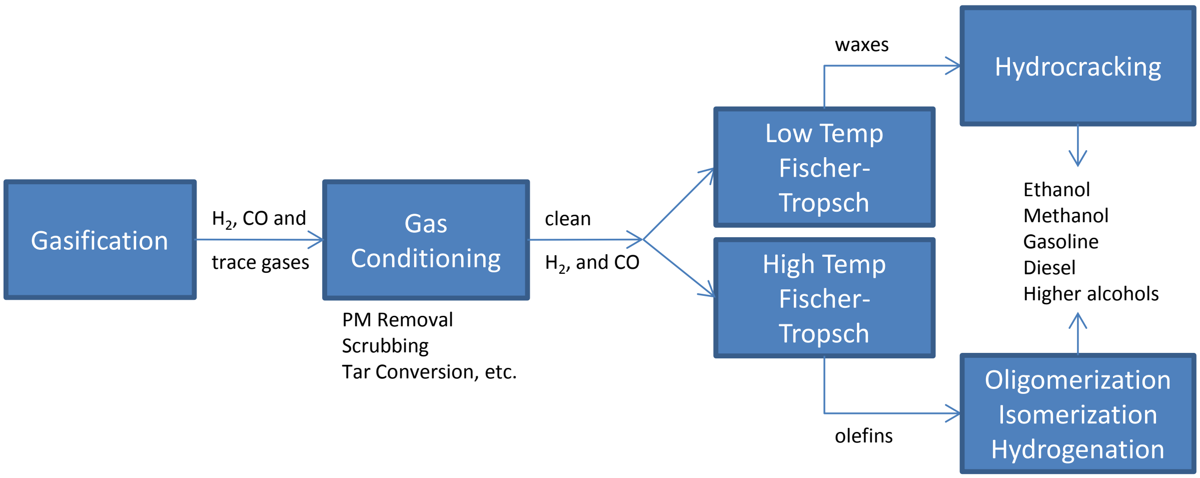
[13] Typical gasoline is a mixture of paraffins, naphthenes, and olefins in varying ratios. "Petroleum-derived diesel is composed of about 75% saturated hydrocarbons (primarily paraffins including n, iso, and cycloparaffins), and 25% aromatic hydrocarbons (including naphthalenes and alkylbenzenes).[24] The average chemical formula for common diesel fuel is $C_{12}H_{23}$, ranging approximately from $C_{10}H_{20}$ to $C_{15}H_{28}$."
http://www.atsdr.cdc.gov/toxprofiles/tp.asp?id=516&tid=91

[14] (Swanson, 2010)

rhodium and can produce solvents, detergents, flavorings, perfumes and commodity chemicals. The Fischer-Tropsch Process is so flexible that the Sasol I, Sasol II and Sasol III plants in South Africa produce over 200 fuel and chemical products.[15]



Energy Requirement

The Fischer-Tropsch Process is highly exothermic and thus can produce significant amounts of energy while manufacturing an array of products. If this process is coupled with gas and steam turbines (i.e., combined cycle) the process of generating liquid fuels from biomass can result in the net export of energy even after the high energy demand of gasifying biomass and cleaning the syngas. Swanson et. al. give estimates for two configurations of plants designed to gasify 2,000 dry metric tons of corn stover per day and then synthesize gasoline and diesel fuels. The study results in the net export of between 14 MW and 16 MW of power for these designs while producing between 32.3 million and 41.7 million gallons of gasoline equivalent per year.[16] Power production will vary based on many factors, including feedstock, plant size, gas processing needs, and products. It is clear, though, that these plants are capable of generating more power than they consume and thus can benefit from the added revenue of selling electricity back to the grid.

Liquid Fuel Products

As mentioned previously, the Fischer-Tropsch Process can be altered through changes in temperature, pressure, and catalyst to create different types of hydrocarbon chains (and hence different types of liquid fuels). The current market price of each product is an important factor in choosing which fuels to create but there are other key factors to consider when designing the plant. Changes to the mix once the plant is running are possible but may complicate long-term contracts with companies that are buying the products and will alter the catalyst costs and energy costs to the system.

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[15] (Spath, 2003)
[16] (Swanson, 2010)

Financial Analysis of a MSW to Liquid Fuel Project

As noted in the introduction above, this model explores the financial viability of a project that converts MSW to diesel, gasoline, or ethanol through first gasifying the MSW and then converting the syngas to liquid fuels through the Fischer-Tropsch process. This particular project type has many financial advantages:

1. Refining transportation fuels from a MSW feedstock actually allows the project to generate revenue from accepting the feedstock, because the project can charge a fee to accept the MSW that other companies are seeking to dispose of at a small discount over local tipping fees. Feedstock is normally a substantial cost for alternative fuels project but for this technology, it is actually a revenue stream.
2. Fischer-Tropsch synthesis allows the refinery to produce gasoline, diesel, or ethanol depending on the operating conditions and catalysts used. This flexibility will allow refineries to make adjustments in their output based on fluctuations in the market price of these end-products.
3. Fischer-Tropsch synthesis is a highly exothermic reaction and that excess heat can be used to generate the power necessary to perform gasification at the beginning of the process.
4. This process has been demonstrated at a laboratory, pilot, and semi-commercial scale so the proof of concept is well underway and feasible. There are several such commercial scale projects in the planning or construction phases.

This model evaluates the financial viability of this type of project under varying economic circumstances. There are many different ways to design this type of plant, and the scenario described below is not necessarily the best design for every circumstance. The focus was to choose a configuration that involves commercially available technology, can produce fuel at commercial scale volumes, can handle a broad range of MSW, and is financially tenable. That configuration was then used to identify the most important financial factors for this type of technology.

Model Methodology

This financial model is primarily based on the paper by Swanson et. al. titled "Techno-Economic Analysis of Biofuels Production Based on Gasification." This study is part of a large collection of studies that the Department of Energy (DOE) National Renewable Energy Laboratory has conducted in order to assess the financial viability of different renewable energy technologies. The plant structure that is examined in Swanson et. al. is similar to several commercial scale plants currently in the planning stages including Enerkem's Pontotoc, MS plant, Ineos Bio's Vero Beach, FL plant and, Fulcrum BioEnergy's McCarren, NV plant (details on these projects can be found in the Appendix). The notable exception between the paper and these planned projects is that the model in the paper uses a feedstock of corn stover rather than MSW. Additionally, the Swanson et. al. model takes a conservative approach that is appropriate given the youth of this industry and the potential unexpected hurdles that may emerge as this technologies are brought to a commercial scale. Swanson et. al. used three criteria when designing the scenario being modeled:

1. The technologies should be, at a minimum, available at a commercial scale in 5-8 years.

2. The refinery size should be a reasonable size given the limitations of feedstock access; the refinery should not be too large given the limitations of obtaining enough feedstock for the plant to run relatively continuously.
3. The end product of the refinery should be compatible with the current fleet of transportation vehicles. No changes in technology are required by the end users.

A model with these conservative assumptions is an excellent base from which to develop a financial model suitable for a MSW to gasoline plant.

The model costs are also based on an "nth Plant Scenario," which means the costs are on a project that is not the first of its type (i.e. a pioneer plant). The use of the "nth Plant Scenario" is appropriate, because it is intended to focus on the viability of this project type in the long term. Since this study is intended to assess the long-term viability of this industry, a model based on the "nth Plant Scenario" is more appropriate than a model based on a pioneer plant.

The largest difference between the two modeled scenarios is that the Swanson et. al. scenario uses only corn stover as a feedstock, while the model developed in this paper assumes a feedstock of MSW. This change results in several key differences between the two models, including the cost of the feedstock (or revenue from feedstock), the required pretreatment of the feedstock, the efficiency of the system (i.e. gallons of end product per ton of feedstock) and modifications to the emissions control technologies needed for the gasification step.

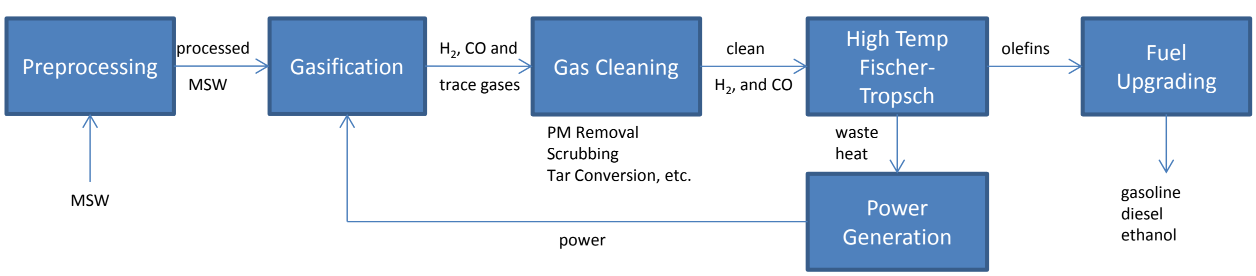
The following sections discuss the design of the modeled plant, capital costs, operating costs, and other financial parameters necessary for the model.

Plant Design

The plant consists of six key stages:

1. Feedstock Preprocessing
2. Gasification
3. Syngas Cleaning and Upgrading
4. Fischer-Tropsch Synthesis
5. Power Generation
6. Fuel Upgrading/Hydroprocessing

Modeled Plant



Each one of these stages is discussed separately in more detail below.

Feedstock Preprocessing

The particular type of gasifier used in this model, called an "entrained flow slagging gasifier" (described in the section below) has many benefits but it requires small particles of MSW of fairly consistent composition. This gasifier therefor requires more effort to be spent on the front end of the process sorting and sizing the feedstock. A grinder is typically used to reach a particle size of 1mm.[17] Substantial sorting costs are also incurred, depending on the homogeneity of the waste stream that the plant receives. No reliable estimates of these costs were available, thus all financial results are presented on a continuum of sorting costs.

Gasification

This model uses a high temperature entrained flow slagging gasifier. High temperature gasifiers are the mostly commonly used gasifiers on a commercial scale.[18] There are many different gasification technologies and all have their pros and cons. This particular gasifier has many qualities that make it appropriate for this analysis:

1. It has a long history of being used at a commercial scale for coal gasification therefor this is not a new technology with uncertain costs and functionality.
2. It is a non-catalytic process that works well for continuous operation.
3. It has high investment costs but is economical at a commercial scale.

As mentioned above, the largest downside to this gasifier is that it requires a fairly uniform feedstock in both size and composition. Providing a uniform feedstock requires more money to be spent on sorting and sizing of the MSW in the preprocessing stage. A different type of gasifier, the Plasma Arc gasifier, is able to accept a highly varied feedstock, however they have high capital costs and have not been demonstrated on a commercial scale as extensively as high temperature entrained flow gasifiers.[19] Plasma gasifiers have many promising characteristics and Coskata, Inc. is employing this technology in its plants. Further financial models should explore this technology.

Syngas Cleaning and Upgrading

After gasification there are still many contaminants present along with the syngas that need to be removed and disposed of in some manner. The steps described below are identical to those employed by Swanson et. al. except where noted.

First, there is fly ash that is removed in a direct-water-quench unit. Another typically waste product of gasification is char, but high temperature entrained flow slagging gasifiers (i.e. the gasifier used in the model) do not produce char.

Second, because the gasifier does not produce H_2 and CO (syngas) at the optimal ratio for the Fischer-Tropsch process, a Water-Gas-Shift reaction is performed to get the ratio closer to 2:1.

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[17] (Arena, 2011)
[18] (BC Ministry of the Environment, 2011)
[19] (Arena, 2012)

Third, CO_2 and H_2S (acid gases) are removed using a chemical gas absorption system that employs an amine-based solvent. This process results in 90% reduction of CO_2 and 99% reduction in H_2S. A stripper is used to restore the amine-based solvent. The stripper does not bring down the sulfur content low enough for the Fischer-Tropsch process, though, so a zinc oxide guard bed is used to reduce the sulfur content further.

Fourth, the acid gases that have been removed from the syngas are diverted to a LO-CAT sulfur recovery system that removes the H_2S and turns it into solid sulfur by oxidizing the H_2S with iron. The solid sulfur can be removed as a cake, the iron can be recycled back into the process, and the remaining CO_2 is vented.

Fischer-Tropsch Synthesis

Synthesizing the syngas into gasoline, diesel, or ethanol requires several steps. Again, these steps are consistent with Swanson et. al. except where noted.

First, the temperature and pressure are increased and the gas is pumped through a zinc oxide/activated carbon fixed-bed sorbent (polishing guard). This step prevents the contamination of the catalytic synthesis process that follows; contaminants can poison the catalyst if they are not removed.

Maximum Gas Contaminant Levels for Fischer-Tropsch Synthesis[20]

Contaminant	Maximum Concentration
Sulfur	200 ppb
Ammonia	10,000 ppb
HCN	10 ppb
Halides	10 ppb

Second, some of the hydrogen from the syngas needs to be removed for use later on in the process. A small stream of the syngas is sent to a PSA unit, which removes pure hydrogen and then sends the remainder of the syngas back to the Fischer-Tropsch process.

Third, the combined streams of syngas are sent into the Fischer-Tropsch reactor; it is a fixed bed reactor that employs a cobalt catalyst. The Fischer-Tropsch process (described in detail in previously in the paper) produces a range of hydrocarbons depending on the ratio of CO to H_2 and the temperature of the reactor along with some unconverted syngas. As the ratio and temperature are increased, the output becomes longer chain hydrocarbons (i.e. progressing from methane to gasoline to diesel to waxes). In the model, the reactor temperature is assumed to be 200°C to maximize the production of longer chain hydrocarbons that can be refined to gasoline and diesel during fuel upgrading. The model assumes 66% conversion of CO to hydrocarbons, which is consistent with Swanson et. al.

Fourth, the liquid product is separated in a gas/liquid knock-out separator.

[20] (Spath, 2003)

Fifth, unconverted syngas is divided into four separate streams and sent either back into the reactor for conversion, back into the acid gas removal area, back into the gasifier, or into a turbine to generate power.

Power Generation

Steam and gas turbines can be coupled to take advantage of the excess heat and unconverted syngas from the Fischer-Tropsch process as well as the fuel gas from the fuel upgrading process (described below). Fishcer-Tropsch synthesis is highly exothermic, so there are substantial opportunities for heat recovery and energy generation. The flu gas from the gas turbine can be used in a heat-recovery steam generator to increase the efficiency of the overall power plant (much like a natural gas combined cycle power plant).[21]

Fuel Upgrading

The hydrocarbon products of the Fischer-Tropsch synthesis must be refined further in order to maximize the production of gasoline, diesel, or ethanol. Long-chain hydrocarbons (e.g. waxes) must be cracked in a hydrocracker using the pure hydrogen that was diverted prior to the syngas entering the Fischer-Tropsch reactor. A distiller is used to separate the lighter molecules such as naphtha and diesel. The models assumed product breakdown is given below:

Product Breakdown After Fuel Upgrading[22]

Product	**Proportion**
Methane	3.46%
Liquefied Petroleum Gas (propane)	8.77%
Gasoline (octane)	26.10%
Diesel (hexadecane)	61.67%

Capital Costs

The capital costs were taken from Swanson et. al. for the majority of equipment and then adjusted to 2012 dollars using the Consumer Price Index. These costs include total purchased equipment costs and total installed costs. Costs for feedstock processing and syngas cleaning were adjusted to account for the differences in processing and gasifying MSW versus corn stover. The following adjustments were made:

Capital Costs of Plant Construction

Feedstock Processing	25,100,000.00
Gasification	75,100,000.00
Syngas Cleaning	37,100,000.00
Fuel synthesis	54,700,000.00
Hydroprocessing	36,500,000.00
Power Generation	50,500,000.00
Air Separation	26,900,000.00

[21] (Swanson, 2010)
[22] (Shah, 1998)

Rest of Plant[1]	36,700,000.00
Total Installed Cost	342,600,000.00
Indirect Costs[2]	143,600,000.00
Contingency[3]	97,200,000.00
Working Capital[4]	87,500,000.00
Total Capital Costs	583,400,000.00
Total Capital Costs + Working Capital	670,900,000.00

1. "Rest of Plant" includes the cooling tower, cooling water system, waste solids and liquid handling systems, and feed water systems.
2. Indirect costs include engineering and supervision, construction expenses, and legal and contractors' fees at 32%, 34%, and 23% of total purchased equipment cost, respectively. Totaled indirect costs are 89% of total purchased equipment costs. This is the same methodology that was used in Swanson et. al.
3. A contingency for construction cost overruns was added in equal to 20% of the total direct and indirect cost.
4. Working capital was set at 15% of the fixed capital investment.

It was assumed that the plant was built in two and a half years and 8% of the capital cost was spent in the first year, 60% in the second year, and 32% in the third year. This building schedule was based on the methodology used in Swanson et. al.

Operating Costs

The operating costs were taken from Swanson et. al. for the majority of equipment and then adjusted to 2012 dollars using the Consumer Price Index, except for small exceptions; raw material costs (e.g. catalysts) were adjusted using Industrial Inorganic Chemical Index. Costs for feedstock processing and syngas cleaning were adjusted to account for the differences in processing and gasifying MSW versus corn stover. The following adjustments were made:

The following operating cost parameters were annualized in the financial model.

LO-CAT Chemicals	$176/tonne of sulfur produced
Amine Makeup	$1.09/lb and set as 0.01% of circulating rate
Process Steam	$8.20/ton
Cooling Water	$0.31/ton
Hydroprocessing	$4.00/barrel produced
Slag Disposal	$23.52/ton
Wastewater Disposal	$3.30/hundred cubic feet (ccf)
Electricity	$0.054/kWh
Sulfur	$40/ton

Annual Operating Costs (2012 $s)

Steam	3,000,000.00
Cooling water	2,500,000.00
Other raw material costs	1,600,000.00
Waste disposal	1,700,000.00
Hydroprocessing	4,900,000.00
Fixed costs[1]	15,800,000.00
Depreciation[2]	33,500,000.00

1. Fixed costs include salaries, overhead, maintenance, insurance, and taxes.

2. The plant is depreciated over 20 years using a straight line approach.

Catalyst Replacement Costs (3 year cycle; 2012 $s)

Water Gas Shift (copper-zinc)	127,000.00
ZnO Guard Bed	470,000.00
PSA Packing	550,000.00
Fishcer-Tropsch (Cobalt)	8,512,000.00

Other Financial Parameters

Electricity Rates

The electricity rates used in the model are the 2012 average wholesale spot market rates made publicly available by nine major electricity trading hubs. There are large differences in average price, so multiple model runs were made using varying electric rates. The rates for each hub are given below:

2012 Average Wholesale Spot Electricity Prices for Selected Major Trading Hubs[23]

Trading Hub	**$/MWh**	**$/kWh**
Mass Hub	40.72	0.0407
NYISO Zone J	46.57	0.0466
PJM West	40.18	0.0402
MISO Illinois Hub	32.06	0.0321
Into Southern	28.89	0.0289
ERCOT Houston Zone	35.91	0.0359
Palo Verde	30.03	0.0300
CAISO NP15	31.72	0.0317
Mid-Columbia	22.56	0.0226

These prices were escalated over the 20 year life of the plant using the Energy Information Administration's estimates of electricity price growth rates published in the 2012 Annual Energy Outlook (AEO 2012). These growth rates under the baseline case, the high economic growth case, and the low economic growth case are given below.

Average Annual Change in Real Prices of Electricity from 2010 to 2035[24]

Scenario	Annual Growth Rate
Reference Case	0.10%
High Economic Growth Case	0.30%
Low Economic Growth Case	0.00%

[23] (EIA, 2013)
[24] (EIA, 2012)

Tipping Fees

The amount charged by landfills to accept MSW is referred to as the "tipping fee." These fees are highly variable across the country; Idaho has the cheapest average rate at 18.43 $/ton while Massachusetts is over five times more expensive at 105.40 $/ton. The national average was used for most model estimates, although sensitivity analysis were performed in order to see the effect that changes in tipping fees have on the financial viability of the project. Waste-to-energy facilities typically offer a discount over the local landfills in order to attract the feedstock they need while maintaining a revenue stream. A flat discount of 10% was used in the model, after conversations with plant operators suggested that this is a typical discount. The table below gives the average prices for several states across the country as well as the national average.

Region	$/tonnes	Notes
Idaho	17.07	Cheapest in U.S.
Massachusetts	97.60	Most expensive in U.S.
Washington	67.57	
New Hampshire	69.10	
Oregon	23.53	
Tennessee	66.47	Might be overestimated
National	45.62	Only for the largest public and private landfills

(Wright, 2012)

Fuel Prices

The fuel prices used in the model are based on the EIA data on refiner prices of petroleum products. These prices fluctuate greatly over time, as demonstrated by the discussion of crude oil prices that is included later on in this paper. Due to these fluctuations the model used several different prices in sensitivity analysis. Below are the data that were used:

Average Refiner Prices of Petroleum Products to End Users[25]

Year	Refiner Price of Finished Motor Gasoline to End Users ($/Gallon excluding taxes)	Refiner Price of No. 2 Diesel Fuel to End Users ($/Gallon excluding taxes)	Refiner Price of Propane (Consumer Grade) to End Users ($/Gallon excluding taxes)
2011 (in 2012 $s)	3.113	3.182	1.744

These prices were escalated over the 20 year life of the plant using the Energy Information Administration's estimates of the change in real prices for refined petroleum products published in the AEO 2012. The growth rates under the reference case, high oil price growth rate case, and low oil price growth rate case are given below.

[25] (EIA, 2013)

Average Annual Change in Real Prices of Refined Petroleum Products from 2010 to 2035[26]

Refined Petroleum Product	Reference Case	High Growth in Oil Price Case	Low Growth in Oil Price Case
Diesel (Distillate Fuel Oil)	1.60%	2.40%	-0.60%
Motor Gasoline	1.60%	2.50%	-0.80%
Liquefied Petroleum Gases[1]	1.70%	2.80%	-0.50%

1. Liquefied Petroleum Gases include propane, butane, and mixes of the two.

Other

Below is a list of other parameters and assumptions that were used in the financial model.

- The plant availability was set to 310 days a year (85% capacity factor) to give time for repairs, maintenance, and other necessary down time. This is consistent with Swanson et. al.
- A startup time of 6 months after construction was assumed during which the plant would not be running at full capacity. During that time it was assumed that, compared to normal operations, revenues would be 50%, variable operating costs would be 75%, and fixed operating costs would be 100%.
- All dollar figures are reported in 2012 dollars.

Results and Sensitivity Analysis

The results of the financial model under various scenarios are presented below. All results show the internal rate of return (IRR) of the project in relation to sorting costs under these scenarios. Sorting costs have a profound effect on the financial viability of the project, but they are not fixed for any one project. They vary according to the contents of the feedstock, which do not have to remain static over the life of the project. If the MSW is relatively homogenous and contains few materials that need to be removed then costs would be low, but costs can be far higher if the MSW is heterogeneous and contains many materials that have to be removed. Additionally, gasification of MSW is a technology in its infancy, and a reliable cost range for sorting could not be obtained. Therefore, instead of choosing a fixed sorting cost that could be inaccurate and could vary over time, the results are presented over a continuum of sorting costs.

Base Case

The parameters of the base case are given below. All further sensitivity analyses are compared to this base case.

- Debt/Equity
  - Project is financed with 25% debt and 75% equity.
  - Loan tenor is 10 years.

[26] (EIA, 2012)

    - The interest rate is 6.375%.[27] This is the composite corporate bond rate for companies with a BBB debt rating. Both Waste Management, Inc. and Republic Services have BBB debt ratings and they are the two largest companies in the waste management industry.[28] Waste Management, Inc. is also a large investor in many of the companies detailed in the "Companies Converting Syngas to Salable Products" section (Appendix).
    - The first two years of interest is capitalized.
- Fuel Prices
    - Growth rates were applied based on EIA projections in the AEO 2012 for the "Reference" case. These rates are given in the "Fuel Prices" section below.
    - Gasoline: 3.11 $/gallon (2011 national average in 2012 $s)
    - Diesel: 3.18 $/gallon (2011 national average in 2012 $s)
    - Propane: 1.74 $/gallon (2011 national average in 2012 $s)
- Electricity Rates
    - Growth rates were applied based on EIA projections in the AEO 2012 for the "Reference" case. These rates are given in the "Electricity Rates" section below.
    - PJM West 2012 Wholesale Day Ahead Average Rate: 47.63 $/MWh
    - PJM West was chosen as the base case, because PJM is the largest wholesale market in the country.
- Tipping Fees
    - Average 2012 national rate for largest public and private landfills: 45.62 $/tonne
    - Discount given by project over landfill rate: 10%
    - Rate charged by project: 41.06 $/tonnes

The following sections graphically compare variations in fuel prices, electricity rates, tipping fees, and financing options to this base case in order to demonstrate which factors have the largest impact on the financial viability of the project.

Fuel Prices

The range of fuel prices to model were chosen based on EIA scenarios published in the AEO 2012. These were used instead of a Monte Carlo simulation based on past prices because the EIA does a thorough analysis of future prices based on past prices, changes in current technology, and many other factors that would not be captured in a Monte Carlo simulation. The scenarios that were modeled are given below.

- Low price scenario: AEO 2012 Low Growth in Oil Price Case
- Baseline scenario: AEO 2012 Reference Case
- High price scenario: AEO 2012 High Growth in Oil Price Case

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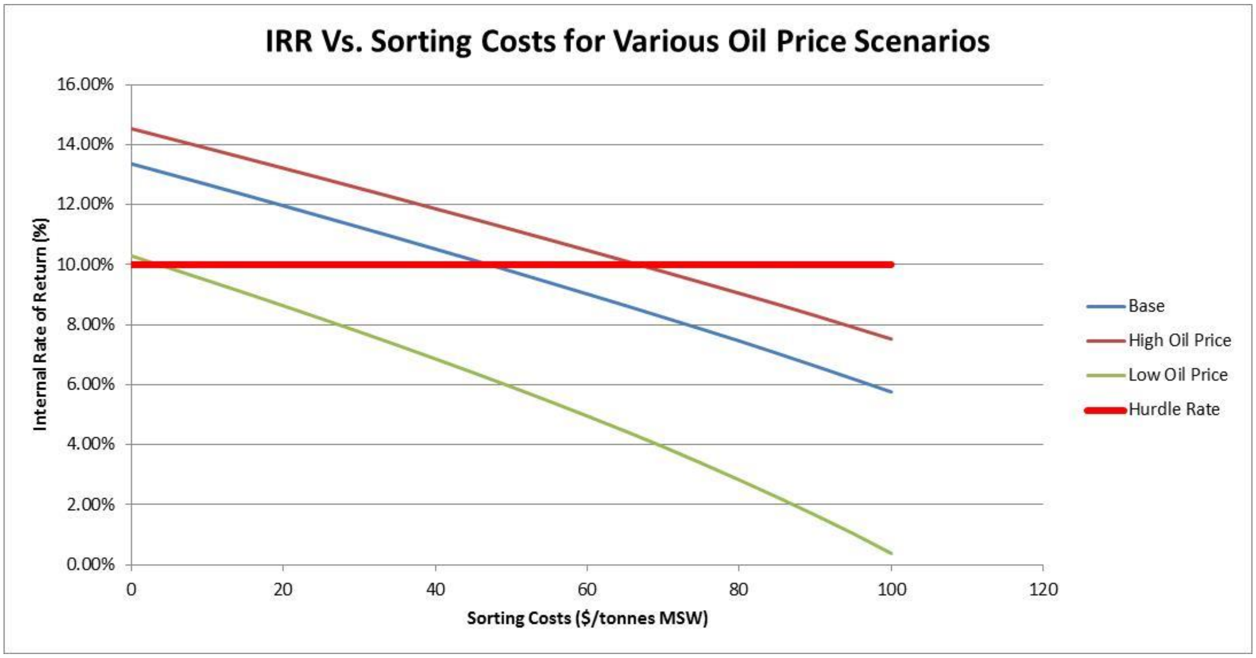
[27] This rate is as of March 18, 2013.
[28] Bond ratings were taken from www.morningstar.com on March 18, 2013.

Average Annual Change in Real Prices of Refined Petroleum Products from 2010 to 2035[29]

Refined Petroleum Product	Reference Case	High Growth in Oil Price Case	Low Growth in Oil Price Case
Diesel (Distillate Fuel Oil)	1.60%	2.40%	-0.60%
Motor Gasoline	1.60%	2.50%	-0.80%
Liquefied Petroleum Gases[1]	1.70%	2.80%	-0.50%

1. Liquefied Petroleum Gases include propane, butane, and mixes of the two.

The results of the model under these various oil price scenarios are given below.



Oil prices have a significant effect on the viability of the project. The majority of the project's revenues come from the sale of liquid fuels that are produced conventionally with crude oil.

Electricity Prices

The range of electricity prices to model were chosen based on EIA scenarios published in the AEO 2012. These were used instead of a Monte Carlo simulation based on past prices because, as previously stated, the EIA does a thorough analysis of future prices based on past prices, changes in current technology, and many other factors that would not be captured in a Monte Carlo simulation. The scenarios that were modeled are given below.

- Low price scenario: AEO 2012 Low Economic Growth
- Baseline scenario: AEO 2012 Reference Case
- High price scenario: AEO 2012 High Economic Growth

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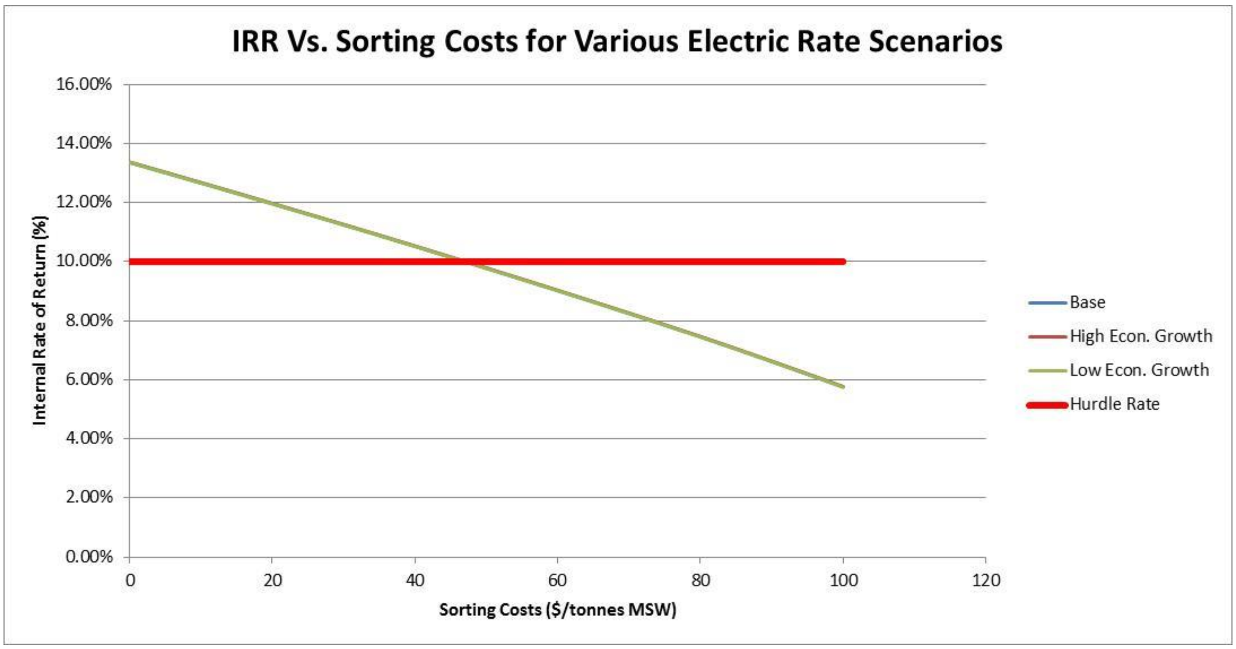
[29] (EIA, 2012)

Average Annual Change in Real Prices of Electricity from 2010 to 2035[30]

Scenario	Annual Growth Rate
Reference Case	0.10%
High Economic Growth Case	0.30%
Low Economic Growth Case	0.00%

The EIA projects little variation in electricity price growth rates in each of these cases. The results are displayed graphically below.

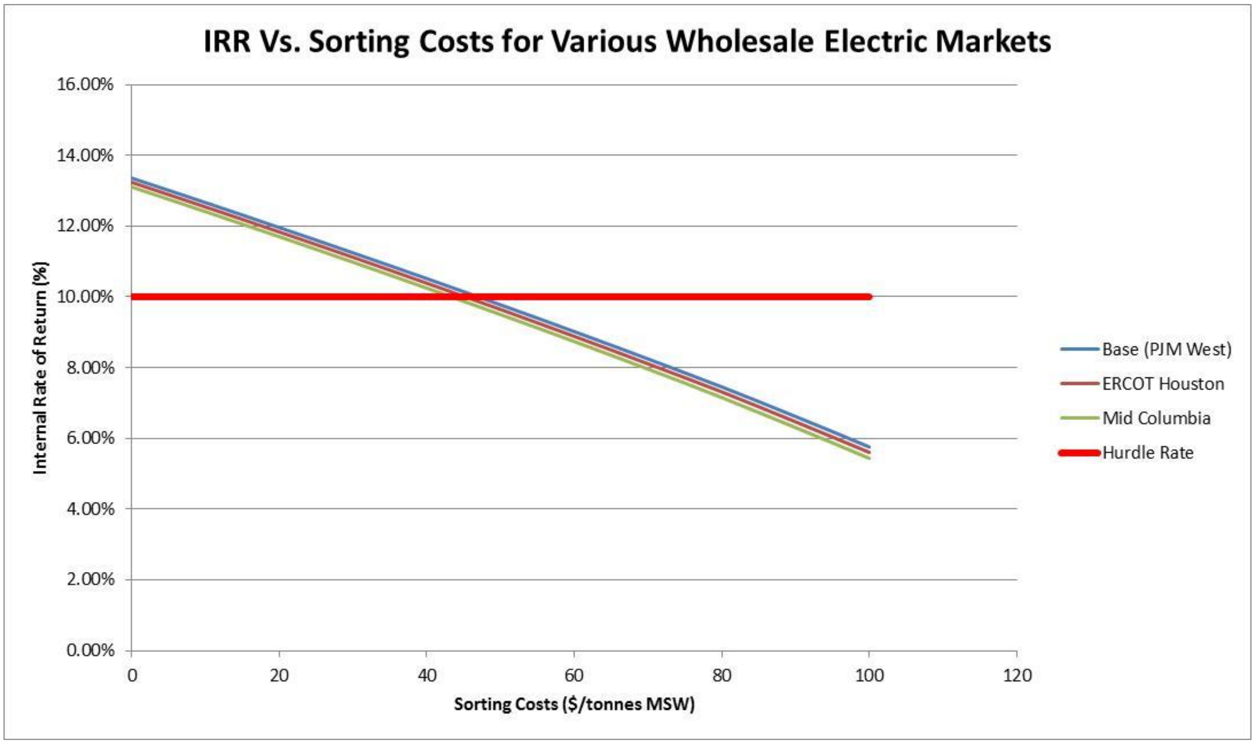


As displayed by the graph, according to EIA projections the change in electricity rates over time will have almost no impact on the viability of the project. The three lines are so close together that they cannot be distinguished from each other.

However, there can be much larger differences in electric rates in different wholesale electric markets than the differences projected over time by the EIA under different economic growth scenarios. The following graph compares:

- PJM West: $47.63/MWh
- ERCOT Houston: $35.37/MWh
- Mid Columbia: $22.02/MWh

[30] (EIA, 2012)

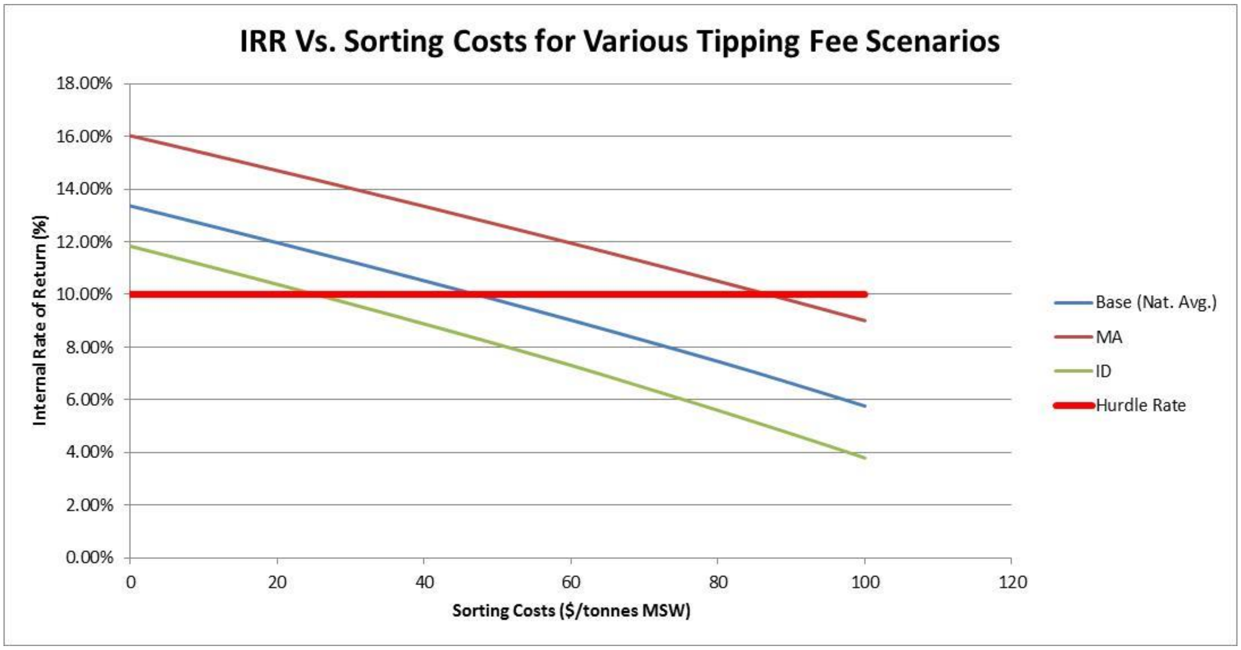


As is demonstrated by the graph, large changes in wholesale electric rates have very little impact on the financial viability of the project. The revenue generated through the sale of electricity is small compared to the revenues from the sale of liquid fuel and tipping fees, and thus changes in electricity prices do not have a significant impact.

Tipping Fees

Robust historical data on tipping fees across the United States is not sufficiently available to estimate a distribution for a Monte Carlo analysis. Therefore, the base case was compared to the state with the highest tipping fees (Massachusetts) and the state with the lowest tipping fees (Idaho).

- Use 10% discount over landfill rates in all cases
- Low price scenario: use Idaho price of 16.72 $/tonne (lowest in U.S.)
- Baseline scenario: national average of 44.70 $/tonne (i.e. baseline)
- High price scenario: Massachusetts price of 105.4 $/tonne (highest in the U.S.)



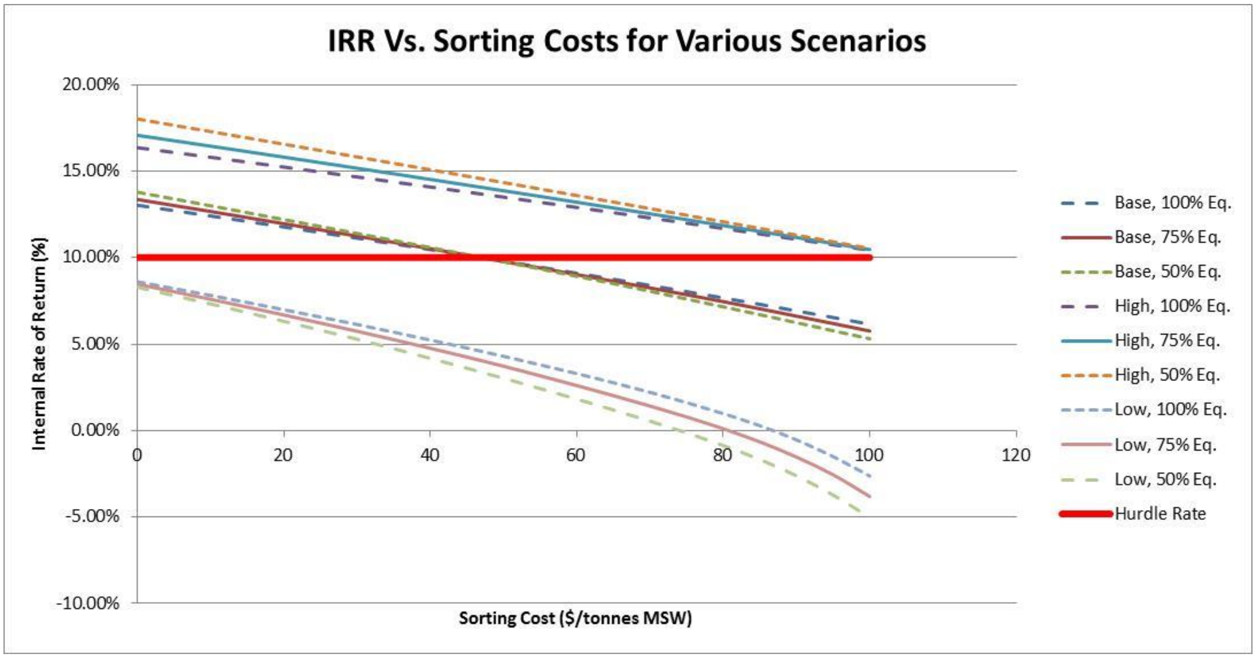
As with oil prices, tipping fees can have a significant effect on the financial viability of the project. Locations with low tipping fees are not conducive to this type of project.

Financing Options

This section compares the IRR of the project under different debt to equity ratios for the project. In all cases the loan tenor is 10 years and the interest rate is 6.375%. The different scenarios are:

- 100% equity and 0% debt
- 75% equity and 25% debt
- 50% equity and 50% debt

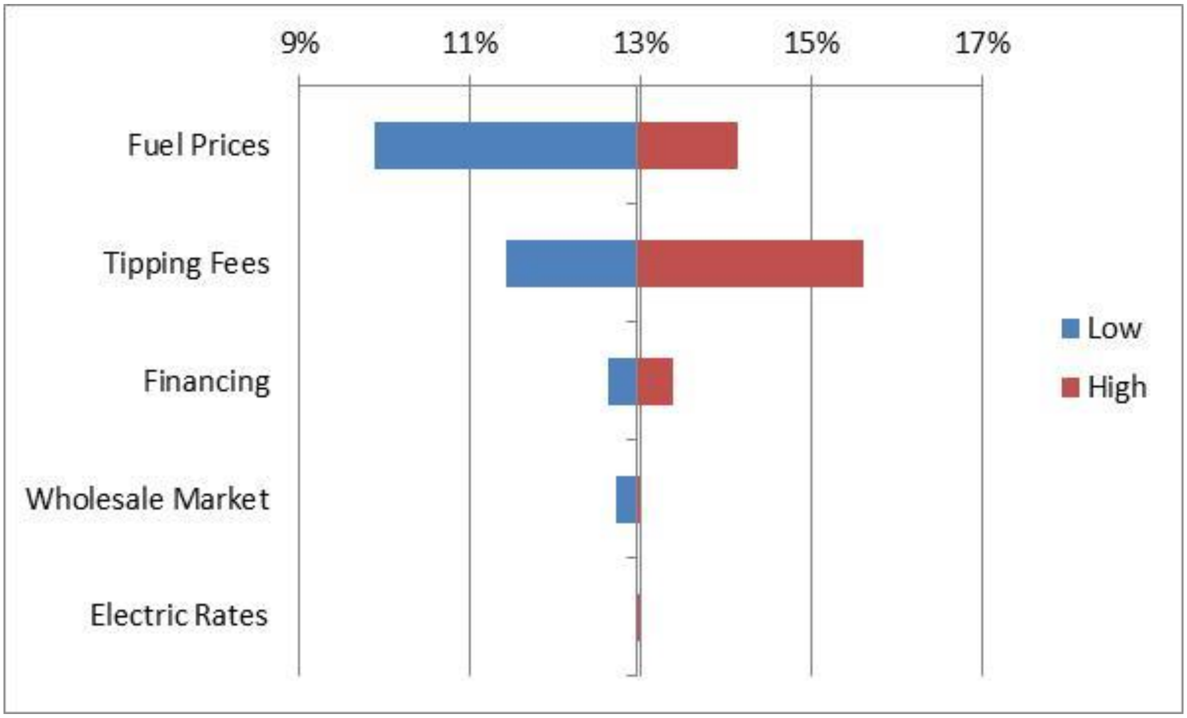
These three scenarios are shown for the base case, the highest revenue case (fuel prices, electricity rates, and tipping fees are set to their “high price” scenarios from the sections above), and the lowest revenue case (fuel prices, electricity rates, and tipping fees are set to their “low price” scenarios from the sections above).



The results shown in the graph demonstrate that financing choices have a relatively small impact on the financial viability of the project when compared to other financial factors, especially fuel prices and tipping fees.

Relative Impact of Model Factors in IRR

As seen in the tornado chart below, the price of the fuel product has the most significant impact on the IRR for the model. This result is to be expected given that the main purpose of implementing such a technology is to sell the products for a profit. The unusual nature of having a feedstock with negative costs, though, results in the tipping fees being the second most significant driver of IRR in the model. Perhaps the most surprising result from the analysis is that the financing structure of such a project has a relatively low impact on the IRR. Most projects with high capital costs rely heavily on altering the debt-to-equity ratio in order to improve their IRR but compared to other factors, this financing structure is less significant. This model may oversimplify the situation, though, because the cost of capital is held constant throughout.



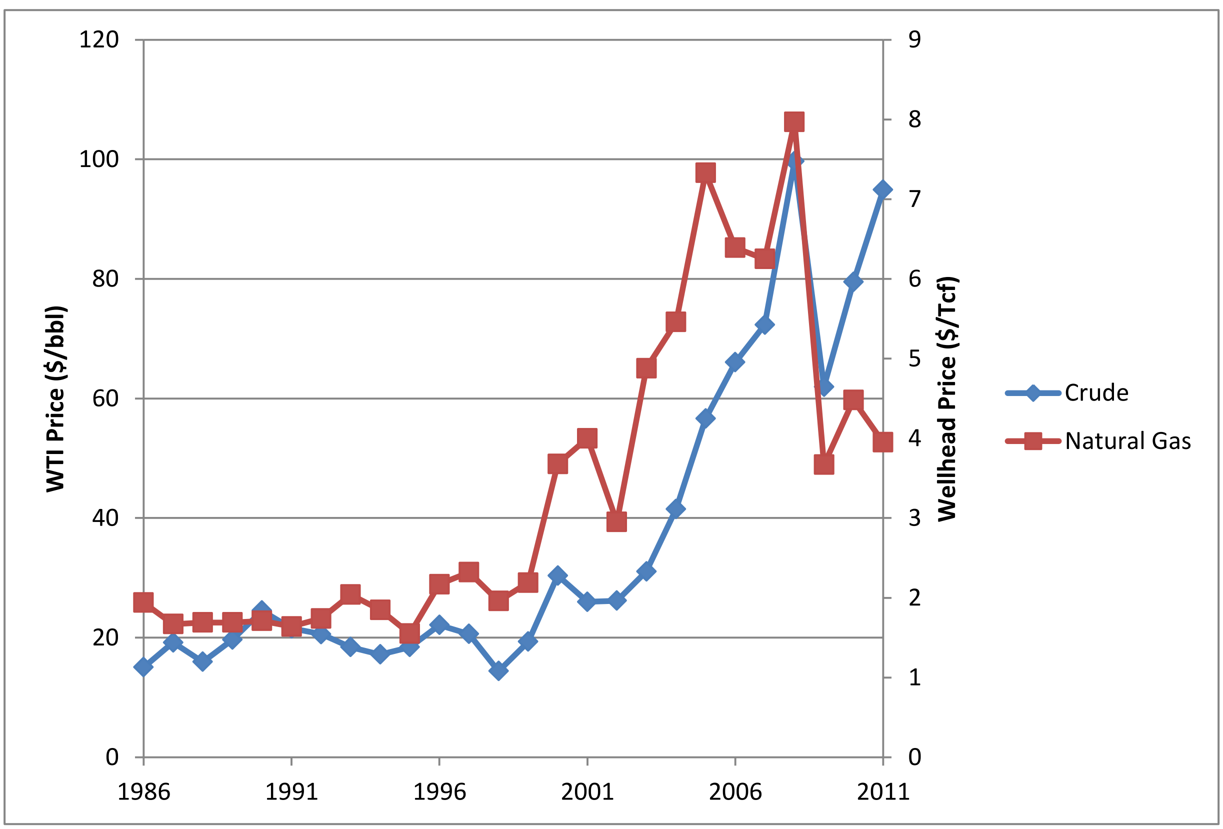
Note: Midpoint set to base case model results with no sorting costs.

Beyond the Model

Relationship with Conventional Fuel Prices

Because the price of the fuel product is so critical to the viability of the project, it becomes very important to understand the factors that control fuel price. In fact, the economic competitiveness of conversion fuel products is often dependent on the price of oil and natural gas because the conversion products are direct substitutes for oil and gas products such as gasoline and petrochemicals. This link is particularly true for the more traditional gas-to-liquids plants because conventional gas-to-liquids plants typically use natural gas as the feedstock to generate syngas.[31] The historically low natural gas prices in the U.S. in recent years (2008-2012) reduce the costs of operating those conventional plants and thus make unconventional plants using MSW as a feedstock less competitive However, the high crude oil prices raise the competitiveness of gas-to-liquid fuels for both conventional and unconventional plants. This concern is really theoretical, though, since there are currently no commercial plants in the U.S. converting natural gas to liquid transportation fuel. The unconventional plants that produce ethanol, gasoline, diesel, or jet fuel are therefor not competing with gas-to-liquids plants; for these plants, crude oil is the primary commodity price affecting their economic competitiveness.

Annual U.S. Crude Oil and Natural Gas Prices



(EIA Natural Gas Wellhead Price data (http://www.eia.gov/dnav/ng/ng_pri_sum_dcu_nus_a.htm) and West Texas Intermediate (WTI) Spot Price data (http://www.eia.gov/dnav/pet/pet_pri_spt_s1_a.htm), accessed August 7, 2012.)

[31] (Spath, 2003)

Policy Implications

Fuels derived through MSW gasification and conversion are relatively new and still fall under an area of policy and regulatory ambiguity that can affect their commercial viability. Clarifying the definition and regulatory category of this conversion fuel with the EPA would remove the risk of it potentially falling into a cumbersome, highly regulated category, such as "refuse-derived fuel" (RFD)[32] or incineration. Being defined as one of these fuels would add an unnecessary cost burden because expensive monitoring equipment and scrubbers would be required wherever the fuel was burned. MSW conversion fuel could also be positively impacted if the definition of a renewable fuel is specifically expanded to include this type of conversion fuel. Demand for conversion fuel would increase because of the Renewable Fuel Standards (discussed below), which set annual targets for mixing renewable fuel with gasoline and diesel in the United States.

One critical regulatory clarification for MSW conversion fuel is whether a facility that burns this fuel for power generation is considered a boiler (or process heater, which falls under Section 112 of the Clean Air Act) or an incinerator (which falls under Section 129 of the Clean Air Act). Commercial entities (like industrial boilers and electric generating unit operators) will only use these products if they can be handled and combusted as conventional fuels (under Section 112). Regulating these products under Section 129 requires monitoring emissions at the point where they meet the ambient air and installing pollution control technology. The fuels produced are actually quite clean, though, because all regulated toxins are removed in the gasification process, before the conversion of syngas into liquid fuel. As mentioned earlier, the syngas must be thoroughly cleaned before it is converted to liquid fuel because otherwise the catalyst (for the Fischer-Tropsch process) will be damaged and would have to be replaced. The fuels produced would be the same grade and quality of any ethanol, gasoline, or diesel produced from a traditional refinery (perhaps with even fewer impurities), so the additional monitoring and pollution control technology would be unnecessary and just add superfluous costs to operation.

While official determination is still forthcoming from the EPA, there are indications that MSW conversion fuels would in fact be regulated under the preferable Section 112. A company called ReCommunity requested clarification from the EPA about whether or not their (solid) ReEngineered Feedstock would qualify as a non-waste fuel product (and therefore come under Section 112). Their product is generated from non-recyclable MSW and used as a coal replacement for combustion in boilers. The EPA agreed that the processing ReCommunity does to the MSW feedstock acts as a pollution control technology and therefore the ReEngineered Feedstock is a non-waste fuel product.[33] This information was confirmed in what is referred to as a "comfort letter", however, and is not legally binding. The ReEngineered Feedstock is a parallel product to MSW conversion to liquid fuels except in solid form, so the EPA's letter bodes well for MSW conversion technology.

Renewable Fuel Standards (RFS)

Under the Energy Policy Act of 2005 (EPAct), the first national Renewable Fuel Standards (RFS) were implemented and required that by 2012, 7.5 billion gallons of renewable fuel were to be blended with

[32] Section 241.3(b)(4) of the Non-Hazardous Secondary Material (NHSM) rule

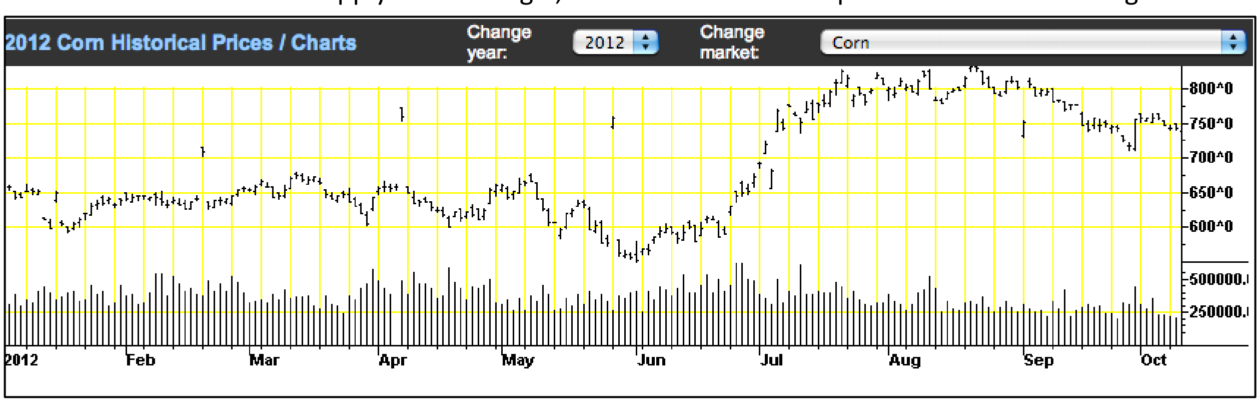
[33] (US EPA Letter, 2012)

gasoline. The Energy Independence and Security Act of 2007 expanded the RFS to require that diesel also be blended with renewable fuel and increased the quantity of renewable fuel from 8 billion gallons in 2008 to 36 billion gallons by 2022.[34] For 2012, the RFS mandated 15.2 billion gallons of renewable fuel to be blended and this number has increased to 16.55 for the 2013 RFS proposal.[35] The fuel products modeled in this paper are derived from MSW and therefore appear to meet the EPA's definition of a renewable fuel, which states "Renewable fuels are those derived from renewable, non-petroleum sources such as crops, animal waste, or municipal solid waste."[36] It seems that conversion fuels might even be of interest in fulfilling the advanced fuels requirement within the RFS, currently referred to as "advanced biofuels". The terminology or definition would need to be altered to include this fuel, however, because it does not currently fall under the "advanced biofuels" definition. The RFS has necessarily driven demand of renewable fuels, particularly corn-based ethanol, and the built-in demand is highly favorable to new technologies such as MSW conversion to liquid fuels.

Comparison to Corn-Based Ethanol Production

Currently, almost all of the renewable fuel in gasoline and diesel used to meet the RFS is corn-based ethanol. Corn-based ethanol uses field corn as its feedstock. In 2010-2011, 35.4% of the field corn produced in the United States was used for ethanol production. Field corn is also used for animal feed and edible processed corn products such as corn syrup and corn oil.[37] Therefore, ethanol is in direct competition with both human food and animal feed for supply of field corn and a shortage of supply can lead to increases in food prices.

This theory was validated during the extreme drought in 2012 that impacted the 2012 corn crop in the United States. As early as June, corn prices began to rise because of the anticipated shortage from the drought. They rose from around six dollars per barrel to over eight dollars per barrel and hovered around the eight-dollar mark through September, of 2012 (see chart below), rising again in January, 2013. This price volatility can make corn-based ethanol production unprofitable very easily because it already has low margins; at eight dollars per barrel, an ethanol producer only makes a profit of about eight cents per gallon. It is difficult to pass through ethanol feedstock costs to the consumer because ethanol is a price taker in the market. It follows gasoline prices because ethanol is an additive in gasoline and therefore increases supply at the margin, so it fetches the same price as that last unit of gasoline.



34 (US EPA, 2013)
35 (US EPA, 2013)
36 (US EPA, 2013)
37 (EIA, 2013)

(Retrieved on February 23, 2013 from http://futures.tradingcharts.com/hist_CN.html)

Furthermore, there was widespread public and industry anger that food availability was directly affected by ethanol fuel production. Ethanol was using a significant portion of the field corn, which caused increased pressure on feed and processed corn products. These field corn price increases are expected to lead to higher food prices in the United States throughout 2013 by three to four percent overall (two and a half to three percent is standard). The higher cost of animal feed caused many famers to reduce the size of their herds of cows, pigs, and chickens. When these herds were culled in the fall, the overall meat supply on the market increased causing a temporary price decrease. Now, however, the number of animals is lower and is expected to create price increases in meat, eggs, and dairy through 2013.[38] Some industry officials and Congressmen even made requests that the EPA relax its Renewable Fuel Standard in 2012 to decrease pressure on the corn and overall food industry (but the EPA did not change the RFS).[39]

Processing MSW to create gasoline, diesel or ethanol has none of these threats to corn availability and food prices. Providing ethanol from MSW would increase the supply of renewable fuel for additive on the market and could alleviate pressure and competition for corn. Ethanol (or other renewable fuels) from MSW would simultaneously meet the Renewable Fuel Standard and act as a hedge against corn price volatility from unpredictable weather patterns. Given all of these benefits to the farming industry, the United States Department of Agriculture (USDA) might even consider investing in the technology (which is discussed in further detail below).

Price Competitiveness Under RFS

While there has been very little published research on the economic competitiveness of converting MSW to liquid fuel or chemical products, there have been substantial studies of converting plant-based biomass to fuels. The processes required for the conversion of biomass are extremely similar to those necessary for the conversion of MSW: gasification, gas cleaning, catalytic synthesis, and separation and further refining. The table below summarizes the results of several studies that quantify the "Minimum Product Selling Price" for the process to be economically viable. There are many assumptions that go into these models that contribute to the large variations in results: feedstock, feedstock price, necessary gas cleaning, capital investment, financing structure, and size of the plant are some examples. One crucial input is the cost of the feedstock, and, in this instance, plants that use MSW as a feedstock may have an advantage over those that use plant based biomass as a feedstock. In cases where the same company is collecting the MSW and converting it to fuel[40], then the company is essentially being paid for its feedstock through tipping fees. In other cases companies are able to enter into low-cost long-term contracts for MSW feedstock. In both cases, price volatility of feedstock and the uncertainty it creates is eliminated. Using MSW as a feedstock creates a substantial advantage over conventional refineries that must deal with the price volatility of crude oil and conventional biorefineries that must deal with the price volatility of agricultural feedstocks such as corn or sugarcane. As previously mentioned, in the drought in the U.S. Midwest during the summer of 2012, corn futures rose by 60%, causing a rise in the

[38] (USDA, 2012)
[39] (Tracy, 2012)
[40] Enerkem and Fulcrum Bioenergy are both partnerships with Waste Management.

price of ethanol of over 33%.[41] During such an event the operating costs of a MSW to ethanol plant would likely remain unchallenged, while its profit margins would increase drastically. Below is a chart of feedstock prices and the corresponding minimum product selling price from a collection of studies on gasification and conversion to liquid fuel technologies. The values are taken from Swanson, 2010.

Study	Product	Feedstock	Feedstock Price	Size	Minimum Product Selling Price
Swanson et al. 2010	Gasoline / Diesel	Corn Stover	$75.00 dry short ton	2,000 dry short tons per day (tpd)	$4.30-$4.80 GGE[42] (2007 $)
Larson et al. 2009	Gasoline / Diesel	Switchgrass	$46.00 dry short ton	5,000 dry short tpd	$1.85 GGE (2003 $)
Tijmensen et al.	Fischer-Tropsch Liquids	Poplar	$33.00 dry short ton	1,919 dry short tpd	$2.00 GGE (2000 $)
Phillips et al.	Ethanol	Poplar	$35.00 dry short ton	2,205 dry short tpd	$1.60 GGE (2005)

Climate Change Policy

Climate change policy in the United States is receiving renewed attention now but the future remains uncertain. Establishing a strong market or a price for carbon would certainly benefit this technology, though, since gasification of MSW diverts garbage from the landfill, thereby preventing methane emissions from the landfill. Turning MSW into a salable product should therefor be eligible for carbon credits. These credits can then be sold or traded for a profit, establishing an additional revenue stream for the plant. A price on carbon would not only be likely to make this technology more attractive and profitable but would simultaneously hurt competing fuels that are from crude oil. Crude oil refineries are currently not subject to the forthcoming EPA regulations but if they were to incur costs from carbon emissions, the price of crude-derived fuels would increase because refineries operate at very low margins as it is. The added burden of carbon costs to crude oil products would give the MSW conversion fuels an added economic advantage over conventional liquid fuels.

Furthermore, many states currently have Renewable Portfolio Standards (RPS) for their electricity generation mix. While the regulations are state-specific, many states include or even require generation from landfill gas for their RPS. MSW conversion to liquid fuels could conceivably become part of the renewable energy portfolio if the products were used for electric power generation. Conversion fuels could replace the crude-based fuel currently used in oil or diesel plants. Classifying the technology such that it fulfills RPS standards would create a significant demand for these products in the marketplace,

[41] (Lefebvre, 2012)
[42] Gallon of gasoline equivalent (GGE)

allowing them to command a higher price over their conventional equivalents and secure long-term purchasing contracts.

Funding Opportunities

The model used to evaluate the financial viability of the project relied on tradition debt and equity financing techniques. There are various government funding opportunities, however, for which MSW conversion to liquid fuels technology could be eligible, including grants, loan guarantees, or cost-sharing cooperative agreements. Because MSW gasification and conversion to fuels is currently being piloted, it is most likely not eligible for the oft-touted Advanced Research Projects Agency-Energy (ARPA-E) funding because ARPA-E is targeted for projects that are too early for private-sector investment. There are many other opportunities, however, and advanced gasification technology applies to both fossil fuel gasification and renewable fuel gasification, potentially making it eligible for an even wider breadth of grant categories. The Department of Energy, Department of Defense, and Department of Agriculture have all previously funded projects that are closely related to this conversion technology.

Department of Energy

The Department of Energy is already involved in many of the pilot projects converting MSW to liquid fuels. One mechanism they use for funding is a cooperative agreement, which is a grant in which the DOE shares costs with the business, research laboratory, or university involved. An example of this agreement is in the "Energy Science and Technology and Other Research and Development" category through the National Energy Technology Laboratory (NETL). The NETL offers a funding opportunity for thirteen million dollars available for "Advanced Gasification Technologies Development and Gasification Scoping Studies for Innovative Initiatives" with applications due April 22, 2013.[43] Another current gasification-related opportunity is for "Crosscutting Research: Development of Novel Architecture for Optimization of Advanced Energy Systems", also through the National Energy Technology Laboratory. Nine million dollars of funding is tied to this project "which aims at bridging the gap between the basic sciences and applied research as it relates to Advanced Power Systems that utilize domestic resources."[44] Funding opportunities are regularly posted and updated on the Grants.gov website. Loan guarantees are another mechanism for funding and the Department of Energy offers Improved Energy Technology Loans.[45] This mechanism alleviates some of the risk involved with new technology projects for the lending institution, essentially allowing lower rates for debt.

Department of Agriculture

The Department of Agriculture already provides significant funding to the biofuels industry through the Biomass Research and Development Initiative which was created in the 2008 Farm Bill. On January 11th, 2013 the Agriculture Secretary Tom Vilsack announced another twenty-five million dollars of funding for projects developing renewable energy and other biobased products. [46] While USDA funding typically has gone to projects with biomass or farm waste feedstock, their mission is also to generate more jobs in rural areas as well as support farmers. MSW gasification to ethanol could help farmers by taking

[43] (Grants.gov, 2013)
[44] (Grants.gov, 2013)
[45] (AFDC, 2013)
[46] (USDA, 2013)

pressure off of animal feed prices, as was needed in the 2012 drought, which might make the project attractive to the USDA. By helping to build pilot projects to scale up the technology, USDA will be able to help the meat, dairy, and poultry farmers who suffered from high feed prices. If sited in a rural, economically depressed area, an MSW to ethanol conversion plant might be even more attractive for USDA funding because it could boost local industry and employment.

Department of Defense

The National Defense Authorization Act of 2007 established a voluntary goal for the U.S. Department of Defense Projects (DOD) to achieve 25% of the energy consumed be provided by renewable energy by 2025.[47] To meet these ambitious goals, the Army is expected to invest over seven billion dollars in ten years. The DOD is therefore an excellent potential source of funding for new energy technologies because projects that are built on military bases may be eligible. Sierra Energy, a waste gasification plant that produces syngas, received a three million dollar grant from the DOD in 2012.[48] They are building a waste gasification system at U.S. Army Garrison Fort Hunter Liggett in California. If this project goes well, the next step would be to build additional and bigger plants at other Army bases around the country (particularly those with MSW disposal constraints).

State Level Funding

The Federal government also distributes funding to each state's energy office through the State Energy Program (SEP) and the state matches twenty percent of this funding.[49] The 2009 Recovery Act provided a total of $3.1 billion to SEP. By financing projects through SEP, the federal government allows each state to decide how the funding is best distributed, enabling states to support projects most pertinent to their own needs and challenges. SEP offers both formula and competitive grants to support their state energy strategy. MSW to liquid fuels technology might be most beneficial to states with high tipping fees and limited landfill capacity such as in the northeast. Moving project development to these areas could then open up more funding opportunities at the state level. Sierra Energy has benefited from state funding and received a five million dollar grant from the California Energy Commission in August of 2012.[50]

[47] (Army Energy Program, 2012)
[48] (Turner, 2012)
[49] (USDOE, 2013)
[50] (Turner, 2012)

Environmental and Human Health Outcomes

MSW Gasification Versus Incineration

Burning synthetic gas is much cleaner than burning MSW directly. There is a common misperception, though, that gasification of municipal solid waste is equivalent or only slightly better than incineration from an environmental perspective. Gasification of MSW offers many environmental and health benefits over standard incineration, in addition to generating a product that is more valuable than electricity.

Incinerators may use some pre-sorting to remove more toxic elements but generally the emissions are controlled at the stack, meaning after the solids are combusted. Post-combustion emission control is generally not as effective as pre-combustion controls, which is partly why incinerators have far more stringent emissions monitoring and scrubbing regulations. With gasification of MSW, however, all toxins that would otherwise be combusted in incineration must be removed from the syngas before the Fischer-Tropsch process occurs, making the end products very clean. The presence of chemicals other than carbon, hydrogen, and oxygen in the syngas will degrade (or "poison") the catalysts used in the syngas-to-fuel conversion process, rendering the catalysts useless and halting the process. Removing the impurities from the gasified products is more effective. It is also easier to collect the precipitates and properly repurpose or dispose of them this way. As mentioned earlier, some byproducts can be separated from the syngas scrubbers and made useful, such as elemental sulfur.

According to Sierra Energy, a municipal solid waste gasification plant, "Ash from the process is recycled into the gasifier to produce a non-leaching slag" and hazardous air pollutants (HAPs) are removed from the syngas using reforming chambers, scrubbers, or catalyst beds. Removing HAPs before the syngas is turned into liquid fuels assures that combustion of the fuels is at least as clean as traditional fuels and protects the catalysts used for the Fischer-Tropsch conversion process. Even when syngas is combusted directly (instead of being changed to liquid fuels that are later combusted), it is a cleaner process than incineration because of pre-combustion scrubbing. In his review of MSW gasification process and technology, Arena states, "Except for fly ash and some volatile components, most of the inert, non-combustible material is collected at the bottom of the reactor, with metals mainly in a non-oxidized form."[51] Separating unwanted toxins and pollutants before combustion enables more effective capture and disposal than allowing them to be emitted into the air or scrubbed from the emissions.

Furthermore, new catalysts are in development to operate at very high temperatures, thus making the overall process more efficient. Many catalysts currently in use to remove undesired elements require the syngas to be brought to a lower temperature for the proper reaction to occur and to maintain the integrity of the catalytic agent. The National Technology Energy Laboratory has developed catalysts for coal-based gasification that may also work for MSW-based gasification that would require less cooling and subsequent reheating after the toxins are removed from the syngas. Not having to cool and reheat the syngas would obviously improve the efficiency of the system.

[51] (Arena, 2012)

Post-Conversion Waste Disposal

Companies currently piloting MSW gasification do not provide concrete quantities of char, slag, ash, and hazardous waste disposal. The high temperature entrained flow slagging gasifier used for the model does not produce char, however (char is unreacted carbon material that can be put back through the gasification process to convert to syngas). RTI International has compiled estimates for residuals over an array of gasification technology, and has estimated that each ton of post-recycled MSW that is converted to syngas generates 297 pounds of char, 75 pounds of slag, 25 to 120 pounds of gasifier solid residues, 45 pounds of inorganic sludge, 13 pounds of nonhazardous solid waste.[52] Slag can be used as building material (as slag-based lightweight aggregate, or SLA) and in some instances can be separated into its two components of char and frit. The char can be cycled back through the gasifier, as mentioned, and the frit can also be used for sand blasting grit, road surfacing, landscaping, and athletic tracks, among others.[53]

These RTI estimates support anecdotal data that gasification of MSW results in just a small amount of true waste material. Given the early stage of this technology, there is not robust data to accurately evaluate the quantity of residual byproducts. However, the remainder appears to be either repurposed or suitable for landfill. If these estimates are accurate, MSW conversion to liquid fuels could divert roughly ninety percent of the MSW feedstock from landfill, converting it to energy instead. These estimates are subject to the feedstock composition, obviously, but could have a significant impact on the quantity of waste going to landfill.

Reducing Landfill Mass

The greatest benefit of producing liquid fuels from gasification of MSW lies in the reduction of MSW sent to landfills. In 2009, the United States alone generated 243 million tons of MSW, 54% of which was sent to landfills (over 131 million tons).[54] Tipping fees and transportation costs (for bringing MSW to landfill sites) is growing increasingly expensive as more landfills are closed and fewer are opened. In 2007, there were 1,754 landfill sites in the U.S., down from 7,924 in 1988.[55] As demonstrated by RTI, MSW conversion to liquid fuels could reduce the tonnage of waste going to landfill by about ninety percent. This type of relief to a constrained landfill system holds enormous promise, particularly for island nations with limited landfill space and regions of the country with high tipping fees for waste disposal.

Landfills are also infamous for air emissions including methane, volatile organic compounds (VOCs), and hazardous air pollutants (HAPs) such as benzene, toluene, ethylbenzene, m p-xylene, o-xylene, and styrene.[56] While some landfills capture and sell landfill gas (methane) as a fuel for electricity generation, most do not and simply flare the gas, converting it into carbon dioxide and wasting the potentially useful energy (a comparison MSW conversion to fuels and landfill gas energy is in the Carbon Emissions section below). While methane is not toxic, it is highly flammable and has been known to cause explosions. The

[52] (U.S. EPA, 2012)
[53] (NETL, 2013)
[54] (U.S. EPA, 2013)
[55] (U.S. EPA Office of Solid Waste, 2007)
[56] (KI-HYUN KIM, 2006)

US Environmental Protection Agency estimates that methane is twenty to thirty times more potent a greenhouse gas than carbon dioxide, so flaring the gas is preferable to it simply being released to the atmosphere. Only large landfills are required to flare methane, though, so most landfill sites are just freely emitting methane to the atmosphere. (More details on the reduction of carbon emissions is below).

Hazardous air pollutants can have significant short and long-term consequences depending on the length and frequency of exposure as well as the concentration of the toxins. Long durations of toxins exposure can increase the chances of developing cancer or other debilitating health effects including "damage to the immune system, as well as neurological, reproductive (e.g., reduced fertility), developmental, respiratory and other health problems."[57] Some VOCs are also considered HAPs but they are commonly referenced separately. VOCs have been known to cause ailments ranging from eye irritation and headaches to central nervous system damage.[58] VOCs contribute to lower atmospheric ozone, which can lead to respiratory issues in humans, as well.[59]

Any reduction in the amount of waste sent to landfills will necessarily result in an overall reduction in emissions. Most MSW to liquid fuels projects today are smaller projects and consume approximately 25 metric tonnes of MSW per day. Larger facilities of over 100 metric tonnes of MSW per day are predicted to be more profitable but as yet do not exist.[60] Using the 2009 landfill quantities above, it would only take about 80 of these larger (100 metric tonnes per day) facilities to consume two percent of the annual U.S. MSW going to landfill.[61] Expanding on these estimates, 604 of these facilities could take away 15% of the annual landfill mass in the United States. (As a reference point, there were 594 operational landfill gas and energy facilities in the country in 2012.)[62] Reducing the total amount of municipal solid waste going to landfill would also reduce the total amount of harmful emissions released from landfills. Quantifying these environmental and health benefits from reduced landfill mass is extremely difficult but reducing methane, VOCs, and HAPs emissions will undoubtedly have a positive effect on environmental and human health.

Carbon Emissions

Comparing gasification of MSW to landfill disposal, RTI determined net carbon emission savings of 0.3-0.6 TCE[63] per dry ton of MSW. This net savings is due mainly to the energy produced through gasification because even in the scenario with the landfill recovering energy, the gasification facility produces energy much more efficiently, with an energy savings of 6.5-13 MMBtu per ton. Obviously the life cycle of MSW conversion fuels will always have carbon emissions associated with it because ultimately the hydrocarbon fuel is combusted. Comparing the net carbon emissions to other options for

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[57] (U.S. EPA Technology Transfer Network, 2013)
[58] (U.S. EPA, 2013)
[59] (Cora, 2009)
[60] (Loulier, 2013)
[61] Using 90% capacity factor, 90% of MSW feedstock being diverted from landfill, and 119.04 million tonnes MSW generated per year
[62] (U.S. EPA, 2013)
[63] TCE is "tons of carbon equivalent"

the waste such as going to landfill is the true way to gauge the incremental improvement of this technology to the status quo.

Furthermore, these fuels will have the same carbon content as traditional fuels so they would be an equal exchange for traditional ethanol, gasoline, and diesel fuels, yet not incur the emissions related to exploration, extraction, and refining. These upstream activities will essentially be reduced or delayed by the production of MSW conversion fuels, generating further (but less easily quantified) carbon savings.

Additionally, the Fischer-Tropsch process is highly exothermic, so after the initial reaction has been started from an external energy source, the process will be self-sustaining and not require further external power. All of this released energy can be used to dry or gasify the MSW in an earlier stage of the process and even generate additional power to go back to the grid. The RTI study examines gasification of MSW without conversion to liquid fuels, so the benefits of capturing the heat from the Fischer-Tropsch Process and making it useful energy are in addition to the benefits noted earlier (of the carbon savings from gasification alone).

Conclusion

This analysis has revealed that there are several factors that are crucial to the future success of MSW to liquid fuels plants. They present barriers but also opportunities for the further adoption of this technology. They fall into four categories: 1. Feedstock, 2. Fuel Prices, 3. Capital Cost, and 4. Regulatory Rulings.

The results of the financial model show that tipping fees (i.e. revenue from the feedstock) is one of the most important variables in the financial success of these plants. These fees are largely determined by location, so plant owners can control this variable when deciding where to build a plant. It appears that locating in a high tipping fee area, such as Massachusetts, has a large positive impact on the viability of the project. However, there are other factors related to the feedstock that need to be considered. These plants need a steady and reliable stream of MSW to maintain operations on a continuous basis. Ideally, the plant would secure a long term contract for MSW at an advantageous price, strengthening the viability of the project and improving the project's ability to obtain financing. Lastly, the quality and heterogeneity of the feedstock must be considered. Reliable data on sorting costs could not be obtained, but it is likely that as the heterogeneity of the feedstock increases the sorting costs increase. These sorting costs could potentially have a large impact on the financial viability of the project and should be a topic of further research.

Fuel prices are the most important factor in the success of these projects, but these plants are price takers in the fuel market and thus have no control over these variables. A trend towards higher fuel prices bodes well for these projects, while if fuel prices track the low estimates for future prices it could be extremely detrimental to the growth of this industry. These plants do have some flexibility to alter their products (e.g. gasoline, diesel, or ethanol) to respond to these price signals, though. Additionally, the Renewable Fuel Standard provides a built-in market for these fuels. Because the RFS is currently met primarily with corn-based ethanol, there has been high competition for corn with the agricultural sector, particularly after droughts. MSW to liquid fuel conversion could alleviate some of the competition and price volatility of corn, as well as alleviate the need to import sugar cane ethanol from Brazil to meet the RFS beyond the U.S. production capabilities.

These plants are capital intensive projects, and thus have high upfront capital costs in the hundreds of millions of dollars depending on the size of the plant. Obtaining financing for these plants, especially for a newer technology, could be extremely difficult. Fortunately, there are currently many non-traditional funding opportunities through the federal and state governments that are available to these projects (e.g. DOE, USDA, DoD, and State Energy Programs). Many of the current projects under development are taking advantage of these sources of funding.

Lastly, further regulatory clarity is required from the EPA, both regarding the Clean Air Act and the RFS. Liquid fuels produced from MSW conversion are essentially a new good in the marketplace and, as such, the EPA has yet to define it in accordance with pertinent regulations. These fuels are not explicitly defined under the Clean Air Act or under the RFS, but the EPA has indicated that these fuels will probably not be regulated as incineration and probably will qualify for RFS credit (and perhaps even as an advanced biofuel). This regulatory uncertainty is makes investing in the technology less attractive. Once legally-binding definitions have been set by the EPA, however, this risk will be removed and investors will be encouraged to fund MSW to liquid fuel conversion technology.

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Appendix A: Alternative MSW Conversion Technologies

Anaerobic Digestion

Overview

Anaerobic digestion is the slow decomposition (hydrolysis) of biologically active organic matter in an oxygen free environment. Organic waste is typically placed inside a digester in the presence of a variety of microorganisms, which break down the waste into CH_4 (often referred to as biogas or biomethane), CO_2, and a nutrient-rich sludge. This gas is colorless, odorless, and non-poisonous. The process consists of three steps.

1. Organic waste is broken down by microorganisms into sugars.
2. Acidogens (a second set of microorganism) break the sugars down into organic acids.
3. Methanogens (a third set of microorganisms) consume the organic acids and generate CH_4 as a biproduct.[64]

The composition of the waste and the type of microorganisms used can have profound effects on the "residency time" (the time it takes the microorganisms to break down the waste) as well as the percentage of the resulting gas that is CH_4 as opposed to CO_2 and undigested waste. For example, the typical gas produced is 55% to 75% CH_4 but some systems have been able to achieve levels of 95% by altering the waste composition and microorganisms. The resulting gas is typically burned in a boiler or an engine to generate electricity.[65]

These feedstocks will naturally decompose over time, but using specific microorganisms in digesters that maintain an oxygen-free environment with warm temperatures (typically between 35^{o}C to 63^{o}C) will speed up the process and capture of the CH_4. Residency times are often in the area of 5 to 15 days. Anaerobic digestion also avoids the emission of volatile organic compounds (VOCs), which occur as organic waste decomposes and are criteria pollutants under the Clean Air Act.[66]

Future Directions

Research and development in this field has been focused on the microorganisms that make this process possible and how they interact (i.e., their ecology). Through understanding how these microorganisms act in the presence of different types of waste (e.g., food waste vs. animal manure) digestion systems can be optimized to handle more concentrated waste (less water) and produce more CH_4, less CO_2, and less undigested material. Processes known as High Solids Anaerobic Digestion (HSAD) have the potential to generate more beneficial product from more highly concentrated waste than previous technologies, vastly reducing the footprint of the facility and improving margins. Orbit Energy, Inc. is working to commercialize a version of this technology that was developed on a laboratory scale by the U.S. Department of Energy (DOE) National Renewable Energy Laboratory (NREL).[67,68]

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[64] (Tabatabaeia, 2010)
[65] (California Energy Commission, 2012)
[66] (U.S. EPA Agency Region 9, 2008)
[67] (Rivard, 1999)

Pyrolysis

Overview

Pyrolysis is a thermochemical process that can convert biomass into bio-oil. Biomass is placed in an oxygen-starved environment and heated to between 400°C and 500°C.[69] The resulting bio-oil resembles crude oil but can be a combination of 300 or more carbon-, hydrogen-, or oxygen-based compounds, all with high oxygen content. Some gas and char (solid fixed carbon) are produced along with the bio-oil. Technologies strive to minimize the production of these byproducts and maximize the production of the bio-oil.[70]

The bio-oil can be burned to generate heat and electricity and certain valuable chemicals can be extracted as well. It is also possible to upgrade the bio-oil to more conventional hydrocarbon fuels through hydrotreating and hydrocracking. When the bio-oil is hydrotreated hydrogen is reacted with the oil to remove sulfur and oxygen. Then the hydrotreated oil is reacted with hydrogen again to form shorter chain hydrocarbons that meet the specifications of gasoline or diesel.[71] However, due to the high variability of the components of the oil and large percentage of oxygen in the components, substantial processing (de-oxygenation and reforming) is required to generate consistent fuel products.

Commercial scale pyrolysis plants do not currently exist due to lack of demand for bio-oil but modestly sized pilot plants have been built and operated for many years.[72]

Future Directions

The high variability of the components of the oil and the large percentage of oxygen in the components has limited the economic viability of pyrolysis. Additionally, removing the char from the bio-oil has proved difficult to accomplish economically. If pyrolysis is going to be used commercially in the future, low-cost methods of standardizing the composition of bio-oil and removing char from the bio-oil must be developed. Additionally, more research is needed to understand the health and environmental effects of exposure to bio-oil or char.[73]

Alternative Synthetic Gas Conversion Technologies

Ammonia Synthesis

In order to manufacture ammonia (NH_3) from syngas the syngas must be "conditioned" to separate the H_2 from the CO. The CO is removed in the form of CO_2 (CO shift conversion) using an absorber-stripper process. Then the H_2 stream and nitrogen (N) are placed under high temperature and pressure in the presence of a catalyst (typically Fe) to synthesize NH_3.

$$N_2 + 3H_2 \rightarrow 2NH_3$$

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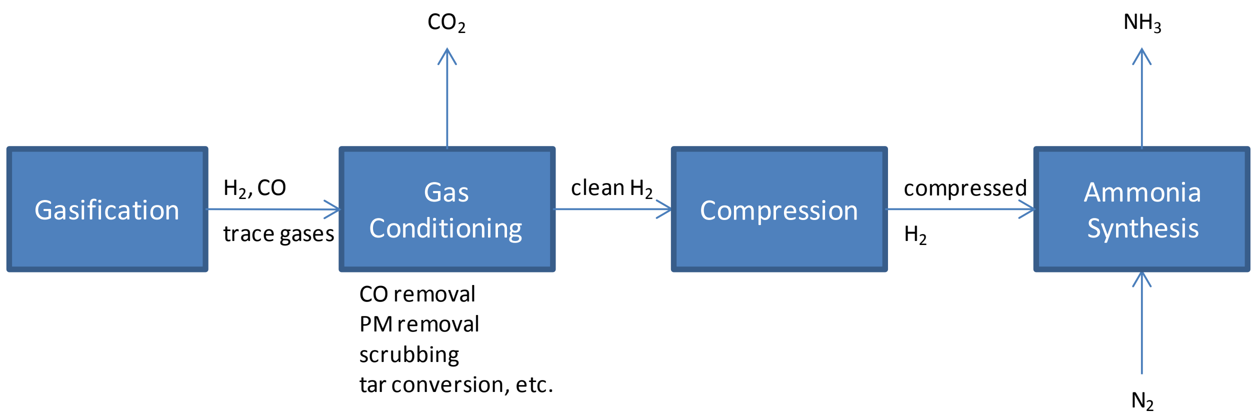
[68] (Orbit Energy, Inc., 2008)
[69] (Hsu, 2011)
[70] (Ringer, 2006)
[71] (Hsu, 2011)
[72] (Ringer, 2006)
[73] (Ringer, 2006)



Ammonia is a highly commercialized chemical product and is typically used in the manufacture of fertilizers.

The main air pollutant produced in this process is the CO_2 generated during the syngas "conditioning" (excluding the pollutants generated during gasification). NH_3 is also toxic and must be handled carefully.[74]

Methanol Synthesis

Methanol synthesis is similar to the Fischer-Tropsch process. CO and H_2 are synthesized to form methanol in a reactor under high temperature (220°C to 275°C) and high pressure (50 to 100 bar) in the presence of a $Cu/ZnO/Al_2O_3$ catalyst. The catalysts typically last two to four years. [75]The reaction is far more efficient in the presence of CO_2 (typically 4-8%).[76]

$$CO + 2H_2 \rightarrow CH_3OH$$

$$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O$$

$$CO + H_2O \rightarrow CO_2 + H_2$$

The resulting products are mostly methanol but also include water, ethanol, higher alcohols, higher ketones and ethers. These products are separated in a distillation plant.

Methanol is one of the most commonly produced chemicals in the world and is typically an intermediary between fuels or chemicals.[77] It can be converted to gasoline using Methanol-to-Gasoline processes (MTG), blended in gasoline with a cosolvent alcohol, or used directly as a transportation fuel with substantial engine modifications. The MTG process was developed by Mobil Oil Corporation to convert methanol to gasoline using a zeolite catalyst. Plants were built on a commercial scale, however, their

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[74] (Spath, 2003)
[75] (Swanson, 2010)
[76] (Spath, 2003)
[77] (Swanson, 2010)

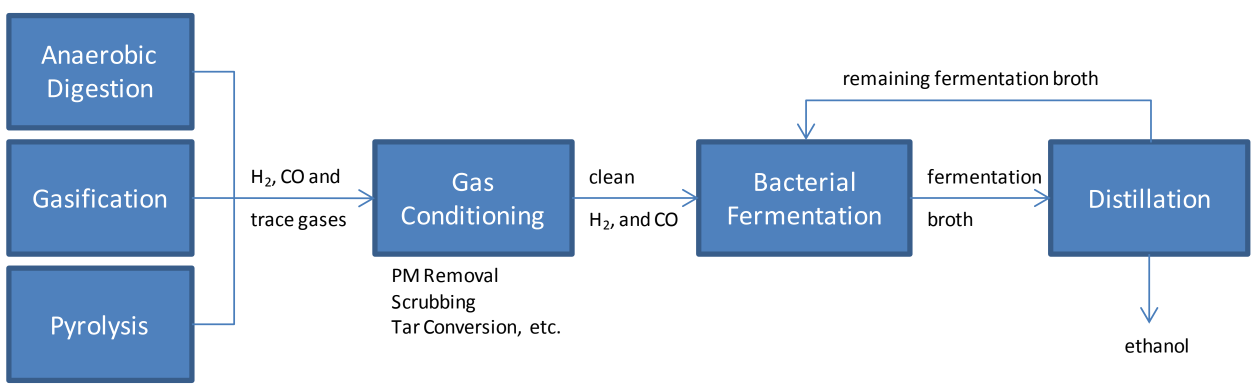
economics are highly dependent on the price of oil and most, if not all, have since shut down. It can also be converted to a number of valuable chemicals (e.g., formaldehyde, dimethyl ether, and acetic acid). [78]

Ethanol Fermentation

Overview

Biomass can be fermented directly, skipping the gasification step involved in all the previously mentioned processes. In fact, the vast majority of the U.S. ethanol industry practices the direct fermentation of corn. However, gasification allows for the fermentation of a far larger variety of biomass feedstocks, while direct fermentation of MSW is not a practical option. Additionally, pyrolysis and anaerobic digestion could also be used to provide a fermentation feedstock, however, currently there are no commercially viable examples of this combination. Therefore, this section will focus on ethanol fermentation that uses syngas as a feedstock even though it is not widely practiced. [79]

After gasification and gas conditioning the cleaned syngas is placed in a fermenter where it is consumed by anaerobic bacteria to produce ethanol (C_2H_6O). The mixture of syngas, bacteria and nutrients are carefully controlled to optimize the production of ethanol. Unlike the previous processes discussed, the ratio of H_2 to CO is far less important for fermentation. The product mixture is then distilled to separate the ethanol from the byproducts.[80] The off-gas can be used to produce additional power and heat, increasing the efficiency of the process. Additionally, this process requires far lower temperatures and pressures than the use of Fischer-Tropsch to produce ethanol. The selectivity of the bacteria is a crucial factor in determining product yields and many companies have developed their own proprietary strains of bacteria.[81]



Future Directions

There has been less of a R&D focus on syngas fermentation as compared to direct biomass fermentation and Fischer-Tropsch synthesis. However, it is more versatile than biomass fermentation and requires less energy than Fischer-Tropsch synthesis. Future research will likely focus on perfecting bacterial

[78] (Spath, 2003)
[79] (Spath, 2003)
[80] (Spath, 2003)
[81] (BioAge Group, 2008)

strains in order to optimize ethanol production and reduce the production of unwanted byproducts. Ineos Bio, Coskata Inc., and LanzaTech have all demonstrated this process successfully on a pilot scale and have plans for commercial scale plants.

Appendix B: Companies Converting Syngas to Salable Products

The following section contains a description of the current companies that are attempting to commercialize variations of syngas to salable product conversion technologies. This is not an exhaustive list, however, it demonstrates the clear efforts towards commercialization in the private sector and the many variations that these technologies can take.

Enerkem Inc.

http://www.enerkem.com/en/technology-platform/process.html

Enerkem uses a modified Fischer-Tropsch process in conjunction with gasification to convert MSW to methanol and ethanol for sale, although methanol can be sold as an end product or converted to valuable chemicals such as acrylic acid, n-Propanol, and n-Butanol. Enerkem has partnered with Waste Management in its efforts to commercialize this process.

Projects

Pontotoc, MS (http://enerkem.com/en/facilities/plants/pontotoc-mississippi.html)

- Under development
- MSW to syngas to ethanol
- Received $50M in DOE grants and an $80M loan guarantee from the USDA

Ineos Bio

http://www.ineosbio.com/60-Technology_platform.htm

Ineos Bio uses a modified Fischer-Tropsch process in conjunction with gasification to convert MSW to bioethanol for sale. The company uses a proprietary biocatalyst during the Fischer-Tropsch process.

Projects

Vero Beach, FL http://www.ineosbio.com/76-Press_releases-15.htm;
http://www.tcpalm.com/news/2011/aug/18/indian-river-bioenergy-center-finalizes-75-in/

- Under construction; operational mid-2012
- MSW, yard waste, and wood waste to syngas to ethanol
- 8 million gallons per year of ethanol and 6 megawatts of renewable power
- Received a $75M loan guarantee from USDA

Rentech

http://www.rentechinc.com/technology.php

Rentech uses several gasification technologies to convert many cellulosic waste streams (e.g., forestry or agricultural waste) to syngas. Rentech then uses a proprietary modified Fischer-Tropsch process to convert syngas to hydrocarbons and then upgrades those hydrocarbons to synthetic fuels and specialty waxes and chemicals.

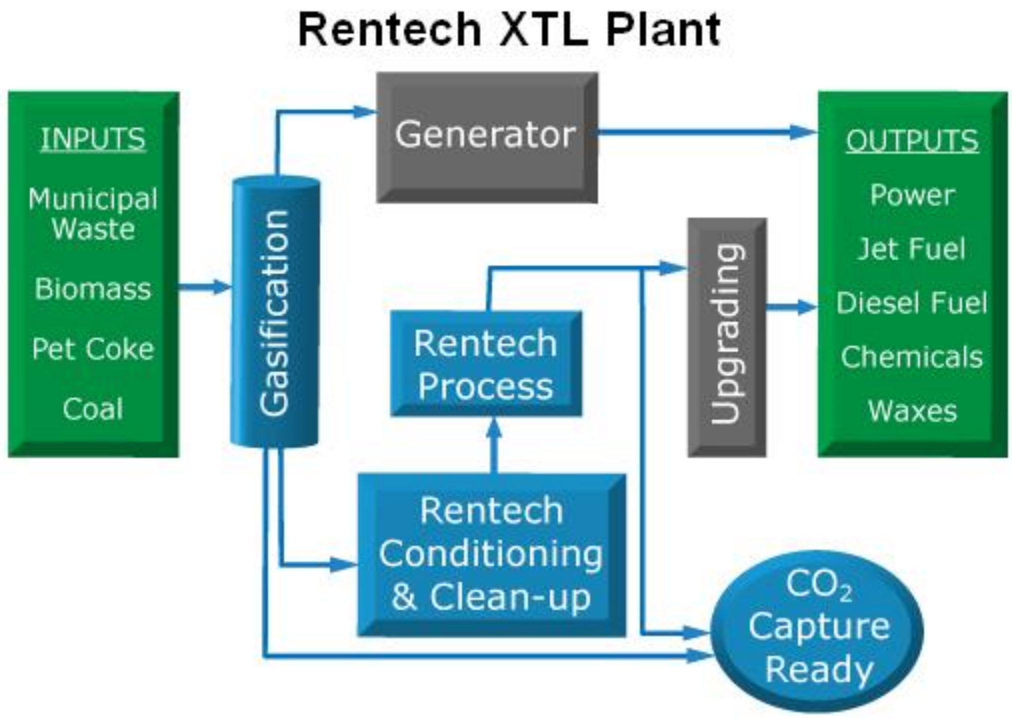


Image taken from http://www.rentechinc.com/rentechProcess.php on 7/31/2012.

Projects

Olympiad Renewable Energy Centre, White River, Ontario http://www.rentechinc.com/olympiad.php

- Under construction
- Timber to jet fuel and naphtha
- 23 million gallons jet fuel and 13 million gallons of naphtha per year
- Working with Sustainable Development Technology Canada (SDTC), whose NextGen Biofuels Fund (NGBF) offers project development and construction funding to be repaid from project cash flows

Coskata Inc.

http://www.coskata.com/process/

Coskata uses plasma gasification to convert solid feedstocks (e.g., MSW, biomass, coal) or gas feedstocks (e.g., natural gas, steel mill gas) to syngas, and biological fermentation to convert syngas to bioethanol for sale.

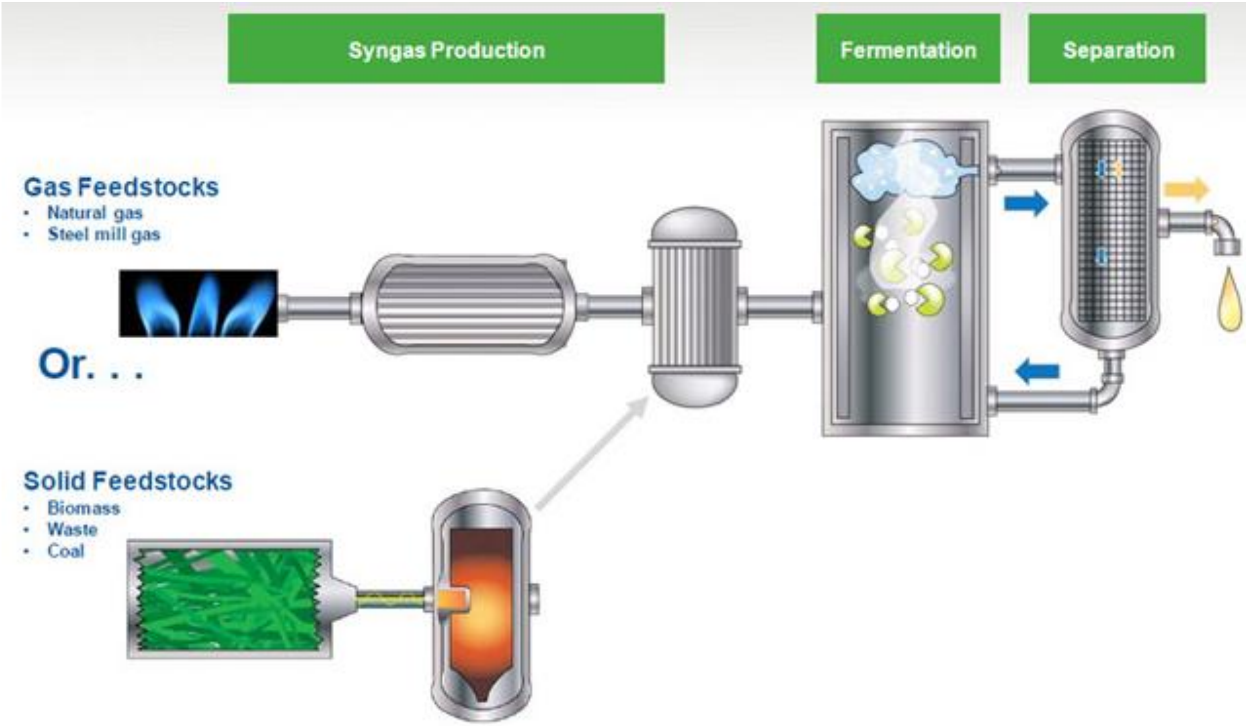


Image taken from http://www.coskata.com/process/index.asp?source=7E352957-657F-44D4-8CEC-3FCA8BBB2D7C on 7/31/2012.

Projects

Lighthouse, Madison, PA http://www.coskata.com/media/index.asp?story=F351125C-9886-4E59-A7BE-317389D1FC03

- Operational
- Semi-commercial
- Wood biomass, agricultural waste, sustainable energy crops, construction waste and natural gas to ethanol
- Can be scaled to 50M or 100M facility (i.e. "minimum scale engineering")
- Using Westinghouse Plasma Corp. technology for gasification

Boligee, AL http://www.coskata.com/facilities/index.asp?source=9982EDF1-D98F-4662-9217-5B889ADB9157

- Under development
- Advanced ethanol facility
- Capable of using waste as feedstock
- 55M gallons of ethanol per year
- Received a $250M USDA loan guarantee in January 2011

Fulcrum BioEnergy

Fulcrum BioEnergy converts MSW to syngas using gasification and then syngas to ethanol using alcohol synthesis. There is one facility under construction and over 20 long-term contracts for MSW across the nation.

Projects

Sierra Biofuels, McCarran, NV (Reno) http://www.fulcrum-bioenergy.com/facilities.html

- Under construction
- MSW to ethanol
- 10.5M gallons per year from 90,000 tons MSW
- Projected completion 2013

LanzaTech

http://www.lanzatech.co.nz/content/lanzatech-process

The LanzaTech process can use CO from steel manufacturing, oil refining and chemical production or syngas from the gasification of forestry and agricultural residues, municipal waste and coal as feedstocks. Those feedstocks are put through a fermentation process using proprietary microbes followed by separation to extract salable fuels and chemicals.

Projects

Glenbrook, New Zealand

- Pilot plant
- Operational
- Steel mill flu gas to ethanol
- 15,000 gallons per year

Freedom Pines Biorefinery, Soperton, GA http://www.freedompines.com/

- Under construction
- Waste biomass to ethanol
- Modifying an existing biorefinery, Range Fuels Biorefinery, with LanzaTech technology