MSW Conversion to Ethanol: Putting Together the Pieces for a Business Model

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Every year, landfill space becomes more and more scarce. As waste totals continue to rise, states attempt to curb the influx of garbage by increasing mandatory diversion rates and recycling requirements. A problem of equal or greater magnitude is the country's insatiable appetite for transportation fuel, and how to achieve a sufficient amount of alternative fuel production to wean America from its "addiction" to foreign sources of oil. This past January, President Bush presented a new Advanced Energy Initiative that proposed the development of enough new technology to replace 75% of the United States' oil imports from the Middle East by 2025[1], which may largely be filled by ethanol. Because of the AEI, there is a great need for high volume, low cost feedstocks for the production of cellulose-based ethanol. The problems of too much landfill waste and not enough cellulosic material could be resolved at the same time, with the deployment of a new kind of biorefinery employing technology that already exists.

The Reno-based engineering firm, Comprehensive Resources, Recovery and Reuse, Inc. (CR^3), has developed a propriety process that exposes municipal solid waste (MSW) to moderate pressure, steam saturated environment designed to ease the separation of usable materials from the "cooked" biomass. Their articulating steam autoclave was originally designed to isolate clean paper fiber to be incorporated into recycled paper products, but can also be used as an effective pretreatment technology for a cellulose-to-ethanol facility. Using the CR^3 process to isolate cellulose from MSW to yield a source of fuel ethanol is ideal for multiple reasons. First, a stable and efficient collection infrastructure already exists, which has proven to be a significant stumbling block for farm based agricultural waste and other cellulosic feedstocks currently being considered. Additionally, waste collectors are currently charged a fee to dump their collected waste at the landfill. Using MSW as a feedstock for ethanol production would obviate any costs associated with collection; by contrast, the plant would be able to collect a tipping fee from waste collectors as long as their fee is competitive with the nearest landfills. Not only might local or state waste reduction and diversion targets be met by using MSW to make ethanol, but the additional revenue from tipping fees would help fledgling first-generation plants towards financial success without the need for additional subsidies.

The Model:

A conceptual model of this waste-to-ethanol plant was created by joining the CR^3 steam autoclaving technology to traditional enzymatic hydrolysis, fermentation and distillation equipment, and adding a cogeneration facility to produce electricity and process heat. The power plant is composed of anaerobic digesters and an indirectly heated, low-pressure gasifier designed by Battelle Labs and licensed by Future Energy Resources Corporation (FERCO). The product gases are combusted in a gas turbine to make electric power for internal use and for sale, while process heat is also generated to satisfy the large heat loads required by the plant's equipment. Two scales of the model were created, the first at a size that could be found in a small city servicing 150,000 people. This small model would convert roughly 300 tons of MSW per day into 2.9 million gallons of ethanol each year. Because of their small size, these plants could be placed nearly anywhere in the country as long as the local tipping fees are high enough to support plant operations and as long as there is a large enough steam of MSW. Since landfill space is often scarce in urban locales (and since tipping fees there are often higher), the model was scaled up by a factor of ten to simulate a more populated area. Economies of scale allow the larger facility to produce ten times the ethanol at higher profit margins than the smaller sized plant.

The Process:

The process is designed to isolate a clean, cellulose-rich stream of paper fiber while concurrently separating the recyclables portion of the incoming MSW for resale and removing as much glass and grit as possible. First, the incoming MSW is subjected to a rotating, pressurized steam environment in CR^3's proprietary articulated autoclave[2], which renders the material into a moist pulp that is easier to process. The volume is reduced by up to 70% at this point, the product is sterilized, and plastics tend to ball up for later separation. The steam autoclaves are set to a timed cycle in order to reuse the pressurized steam between each module, reducing energy demands. After autoclaving, the biomass is then dumped into a trommel screen, which separates out intact bottles and cans as well as larger items such as car batteries or discarded clothing. The middles portion is composed largely of plastics, such as children's toys and high quality plastics like PET bottles and Tupperware. It is very likely that this "middles" stream could be used as additional fuel for the FERCO gasifier, since it has a high BTU content suitable for gasification, but this study did not include it because of a lack of test data. The large items side stream is separated into recyclables for wholesale and an unusable waste stream to be returned to landfill. The waste portion sent to landfill constitutes roughly 10% of the overall incoming stream, resulting in a net diversion rate of 90%. The biomass smaller than ½" continues on to a rotary dryer to be reduced to 30% moisture. It is then sent through a bank of air classifiers, which yields a clean, isolated stream of cellulose ready for hydrolysis. The majority of the ash, glass and grit drops out of the bottom of the air knife, while the "lights" portion, composed predominantly of chipped plastics and other organic material, can be separated off for steam and electricity generation.

Once the cellulose passes through the air classifier, an "enzyme cocktail" is added to it in order to yield a hydrolysate rich in sugars. These sugars can then be exposed to a yeast culture, which consumes them and produces ethanol and carbon dioxide. The broth is distilled to recover the ethanol, while the still bottoms (unfermented material and water) is sent to a bank of centrifuges. These centrifuges separate the stillage from fermentation into the particulates, or the "cake," which is sent to be gasified, and the soluble fraction which is then directed towards a dissolved air flotation system (DAF) for further refinement. The DAF pumps streams of tiny bubbles through the influent, pushing the remaining solids and high-BTU content inks and oils to the surface to be skimmed off for gasification. The remaining soluble material is then routed into the anaerobic digestion system, where bacteria feed off of the plentiful source of volatile organics and produce a continuous stream of methane gas that is captured and combusted in a gas turbine for electricity. It has been shown that the effluent from the fermentation process is rich in volatile organic compounds highly suitable for anaerobic digestion[3]. The large amount of embedded food particles and organic waste present in MSW creates a rich brown liquor for anaerobic digestion, which is an important energy source for the process needs of the plant.

Cogeneration Plant:

One of the most critical aspects of the system is its ability to generate its own energy. Unlike corn-based ethanol, which has its dried distiller's grains (DDG) as a high-value coproduct to sell, MSW-based ethanol lacks profitable byproducts and is dependent on cost savings wherever they can be found. The ability to use waste streams to create energy to power the plant is an effective tool to increase the profitability of the operation in the absence of multiple salable products. The composition of the MSW feedstock ensures that a considerable portion of the incoming material can be used to generate energy to power the autoclaving, fermentation and distillation processes. Along with the paper-based cellulose that is used to make the ethanol, there are significant amounts of soluble organics and combustible solids found in the MSW stream. The organic fraction, mostly composed of food waste embedded in napkins and packaging and otherwise discarded food scraps, is eventually separated and sent to the anaerobic digestion system, which employs microbes to consume the available BOD and produce a medium-BTU biogas[4]. The combustible solids that are unreacted after ethanol production (lignin, plastics, inks and oils) are sent to the Battelle/FERCO-designed high throughput, indirectly heated gasifier. The gasifier's reactor uses a sustained thermochemical conversion process that heats the substrate in the absence of oxygen. This yields a medium-BTU syngas and a char that is further combusted to heat the gasifier[5]. By cofiring the biogas produced in the anaerobic digestor and the syngas from the Battelle gasification system in a gas turbine, electricity is generated for process needs while a large amount of excess power is sold to the grid. The original design of the FERCO gasifier includes a heat recovery steam generator (HRSG) that converts the high-temperature exhaust from the gas turbine into usable steam[6]. This steam was then fed to an advanced three stage steam turbine system in order to generate additional electricity. Because the distillation and drying requirements of the ethanol plant require much more process heat than a stand-alone gasification plant generating only electricity, the steam turbine was eliminated and the steam generated by the HRSG was directed to process needs instead. Because the steam turbine generated only 28% of the overall electricity produced by the system, eliminating it for process heat does not overly compromise the ability of the gasification plant to produce electricity[7]. The removal of the turbine not only saved a considerable amount of money in the initial capital investment, but it also dramatically reduced the plant's need to import energy to fulfill its sensible heat demands. This way, roughly 20% of the plant's heat load is fulfilled by purchased natural gas, which lowers costs and increases the efficiency at which power and ethanol are produced.

The political climate is becoming increasingly favorable towards sustainable energy production; with rising public concern about global warming and the effects of fossil fuel use, political officials have been paying more attention to the growth of the renewable energy industry on a state and federal level. Economically speaking, producing renewable energy in the form of electricity can be beneficial to the producer despite higher production costs than large scale coal or nuclear facilities. In the case of the MSW to ethanol plant, any benefits from renewable electricity production would help the operation's bottom line, further reducing the price of the ethanol sold. One of the most common incentives for new renewable power plants are "Renewable Electricity Standards" or "Renewable Portfolio Standards" (RPS), which mandate increasing amounts of states' electricity to be produced from renewable sources. Twenty one states and Washington D.C. already employ RPS systems to help stimulate growth in the renewables sector[8]. The RPS is designed to diversify power sources and stimulate a long-term market for renewable energy, and thereby reduce risks for new technologies and optimize financing options. Operating a waste-to-ethanol facility in a state with an existing RPS would be an excellent fit. California, for example, uses a rule where for a hybrid system using both renewable and fossil fuels, the renewable portion qualifies under the RPS and may be eligible for Supplemental Energy Payments (SEPs). This is good for this model, which qualifies as a hybrid system since it provides 20% of its heat load by purchased natural gas. These SEPs provide a financial incentive per kilowatt-hour to be determined by the California Energy Commission and paid with state funds. Furthermore, the implementation of a trading system based upon Renewable Energy Credits would have very positive ramifications for renewable energy producers, since they would be able to sell their RECs to other, non-renewable sources, further bolstering their revenues.

Environmental Benefits:

Because the primary source of energy and materials for the plant is diverted landfill waste, there are numerous environmental benefits to be had from the process. Using MSW as an ethanol feedstock results in a liquid transportation fuel that emits renewable carbon; since the carbon dioxide present in tailpipe emissions is not sourced from fossil fuels, its negative environmental effects are greatly lessened. Because the facility fills all of its electrical needs and 80% of its heat load from its own power plant, each kilowatt-hour exported to the grid and each gallon of ethanol produced can be considered over 80% renewable. The remaining 20% of the plant's heat load could instead be met by installing electrically powered boilers to generate steam, but doing so would not be as efficient on a cost or energy basis. Additionally, each ton of MSW that is diverted from a landfill reduces the potential of that material to degrade into methane on its own. In landfills that do not employ the technology to capture landfill gas and generate electricity from it, the gradual breakdown of the waste into methane poses a considerable greenhouse gas (GHG) problem. Methane gas has 23 times the global warming potential as carbon dioxide does. By capturing the MSW to make it into ethanol and digesting the remainder into methane in a controlled environment, not only is the potential for harmful GHG emissions averted, but a renewable source of energy is captured as well. Furthermore, when compared to existing conversion technologies for MSW, this new type of facility would hazard less pollutants in the air and water than past waste-to-energy plants have been able to do. Combustion of trash has always been a contentious issue due to pollution concerns and emissions of dangerous compounds like dioxins. Gasification, on the other hand, has been shown to be a safe alternative that falls well within range of emissions standards[9], since its thermal conversion process is fundamentally different than combustion. The anaerobic digestion and aerobic polishing tanks also clean the plant's wastewater so it can be safely disposed of. As with all power generation scenarios, demand side management is the most efficient means towards climate change mitigation and national security. However, the technology to turn MSW to ethanol has the potential to support both the environment and a healthy economy, while simultaneously aiding the effort for national energy independence.

Impact:

As well as producing clean electricity with minimal environmental impact, using MSW to produce ethanol has the potential to make an impact in transportation fuels. Conservative modeling shows that 25 gallons of ethanol per dry ton of MSW is a very reasonable expectation for ethanol production. The US sent nearly 250 million tons of MSW to the landfill in 2006, not including construction and demolition debris[10]. If this stream were converted to ethanol, it would yield 6.25 billion gallons of fuel each year. Given a rough figure of US consumption at 145 billion gallons per year, MSW has the potential to replace 2.9 percent of the nation's gross usage[11], assuming that the difference in energy content makes ethanol 2/3 as effective in automobile engines. By volume, 4.3 percent would be displaced. This is no trivial number – at the very least, MSW could satisfy the majority of the country's oxygenate demand for liquid fuel with renewable carbon, while producing excess electricity at the same time. Indeed, the electricity produced would be equally as substantial: by generating 17.4 kWh per gallon of ethanol produced, converting the country's waste into fuel would result in 1.08x1011 kWh per year, or 298 GW of added capacity to the grid. Despite these already significant figures, further developments of the process would have a large impact upon the yields of ethanol per ton. The integration of the facility with an existing petrochemical refinery would satisfy the plant's heat loads and reduce shipping costs to the price of a pump to send the ethanol over the fence to be mixed. The heat from the refinery would free up additional energy resources for electricity production, furthering efficiency, output and profits. Also, there is a great deal of work being done to develop microbes that can ferment both 5 and 6-carbon sugars to ethanol – this model only incorporates the existing 6-carbon utilizing microbes. This could ostensibly multiply by 150% the amount of ethanol fermented from the same amount of cellulosic material, drastically improving the efficiency of the plant as well as its balance sheet. There is a large amount of room for growth, refinement and expansion of the process, but even with today's technology, producing ethanol from MSW can be done in an efficient, environmentally sound and profitable fashion.

Assumptions:

In order to simulate the function of an MSW-to-ethanol plant as accurately as possible, a few assumptions about certain process parameters had to be made. The relationship between solids concentration at hydrolysis and the energy required for distillation is an important point. In order to reduce the amount of water to be removed at distillation and yet maintain enough liquidity at hydrolysis for effective enzyme function, a portion of the hydrolyzate is re-circulated back into the saccharification tank with some wash water in order to reduce solids content, and increase the final concentration of fermentable sugars. Additionally, low levels of inhibition at fermentation were assumed. Because MSW is a heterogeneous feedstock with a great number of potential contamination sources, inhibition of the yeast culture could pose to problem. At lab scale tests on post-autoclave material, however, no inhibition was noted and it was assumed that this could be scaled up to an industrial operation. For the Battelle gasifier, it was assumed that the BTU value of the Refuse Derived Fuel (RDF) was 8500 BTU/lb. The RDF is the treated MSW to be fed into the cogeneration system. This number may end up being on the low side by a significant margin, since a large amount of plastics and high heating value materials are present that are currently not fully accounted for (in order to create a conservative estimate of profitability). Calorimetry tests on the RDF will confirm the true higher and lower heating values, while ash fusion testing will be done to assess if the RDF would cause slagging or fouling in the gasifier. Past studies indicate that the Batelle gasification unit, which is specifically designed for biomass feedstocks, would function well with the CR^3 treated MSW[12]. The feed for the aerobic treatment plant has been tested and has been shown to be highly suitable for methane generation as well. For the sake of efficiency, it is assumed that the methane produced by the anaerobic digesters could be burned in the rotary dryers.

Economics:

The modeling of the initial capital investment was based upon information from a variety of sources. The autoclaves were priced by CR^3, including all the necessary conveyors and lifts as well as the costs associated with construction and permitting. The hydrolysis, fermentation and distillation processes were adapted from a dry-grind corn ethanol plant, while the cogeneration plant was modeled from papers examining the economics of the Battelle/FERCO gasification system[13,14,15]. Equipment costs were scaled by an exponential factor of 0.65, in order to reflect the economies of scale that come with a large scale facility as well as the economic challenges of building a smaller operation. The factor of 0.65 was chosen as the midpoint of the most common range as reported by NREL[16]. The formula for scaling is as follows:

$$Cn = Co\left(\frac{New}{Original}\right)^{0.65}$$

Where Cn represents the new equipment cost, Co represents the original price, and the new size is divided by the original size and then scaled to the factor of 0.65. For our purposes, the ratio of equipment size was measured by the throughput of material each piece of equipment was required to handle, as opposed to a universal scale from one plant to another based on ethanol output or feedstock input, for example.

By far the most substantial initial costs are levied by the cogeneration plant. For the small plant, the costs of the power station alone represents 47% of the total capital cost, while for the large model, 41% of the initial costs are allocated to power production (the difference is a result of the aforementioned scaling factor). However large the cost at the onset may seem, it is, in fact economical to invest in a cogeneration station because of both the costs saved from purchased energy requirements, and the addition of another income stream in the form of electricity. Should the cogeneration station be removed and all power production capability along with it, the averted capital costs barely make up for the loss of revenue and saved annual natural gas expenses. However, with any fluctuation of the price of electricity, the lack of the capability to produce power becomes a significant loss. Although cutting out the gasifier from the small model saves $1.6 million of the plant's net value, a modest 2 cent per kWh price increase to 7 cents would lose the plant $3.6 million over its lifespan. Despite the high capital costs and increased labor requirements, including the means to generate power within the plant proves to be a more financially sound option, with the environmental benefits from sustainable heat and electricity as an added bonus.

The annual operating costs were calculated in a similar fashion, with CR^3 providing the data for the autoclaving and separation processes and the ethanol production equipment coming from the corn dry-grind model. Rollins et al. provided a detailed outline of operating costs for the cogeneration plant[17]. Private bids and price quotes filled in the gaps of specialty equipment that were not provided by the other models. Personnel requirements for the facility were estimated by CR^3. The price of ethanol, gasoline (to denature the product) and electricity were based off the dry grind plant, although the variation of the prices as a factor of geographic location and other factors proves to be a significant player in the profitability of the plant for a specific area.

Along with the tipping fee, the selling price of ethanol and electricity are the key to financial success. The most significant operating costs come from energy as well – the plant's sensible heat load is quite large, and a variety of equipment requires electricity. The electrical and BTU loads were calculated from existing data, or estimated on the basis of horsepower required (for conveyors or mixers) or pounds of water evaporated (for the rotary dryers). The end result is a conservatively large prediction of the heat and electricity loads of the plant. The output of the cogeneration plant fulfills 79% of the plant's heat requirements, and 15.2 times the electrical need. The remaining 21% of the BTUs required is supplied by purchased natural gas and is an annual operating cost, while the excess electricity provides revenue. The largest individual operating cost, including the cost of employee salaries, is the discharge of wastewater out of the anaerobic digestion and aerobic polishing systems.

In order to calculate the state tax burden upon the plant's operations, it was necessary to determine the appropriate system to determine the depreciation of the plant's assets. The value lost as capital depreciation can be subtracted from a business' annual taxable income. Because an industrial operation such as this would find itself in a tax bracket of 39%[18], the tax savings from depreciation can be significant. Since the plant is a hybrid between an ethanol plant, a power plant and wastewater treatment facility, the facility was depreciated using the double-declining balance method (DDB) for the sake of simplicity. DDB accelerates the depreciation of an asset to reflect greater loss in the earlier stages of its lifetime, which is a more realistic approach than straight line depreciation. The US government's Modified Accelerated Cost Recovery System (MACRS) uses a more complex declining-balance model. Each item of equipment was depreciated on the basis of its expected productive life, while the entire plant was economically evaluated on a 20 year lifespan. If a piece of equipment was expected to last for 10 years, it was depreciated for that period of time and then repurchased after its 10 years were up. No scrappage value was included in this model[19].

One of the most commonly used metrics to determine the profitability of a new project is to find its internal rate of return (IRR). This is done by quantifying all of the annual cash flows in and out of the firm for the entire lifespan of the operation, and then putting those funds in present value terms. This reflects the time value of money: a dollar earned today is more useful than a dollar earned a year from now because today's dollars have the ability to earn interest in the future. Conversely, money earned in the future is less valuable than today's money because the interest that could be earned in the meantime is forfeited. In order to find the IRR, the net total of all of the plant's future earnings must first be calculated. The sum total of every year's profits, converted to present value by a chosen discount rate, is called the net present value (NPV) of the plant. The IRR, then, is the discount rate that results in a net present value of zero. Consequently, the higher the IRR and the higher the NPV, the more profitable the operation is likely to be. As may be apparent, the NPV of the plant is subject to change drastically with the choice of the discount rate. An *r* of 10% was chosen for our purposes as per the recommendations of Short et al. No grants or subsidies were included in the model except for the Small Producer Credit, which offers 10 cents a gallon up to 15 million gallons per year as long as the plant is under a capacity of 60 MGY (both the large and small models fulfill this requirement). However, should any grants or renewable energy credits be provided to the facility, especially as a financial premium per kWh produced, the facility would stand to gain a large amount of money. For example, green power stations usually sell Renewable Energy Credits (REC's) separately at a median price premium of 2.5 cents/kWh. This would make the small plant $5 million more profitable, and the large plant would stand to gain $48.7 million. The balance sheet of the operation is most sensitive to a few factors, namely the selling price of the electricity and ethanol it produces and the tipping fee it collects from the incoming feedstock.

Results:

Annual costs and revenues for the 300 and 3,000 TPD models are shown in Figures 1, 2, and 3. The two different size scenarios create a very clear picture of the benefits of large-scale operations. The large scenario of 3000 TPD of MSW is highly profitable: by taking advantage of the economies of large-scale operation, it will manage to pay for itself within the first four years of operation. Over a 20 year lifespan, the large model brings in $275 million of present-value profits, at an IRR of 31.5%.

The sensitivity of profitability to tipping fees, and the selling prices of ethanol and electricity, is shown in Figures 4a and 4b for the two models. The large model proved to be well in the black even if the money generated from tipping fees was completely eliminated. For both models, any increase in tipping fee, selling price of electricity or price of ethanol would further increase the profitability of the plant over the values exhibited by the base case.

For the small 300 TPD plant, conservative estimations throughout the creation of the model and the very small scale of the plant stacked the odds against financial success. This is reflected by the base case's negative net present value, of -$8.4 million. Although that case does not make money with a discount rate of 10%, it still exhibits a positive IRR of 5.9%. More importantly, however, the small plant may still prove to be a lucrative option in certain scenarios, because how much money the plant makes is dependent on the aforementioned factors. For example, in a smaller population base with a $50 tipping fee and an electricity price of 8 cents/kWh, a 300 TPD plant would be profitable operation with a NPV of $4.12 million and an IRR of 12%. The fact that the small plant has the capability of being a worthwhile investment despite the initial disadvantages that come with its size is an added bonus, increasing the impact and applicability of the MSW-to-ethanol technology.

Another option that could potentially be more viable for low population areas would be the adoption of a distributed model, where small autoclave-only plants are decentralized around small town landfills. The processed cellulose rich pulp would then be shipped by truck or rail to a central facility to make ethanol, which would ideally be co-located with an existing petrochemical refinery for heat sharing and over the fence sales of the finished ethanol. Minimization of transit and storage time would be important as the pulp is susceptible to microbial action. Shipping would most likely not pose a prohibitive cost: each satellite plant would make 150 tons of biomass per day, which could easily fit in two daily railroad cars. This may be an effective way to reduce the costs of building a small facility, and is likely to fall in between the existing small and large models in terms of profitability.

Future Work:

There are several areas where further development is needed to confirm or improve on the assumptions made in the models: 1) The hydrolysis and fermentation steps and the ability to recycle much of the hydrolyzate to increase sugars concentration before fermentation; 2) The high water discharge costs, and ways to decrease these, perhaps by recovering a portion via reverse osmosis; 3) The biogas potential of the waste streams, by determining their actual BOD and biogas potential; 4) Whether significant variations in the feedstock are likely to occur (for example, by the addition of significant amounts of crop residues, which would be seasonal in nature), and whether these would have any significant impact on operations.

Conclusions:

With increasing effort being put towards the development of alternative energy, it becomes important to separate the technology that may be viable in the distant future from what could be implemented in the present. This model attempted to determine whether existing equipment combined in a new way could be financially successful under current circumstances, and what impact that might have upon the climate of both landfill use and ethanol production. Needless to say, being able to produce renewable transportation fuel from what was previously a cumbersome waste stream would be a boon. With emerging technologies and markets, however, the establishment of new operations becomes more successful and expeditious if those operations are able to stand on their own feet financially. This has proven to be a problem with most alternative energy options; since new technology is often more expensive to start off, it is problematic to build the first generation facilities and products that are less likely to be profitable. Cheaper, later generation businesses require those initial plants in order to drive down costs. But most of the technology utilized in the MSW to ethanol plant has been scaled up to varying degrees already, so the first generation plant problem would be minimized. The financial incentive is the most motivating factor in a free market economy like the United States, and could be more effective at spurring investment and construction of new facilities than if they were supported by subsidies and grants. The model shows significant promise for turning MSW into ethanol, not only at a large scale but potentially on a smaller scale or in a decentralized fashion as well. Further developments in the fields of cellulose hydrolysis, fermentation and distillation will only increase profitability, as would rising gasoline prices and increasing demand for renewable fuel. Among a myriad of energy options that could be implemented in the future, turning waste into ethanol is one that should be explored now.

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Figure 1 – 300 TPD Annual Costs ($9.8M)

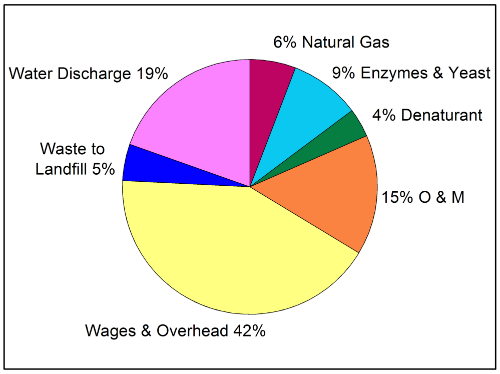

Figure 2 – 3,000 TPD Annual Costs ($52.3M)

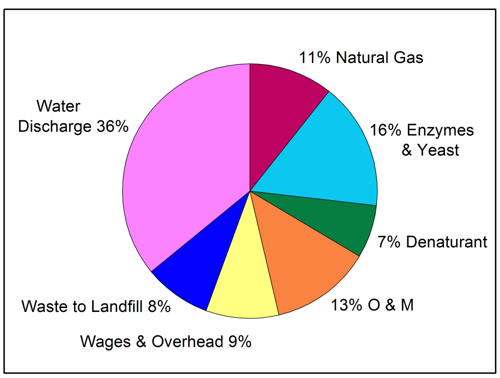

Figure 3 – Annual Revenues. 300 TPD = $13.2M, 3,000 TPD = $131.9M (proportions are identical)

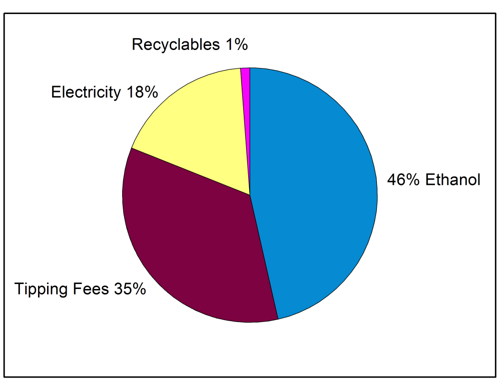

Figure 4a – Profitability as a function of input factors, 300 TPD model

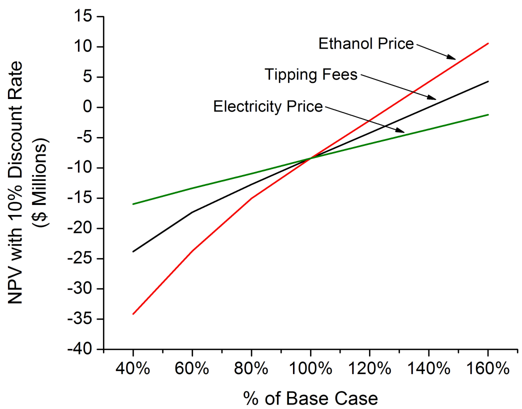

Figure 4b – Profitability as a function of input factors, 3,000 TPD model