Environmental and Economic Impacts of Energy Production from Municipal Solid Waste

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Report #

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List of Abbreviations & Acronyms

i.	Municipal Solid Waste	MSW
ii.	Anaerobic Digestion	AD
iii.	Landfill Gas	LFG
iv.	Combined heat and power units	CHP
v.	Fischer-Tropsch Synthesis	FTS
vi.	Compressed Natural Gas	CNG
vii.	Greenhouse Gas	GHG
viii.	Waste to Energy	WtE
ix.	Nitrogen, Phosphorus, and Potassium	NPK
x.	Chemical Engineering Plant Cost Index	CEPCI
xi.	Activated Carbon	AC
xii.	Waste Water Treatment Plant	WWTP
xiii.	Net Present Worth	NPW
xiv.	Waste to Energy	WtE
XV	Pressure Swing Adsorption	PSA

FINAL REPORT

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ABSTRACT

The average amount of waste generated in the United States is 4.4 lb/day/person, and the vast majority of it is landfilled. The enormous amount of energy contained in these wastes presents an opportunity for renewable energy production. Comparison and analysis of energy production methods in terms of economic and environmental impacts are needed to make best use of resources. Therefore, it is crucial to implement waste to energy technologies when advantageous to reduce landfilling, to generate profit, and to minimize environmental impact.

Municipal Solid Waste (MSW) can undergo processes like Anaerobic Digestion (AD), Incineration or Gasification to produce biogas or syngas. In addition, gases produced in landfills (Landfill Gas or LFG) can be used as an energy source as well. These gases can be purified and upgraded to be used in energy recovery methods such as combined heat and power units (CHP), Fischer-Tropsch Synthesis (FTS) for the production of liquid fuels, or the production of Compressed Natural Gas (CNG). These technologies are emerging and minimal data has been reported for the operation of these plants. A limitation encountered when trying to implement and build one of these plants is that there is no set tool that compiles and analyses the techno-economic data of the existing plants and can provide fast cost estimation for the screening of these alternative projects. The goal of this research is to create a software tool based in Excel to assist decision makers such as municipalities and waste management companies. Using this tool, the user is able to select the technology desired: AD, Gasification, Incineration or Landfilling, as well as the energy recovery method: CHP, liquid fuel or CNG production. The user will also provide the feedstock type (Municipal Solid Waste (MSW), Food Waste, Animal Manure, and Farm Waste), feed properties and plant capacity. The software tool is set to provide the user with the capital and operational cost requirements, biogas production rate and its composition, and where applicable,

liquid and solid production rates. The calculator also includes the cost of biogas purification based on the purity requirements for each energy recovery technique.

The use of the tool is illustrated using a base case AD plant that will generate biogas that will be used to produce liquid fuels via FTS. The plant processes 60,000 dry tons/year of MSW with a moisture content of 30%. Using the calculator, the capital cost of the AD plant is computed at \$21.0 million and the operational expenses at \$1.7 million /year. The capital cost associated with purifying the biogas up to liquid fuel production standards is \$500,000 and the operational expenses are \$163,000/year. The software tool provides the user with the ability to compare and contrast alternative waste-to-energy options and incentivize building these plants.

Disclaimer: While we have attempted to get the best estimates possible for the costs involved, the results should be considered as preliminary estimates only and actual costs can vary substantially depending on the feed types and specific technologies used.

KEYWORDS: Municipal Solid Waste (MSW); Energy Recovery; Material Recovery; Waste-to-Energy (WtE); Support Tool,

METRICS:

1. List graduate or postdoctoral researchers funded by THIS Hinkley Center project.

Name	Rank	Dept.	Professor	Institution
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2. List undergraduate researchers working on THIS Hinkley Center project.

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Wright, Anna	Chemical Engineering	USF	Kuhn/Joseph

3. List research publications resulting from **THIS** Hinkley Center projects.

Naqi, A., Kuhn, J.N., and Joseph, B., "Techno-economic Analysis of Producing Liquid Fuels from Biomass via Anaerobic Digestion and Thermochemical Conversion" submitted.

Cerna, Daniela, "Economic and Environmental Analysis of Waste-to-Energy Technologies Processing Urban and Rural Waste" (2018). Honor's Thesis, Chemical and Biomedical Engineering, USF, Tampa.

Naqi, Ahmad, "Conversion of Biomass to Liquid Hydrocarbon Fuels via Anaerobic Digestion: A Feasibility Study" (2018). M.S. Thesis, Chemical and Biomedical Engineering, USF, Tampa.

Stachurski, Paul, "An Investigation of Technologies for Energy Recovery from Municipal Solid Waste" (2018). Honor's Thesis, Chemical and Biomedical Engineering, USF, Tampa.

Zhao, X., Naqi, A., Walker, D.M., Roberge, T., Kastelic, M., Joseph, B., and Kuhn, J.N., "Conversion of landfill gas to liquid fuels through TriFTS (Tri-reforming and Fischer-Tropsch Synthesis) process: A feasibility study" submitted.

4. List research presentations resulting from **THIS** Hinkley Center project.

Cerna, D., Kuhn, J.N., and Joseph, B., "Economic Analysis of Waste-to-Energy Technologies for Urban and Rural Areas", SHPE National Convention, Cleveland OH, November 2018.

Stachurski, P., Joseph, B., and Kuhn, J.N., "Waste-to-Energy Technologies: Developing a Decision Making Tool for Municipalities and Private Companies", USF UG Research Colloquium, Tampa, FL, April 2018.

Naqi, A., Joseph, B., and Kuhn, J.N. "Techno-economic Analysis of producing Liquid Fuels from Waste through a combined Biochemical and Thermochemical Route", 2018 AIChE North Central conference, West Lafayette IN, April 2018

Naqi, A., Joseph, B., and Kuhn, J.N., "A Feasibility Study on Biofuel Production Using Anaerobic Digestion and Thermochemical Catalysis", AICHE Annual Meeting, Pittsburgh PA, October 2018.

5. List who has referenced or cited your publications from this project?

None at this time.

6. Provide an explanation of how the research results from this Hinkley Center project and previous projects have been leveraged to secure additional research funding.

We have submitted the following proposals:

Intensified biogas conversion to value-added fuels and chemicals (in collaboration with National Renewable Energy Laboratory (NREL), and an industrial partner). Submitted to DOE BETO. This proposal approved for ~\$1,800,000 with about half going to USF.

Sustainable Energy, Nutrient and Water Recovery from Organic Wastes for Space Applications (in collaboration with Dr. Ergas, Professor of Civil and Environmental Engineering, USF, T2C-Energy, LLC). Submitted to Florida-Israel Innovation Partnership. This will be resubmitted in 2019.

Development of a Decision Making Tool to Evaluate Sustainability of Alternative Approaches to Waste-to-Energy Projects. Submitted to EREF. Pending since Nov. 2018 for 2 year, \$120,000 fund request.

7. List new collaborations that were initiated based on this Hinkley Center project.

A collaboration was initiated with Dr. Ergas of USF, National Renewable Energy Laboratory, and an industrial partner, which resulted in the above named proposals. We also have a funded DOE project with a NREL and an industrial partner operating digestors commercially.

8. Provide an explanation of how have the results from this Hinkley Center funded project have been used (not will be used) by the FDEP or other stakeholders?

To date, the results have not been used by the shareholders.

1. INTRODUCTION AND BACKGROUND

A recent population projection study states that in 2051 the population in the US will reach 400 million, compared to 319 million in 2014 (Colby and Ortman 2017). As population grows, demands for food and consumer products are bound to increase. This phenomenon will have several impacts, but the main concern evaluated in this work is that there will be more waste being produced that must be properly disposed. For example, the average person produces 4.4 lbs. of waste per day (EPA 2014), meaning that nearly 250 millions of tons of trash will be produced per year in the US.

Currently, most of this waste in the U.S. is being landfilled (53.8%), and the rest is being recycled (34.5%) or incinerated (11.7%) (2017, Di *et al* 2013, Liu *et al* 2015). However, there are downsides to these options. Landfilling leads to undesirable gas emissions, ground water contamination, and the waste of valuable land (Hoornweg and Bhada-Tata 2012). Additionally, when only a part of the generated waste is recycled, the rest has to be landfilled. Therefore, incineration is considered an option because it helps reduce, by approximately 90%, the volume of the mass that requires landfilling (Hoornweg and Bhada-Tata 2012). However, incinerating can produce harmful gases, as well as gases that contribute to Green House Gas (GHG) emissions.

Therefore, municipalities and private entities are faced with the challenge to create solutions to the current waste disposal problems. These solutions have to be both economically and environmentally feasible. That is why these entities are adopting Waste to Energy (WtE) technologies to handle the waste generated in different locations around the U.S. A Waste to Energy technology is a waste management option that uses waste to create power or fuels such as high heating value gases, biogas or landfill gas.

In current work, we will evaluate biogas production through anaerobic digestion, syngas production by means of gasification, and compare them to LFG production from landfills. These gases are in turn purified with various adsorption and chilling operations. These processes upgrade the gas to be suitable for use in energy recovery processes such as power production, heat generation, Compressed Natural Gas (CNG), and liquid fuels. Another method that will be evaluated is incineration. However, this process is different from the ones mentioned above it only capable of producing heat and/or power.

These WtE technologies are new, and constantly under development and improvement. That is why the focus of this work is to compile and analyze economic and environmental data on each of the mentioned waste to energy options. Then, this data will be used to create a decision-making tool in Excel that can be used by municipalities and private entities to get a cost and an environmental impact analysis if they were to build and implement a plant that uses one of these technologies. Additionally, the program will report financial aspects such as: required capital investment, operational expenses, cash flows, and rate of return. For the environmental impact evaluation, the program will report: Carbon balances and CO_2 emissions from these processes. This tool will allow users to get preliminary estimates of project costs and environmental benefits. The aim of the tool is not only to allow the user to get fast estimates, but also to incentivize the implementation of WtE projects by allowing the user to see how profitable and beneficial the installation of such plants can be.

The waste to energy technologies mentioned in the section above have various advantages and disadvantages in both the economic and the environmental aspects. Some of those highlights, in terms of advantages and disadvantages, are listed in Table 1 below.

Table 1. Economic and Environmental Advantages and Disadvantages of Waste to Energy Technologies

	Economic	Environmental
Advantage	 Feedstock for waste to energy processes are renewable and widely available, therefore the production of gases through WtE can be done at any time and in the quantities desired (Kothari <i>et al</i> 2010). By-product of WtE processes can be sold increasing plant's revenues Increase jobs in the region where these projects are implemented (Stehlík 2009). 	 Less waste is diverted to landfills (Kothari <i>et al</i> 2010). Biogas is carbon-neutral(Kothari <i>et al</i> 2010). Using WtE technologies reduces Green House Gas Emissions AD produces digestate as a by- product which can be used as fertilizer In general, WtE technologies contribute to environmental protection (Tabasová <i>et al</i> 2012).
Disadvantage	 Few techno-economic data have been gathered for the operations of these plants. WtE plants have higher investment costs than traditional waste management options (Tabasová <i>et</i> <i>al</i> 2012). With the exception of incineration, there are very few commercial scale WtE plants of emerging technologies that can be used to verify the costs in the model's output 	 There is a need for software packages and plant designs that can model the actual environmental impact of each WtE project (Stehlík 2009). Due to the young nature of these plants, there is no clear environmental legislation that regulates the operations of such plants (Stehlík 2009).

2. WASTE TREATMENT OPTIONS AND ECONOMICS

2.1 Anaerobic Digestion Description

Anaerobic Digestion (AD) is a type of biological process caused by a variety of microorganisms, acting in the absence of oxygen. During AD, organic matter in the feed is broken down into two main products: biogas and digestate. The main steps in an AD process are: hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Khalid *et al* 2011). Additionally, AD processes are separated into two main categories: Low-Solids AD (<10% solids) and High-Solids AD (<20% solids) (Verma 2002).

Another parameter by which AD is classified is the temperature ranges inside the digester. AD can be mesophilic if temperatures inside the digester range from 30-38°C, and it is considered thermophilic if the temperatures range from 50-60°C (Buhr and Andrews 1977). For the design parameters of the digester type used in the Excel calculations, a thermophilic digester was selected. This type of reactor is considered to be better, compared to a mesophilic one, because the higher temperature causes the reaction rate to increase therefore having a higher conversion of the feed into biogas (Buhr and Andrews 1977). Another reason to select this digester is that it yields a safer digestate bi-product to utilize in farming without any additional treatment, since the high temperatures cause destruction of the pathogens (Buhr and Andrews 1977).

Biogas produced during the AD process is mainly composed of ~50% CH₄, ~50% CO₂, and traces of impurities like H₂S, siloxanes, and moisture. Biogas can be purified from these impurities and used for energy recovery applications. Digestate can be settled and used as compost, because it is rich in Nitrogen, Phosphorus, and Potassium (NPK).



Figure 1: Anaerobic Digestion Process Flow Diagram describing how waste can undergo AD to produce biogas and digestate.

2.1.1. Biogas Production Rate

The main product of Anaerobic Digestion is biogas, which is mainly composed of methane and carbon dioxide. In biogas, traces of water vapor and impurities can also be found. The impurities found in biogas will be linked to the type of feed processed in the digester. In order to estimate the biogas production rate, the Buswell and Mueller equation shown below (Eqn. 1) was use (Achinas and Euverink 2016).

$$C_{a}H_{b}O_{c}N_{d}S_{e} + \left(a - \frac{b}{4} - \frac{c}{2} + \frac{3d}{4} + \frac{e}{2}\right)H_{2}O$$

$$\rightarrow \left(\frac{a}{2} + \frac{b}{8} - \frac{c}{4} - \frac{3d}{8} - \frac{e}{4}\right)CH_{4} + \left(\frac{a}{2} - \frac{b}{8} - \frac{c}{4} + \frac{3d}{8} + \frac{e}{4}\right)CO_{2} + dNH_{3} + eH_{2}S$$
(Eqn. 1)

The variables a, b, c, d, and e are found using the weight percent dry basis ultimate analysis of the feed, in combination with the proximate analysis of the feed. An ultimate analysis gives the percent of carbon, hydrogen, oxygen, nitrogen and sulfur in feed. The proximate analysis gives the percent of fixed carbon, ash, and volatile matter. With these two analysis available, the volatile matter carbon was found by subtracting the amount of fixed carbon from the total percent of carbon determined by the ultimate analysis. This adjustment is done to account that not all carbon will become biogas, as a fraction of it will be part of the solid digestate.

As described by Curry and Pillay in their study of biomass conversion to biogas, only 40-65% of the volatile matter will be broken down and become biogas (Curry and Pillay 2012). Therefore, another adjustment to the ultimate analysis was made, the percent weights for each compound were multiplied by 52%, which is the arithmetic average of 40 and 65%. After these adjustments were made the weight percent, ultimate analysis was converted to mole percent. This was done by assuming a basis of 100 kg and multiplying each weight % by the basis. After this step, the mass was divided by the molecular weight to find the moles of each component. The total moles were found by adding each component's moles. Finally, each components moles were divided by the total moles to find the mole fraction of each component. This mole fraction corresponds to the variables a, b, c, d and e in the feed's chemical equation, as show in Table 2.

Compound	Weight %	Mole %
С	А	a
Н	В	b
0	С	С
N	D	d
S	Е	e

 Table 2. Variables for Feed Chemical Formula Derived from Dry Basis Mass Ultimate

 Analysis of the Feed

Once a, b, c, d, and e are found, the coefficients of the balanced chemical equation can also be determined. From these coefficients it is possible to estimate the production in kmoles of H_2O , CH_4 , CO_2 , NH_3 , and H_2S based on the kmoles of feed fed to the reactor. This estimation is done using stoichiometric ratios. The mass of products and feed can be found by multiplying kmoles by molecular weight, and volume of each product can be found by multiplying the mass of products by density. This way estimation of total biogas production, as well as production of each individual component can be achieved.

2.1.2. Mass Balance on an Anaerobic Digestion System

The balance done around the AD system was done by determining the mass coming into the digester and the mass coming out of it. The mass coming into the digester corresponds to the dry feed, the moisture in the feed, and the additional water added into the system to achieve a certain percentage solids inside the digester.

To determine the total feed into the digester including dry feed, moisture, and extra process water equation 2 is followed.

$$Total Digester Feed = \frac{Dry Feed}{\% \text{ solids}}$$
(Eqn. 2)

To find the part of the total digester feed corresponding to wet biomass, dry feed and moisture, equation 3 is followed.

$$Wet Feed = \frac{Dry Feed}{(1 - \% moisture)}$$
(Eqn. 3)

To determine the amount of moisture contained in the feed follow equation 4.

$$Moisture in the Feed = Wet Feed - Dry Feed$$
(Eqn. 4)

The amount of water added to the system can be calculated using equation 5.

$$Water Added = Total Digester Feed - Wet Feed$$
(Eqn.5)

For the mass coming out of the digester, the following stream masses were accounted for biogas, liquid digestate, and solid digestate. The mass of the biogas was determined as explained in the previous section, by using the Buswell and Mueller equation. The solid part of the digestate was determined by using the dry basis ultimate analysis and the proximate analysis of the feed. The digestate is composed of the ash, fixed carbon, and the portion of the volatile mater that did not have the potential to become biogas, which will correspond to 48% (Curry and Pillay 2012). The liquid part of the digestate is determined by subtracting the amount of water stoichiometrically needed to react with the feed, determined by the balanced Buswell and Mueller correlation, from the sum of the results yielded from equation 4 and 5.

2.1.3. Energy Balance on an Anaerobic Digestion System

The energy content of the feed was determined using the Dulong equation (Capareda 2013), shown below. Where C, H, and O are taken weight fractions from the dry basis ultimate analysis of the feed.

$$Q\left(\frac{J}{g}\right) = 338.3 * C - 1442(H - \frac{o}{8})$$
 (Eqn. 6)

The solid digestate's energy content was estimated using equation 6, with the exception that C, H and O are the adjusted weight fractions which account for the 48% of volatile matter that does not become biogas, from the dry basis ultimate analysis. In addition, the weight fraction of fixed carbon is included in the value for C.

The energy content in the biogas is estimated by finding the energy content in methane, since it is the gas with the highest heating value in biogas. The heating value of methane is 52 MJ/ kg; by

multiplying this value by the mass of methane in the biogas the energy content of the biogas is obtained.

2.1.4. Anaerobic Digestion Economics

2.1.4.1. Capital Expenses

Several Anaerobic Digestion plants have been implemented around the world. The following case studies were evaluated to retrieve the economic data parameters, such as capital cost to develop an anaerobic digestion plant based on plant capacity in tons of feed/year and feedstock type being processed. When gathering data from literature, it was concluded that AD plants processing waste with a higher moisture content had a lower capital cost than plants processing waste with a low moisture content. It was concluded that due to the nature of the AD process, were a high moisture content is needed inside the digester; it is more expensive to run AD for waste with a low moisture content. Therefore, two separate equations were fitted to accurately represent costs for low and high moisture content feeds.

For high moisture content feeds the data in Table 3 was used to fit the equation for Fixed Capital cost. According to a study done by Monnet, an anaerobic digestion plant processing 10,000 dry tons/yr of farm waste, such as manure, would require a total capital expense of \$1.3 million. The same study also reported that a plant processing the same feedstock, but with a capacity of 200,000 dry tons/yr, would require \$11.3 million as total capital investment (Monnet 2003). Additional sources reporting data for farm waste include a paper written by Karellas et al., were total capital expenses for plants processing 20,000 and 45,000 dry tons/yr were reported. The required capital was \$1.28 million and \$2.15 million, respectively (Karellas *et al* 2010).

Capacity thousand dry tons/yr	Capital Cost Million \$	Source
10	\$ 0.452	(Monnet 2003)
20	\$ 0.513	(Karellas et al 2010)
45	\$ 0.860	(Karellas et al 2010)
200	\$ 4.517	(Monnet 2003)

Table 3. Fixed Capital Cost Data for Different Plant Capacities for High Moisture Feeds

All these capital cost data was recorded in the Excel calculator, all data sources were studied to determine if the fixed capital cost they reported included the same parameters. These parameters included equipment used to estimate the plant cost, type of feed processed, and if the plant capacity was reported on a dry or wet basis. After analyzing all the data, the data sources representing the same parameters were selected. Time vale of money calculations were done using CEPCI indexes to assure all data points represented 2017 dollars. After all these steps were completed, the data points were plotted in Excel, and a line was fitted through the data to create an equation for fixed capital expenses as a function of capacity in dry tons per year, as show in Figure 2 below. The fitted equation is:

Fixed Capital Expenses for AD in high moisture feed =22.053*(*Plant Capacity (dry tons/yr)*) + 69,347



Figure 2. Fixed capital cost for an AD plant using high moisture feeds such as Animal Manure and WWTP sludge.

For low moisture content feeds the data in Table 4 was used to fit the equation for fixed capita cost as a function of capacity. Another report by Rogoff and Clark deals with the disposal and anaerobic digestion process of low moisture content feed, like MSW or yard waste. The authors report that for a capacity of 5,000 dry tons/yr, the capital expense needed is \$2.48 million (Rogoff and Clark 2014). Another report written by Seldman summarized relevant data for several anaerobic digestion projects around North America. Projects of different capacity were considered, but all projects had one thing in common; the waste they processed. All these plants accepted organic waste, specifically food waste. The plants reported processed 6, 10, 40, and 48 thousand dry tons/yr. The corresponding total capital expenses for these plants were \$2.3, \$6.0, \$18, and \$23 million (Seldman 2010). In the same study a plant processing 280,000 dry tons/yr of waste was also investigated. This plant receives waste from several locations, and is currently being examined to see how effective it is to have a centralized AD plant, as opposed to having multiple AD plants processing lower feed capacities. The total capital expense for a plant that size was reported to be \$87 million (Seldman 2010).

From the data gathered from these reports, it is clear that as feed capacity increases, there is also an increase in fixed capital investment needed to develop the project. Additionally, the equation fitted in Figure 3 below, was done following the same steps previously described for the high moisture content feed case. The fitted equation is:

Fixed Capital Expenses for AD in low moisture feed =119.69*(Plant Capacity (dry tons/yr))+1E6

Table 4. Fixed capital	cost for an AD plant using	high moisture feeds s	uch as Animal Manure
and WWTP sludge.			

Capacity (thousand dry tons/yr)	Capital	Cost Million \$	Source
5	\$	0.991	(Rogoff and Clark 2014)
6	\$	0.920	(Seldman 2010)
10	\$	2.401	(Seldman 2010)
40	\$	7.203	(Seldman 2010)
48	\$	9.203	(Seldman 2010)
100	\$	11.48	(Monnet 2003)
280	\$	34.81	(Seldman 2010)



Figure 3. Fixed capital cost for an AD plant using low moisture feeds such as MSW and yard waste

2.1.4.2. Operational Expenses

The operational expenses for an Anaerobic Digestion plant take into consideration labor cost, utilities, raw materials, and waste treatment. The operation expenses were also separated for high moisture and low moisture feeds.

For high moisture and low moisture feeds, the gathered data is shown in Table 5 and Table 6, respectively. The operational expenses for AD plants ranging from 10,000 to 45,000 dry tons/yr of farm waste range from \$7 thousand/yr to \$1.2 million/yr (Monnet 2003) (Karellas *et al* 2010). On the other hand for low moisture feeds, the operational expenses for an AD plant with capacities between 5,000-200,000 dry tons/yr range from \$290 thousand to \$4.8 million (Moriarty 2013) (Monnet 2003).

 Table 5. Operational Expense Data for Different Plant Capacities for High Moisture Feeds

Capacity thousand dry tons/yr	Operational Expenses Million \$	Source
10	\$ 0.280	(Monnet 2003)
20	\$ 0.418	(Karellas <i>et al</i> 2010)
45	\$ 0.902	(Karellas <i>et al</i> 2010)

Table 6. O	perational Ex	xpense Data for	r Different	Plant Cap	acities for 1	Low Moisture	Feeds
	F						

Capacity	Operational Expenses	Sourco
thousand dry tons/yr	Million \$	Source
5	\$ 0.114	(Monnet 2003)
50	\$ 0.650	(Moriarty 2013)
100	\$ 0.816	(Monnet 2003)
100	\$ 1.192	(Moriarty 2013)
200	\$ 1.918	(Moriarty 2013)

The data in Tables 5 and 6, was plotted in Excel to fit an equation for operational expenses as a function of plant capacity, in dry tons/yr. The fitted equation for the high moisture and low moisture feed cases can be seen in Figures 4 and 5, respectively.

The fitted equations are as follows:

Operational Expenses for AD in high moisture feed = 45.247 * (Plant Capacity (dry tons/yr)) + 203,463

Operational Expenses for AD in low moisture feed = 22.618 * (Plant Capacity (dry tons/yr)) + 310,343



Figure 4. Operational Expenses for an AD plant using high moisture feeds like animal manure and WWTP sludge.



Figure 5. Operational Expenses for an AD plant using low moisture feeds MSW and yard waste.



Figure 6. Operational expenses per dry ton for an AD plant using high moisture such as animal manure and WWTP sludge



Figure 7. Operational expenses per dry ton for an AD plant using low moisture feeds.

The data in Figures 4 and 5 follows the same trend as the capital expense data for AD, as capacity increases so do operational expenses. However, when compared on a \$/ton basis the operational expenses decrease as the plant capacity increases, as shown in Figure 6 and 7.

2.2. Gasification Process Description

Gasification is a process that converts dry feeds into gas. This process produces hydrocarbons that have a high H/C ratio, and that have energy stored in their bonds (Basu 2018). This energy can later be released in energy conversion technologies. Some of the advantages of gasification is that it is not utility intensive with respect to water, as low-moisture feeds are desired. Utilizing air as a gasifying medium keeps the operational expenses relatively low. Another benefit is that flue-gas cleaning is easier in gasification than in regular incineration plants (Basu 2018).

For the purpose of the Excel calculator, a low-temperature gasifier was selected. This gasifier is run at a temperature of $\sim 1000^{\circ}$ C. The main reason for the selection of this gasifier, is that this type is commonly selected when air is used as the gasifying medium (Basu 2018).

The main product of gasification is syngas, or synthesis gas. This gas is mainly composed of H_2 and CO. In addition to containing these two elements, the gas also has moisture, CO₂, CH₄ Gasification of biomass has been in the spotlight recently, since using biomass as the feedstock is carbon-neutral and renewable (Luz *et al* 2015).

2.2.1. Syngas Production Rate

As mentioned before, gasification of biomass produces syngas. The gasification of biomass follows the chemical reaction described in the equation below:

$$CH_X O_Y N_Z + X_g (0.21 O_2 + 0.79 N_2)$$

$$\rightarrow X_1 CO + X_2 H_2 + X_3 CO_2 + X_4 H_2 O + X_5 CH_4 + \left(\frac{Z}{2} + X_g 0.79\right) N_2 \quad (Eqn. 7)$$

The inputs for eqn. 7 are the following:

 $i. X_g = \frac{mol \ of \ air}{mol \ biomass}$

ii. X, Y, Z from the dry basis ultimate analysis of biomass. These variables are found following the same procedure explained under the biogas production rate section, where weight fraction were converted to mole fractions.

From the correlation listed by Gautam et al., we have the following equations used to calculate the percent of CO, H_2 , and CO₂ in syngas (Gautam *et al* 2010):

$$CO(\% mol) = 0.71 * C - 1.35 * H + 0.40 * O - 22.43$$
 (Eqn. 8)

$$H_2(\% mol) = 0.223 * C + 1.022 * H + 0.332 * O - 15.36$$
 (Eqn. 9)

$$CO_2 (\% mol) = -0.41 * C - 0.04 * O + 31.65$$
 (Eqn. 10)

In equations 8-10 the values for C, H, and O are the weight percent of Carbon, Hydrogen and Oxygen given by the dry basis ultimate analysis.

The unknowns in this model are: X_1 , X_2 , X_3 , X_4 , and X_5 , and the air flowrate needed. It is important to note that varying the air flowrate will cause the value for X_g to change.

The model must meet atom balances for C, H, and O, while ate the same time satisfying the correlation.

The atom balance equations are as follows:

 Carbon:
 (Eqn. 11)

 1 = X1 + X3 + X5 (Eqn. 11)

 Hydrogen:
 (Eqn. 12)

 X + 2 * Mw = 2 * X2 + 2 * X4 + 4 * X5 (Eqn. 12)

 Oxygen:
 (Eqn. 13)

The correlation equations given by Gautam et al. need to equal the mole fraction equations listed below:

$$CO(\%mol) = \frac{X1}{X1 + X2 + X3 + X4 + X5 + \frac{Z}{2} + Xg * 0.79}$$
(Eqn. 14)

$$H2 (\% mol) = \frac{X2}{X1 + X2 + X3 + X4 + X5 + \frac{Z}{2} + Xg * 0.79}$$
(Eqn. 15)

$$CO2 (\%mol) = \frac{X3}{X1 + X2 + X3 + X4 + X5 + \frac{Z}{2} + Xg * 0.79}$$
(Eqn. 16)

The sum of squares for equations 11-16 need to be minimized by changing X_1 , X_2 , X_3 , X_4 , and X_5 , and X_g . There are 6 equations and 6 unknowns, so utilizing Excel solver the unknown variables can be solved for.

2.2.2. Mass Balance on a Gasification System

The mass balance done around the gasification system was done by determining the mass coming into the system and the mass coming out of it, as described in Figure 8. The mass coming into the gasifier corresponds to the dry feed, and the air added as a gasifying medium. The mass of air added is determined by solving the equations in the previous section, and the mass of the feed is a user-defined input. From the mass coming into the gasifier, only the volatile matter portion can become syngas. The volatile matter portion is determined by subtracting the ash% and Fixed Carbon % from 100%, using the values given in a dry mass basis proximate analysis of the feed.

The mass coming out of the gasifier corresponds to the masses of CO, H_2 , CH_4 , CO_2 , H_2O and N_2 in the syngas. Additionally, the mass from the tar produced from the gasification is also allotted. This tar material is composed of the fixed carbon and ash contained in the feed.



Figure 8. Mass balance inputs and outputs in a gasification system.

2.2.3. Energy Balance on a Gasification System

The energy into the system corresponds to the energy content in the feed. This is determined using equation 6, the Dulong Equation, as described in the AD section. For the energy coming out of the system, the energy content of syngas and tar was determined. The tar's energy content was estimated using equation 6, whit the exception that C corresponds to the Fixed Carbon, determined by the dry basis proximate analysis. Additionally, the syngas energy is determined based on literature values. According to the book *Biomass gasification, pyrolysis and torrefaction: practical design and theory,* the energy content of syngas produced from biomass and air as a gasifying agent is between 4 and 7 MJ/ m³ of syngas (where syngas in this case is considered to be comprised only of CO and H₂, as they are the gases of interest).

2.2.4. Gasification Process Economics

2.2.4.1. Capital Expenses

The capital expenses of gasification are modeled by fitting an equation for fixed capital expenses as a function of plant capacity as graphically described in Figure 9.

The data used to fit these equations is detailed in Table 7

Capacity	Fixed Capital Investment	Source
thousand dry tons feed/yr	Million \$	Source
9	\$ 13.91	(Gasafi <i>et al</i> 2008)
161	\$ 71.03	(Lau 2002)
176	\$ 69.69	(Lau 2002)
177	\$ 70.07	(Lau 2002)
321	\$ 117.3	(Lau 2002)
353	\$ 116.34	(Lau 2002)
642	\$ 193.71	(Lau 2002)
707	\$ 193.71	(Lau 2002)

Table 7. Fixed Capital Expense Data for Different Plant Capacities for Gasification





The fixed capital expenses are modeled by the following equation:

Fixed Capital Expenses for Gasification () = 256.3*(Capacity (dry tons/yr)) + 2E+0 (Eqn. 17)

2.2.4.2. Operational Expenses

The operational expenses for gasification plant take into consideration labor cost, utilities, raw materials, and waste treatment. The techno-economic plant data obtained from literature is summarized in Table 8

Capacity	Operational Expenses	Source	
Dry tons/yr	Million \$/yr	Source	
3,650	\$0.64	(Choy et al 2004)	
3,650	\$0.64	(Choy et al 2004)	
3,650	\$0.61	(Choy et al 2004)	
3,650	\$0.56	(Choy et al 2004)	
3,650	\$0.56	(Choy et al 2004)	
7,300	\$0.86	(Choy et al 2004)	
7,300	\$0.86	(Choy et al 2004)	
7,300	\$0.84	(Choy et al 2004)	
7,300	\$0.77	(Choy et al 2004)	
7,300	\$0.77	(Choy et al 2004)	
19,710	\$0.99	(Luz et al 2015)	
52,195	\$1.73	(Luz et al 2015)	
115,000	\$2.55	(Luz et al 2015)	
266,000	\$5.1	(Luz et al 2015)	

Table 8. Operational Expenses for Gasification Plants at Different Capacities

The equation that models the relationship between operational expenses and plant capacity is: Operational Expenses for Gasification ($\frac{y}{yr}$) = 16.887*Capacity(dry tons/yr) +636,300 (**Eqn. 18**) The equation was obtained by fitting the obtained data using Figure 10 below.



Figure 10. Operational expenses of a gasification plant in relation to plant capacity in dry tons/year.

2.3. Incineration Process Description

Incineration is a process that is also known as combustion. In this process biomass is thermally converted, in the presence of oxygen as the oxidizing agent. The products are heat, water, and carbon dioxide. The heat produced during this process is termed, heat of combustion of biomass, which is related to the heating value of the combusted biomass. The heat produced during this process is used to generate electricity or to provide thermal energy for a furnace.

2.3.1. Material Balance on an Incineration Plant

The complete combustion that mass undergoes in an incineration plant follows the chemical reaction shown in equation 19, taken from "*Introduction to biomass energy conversions*" (Capareda 2013)

$$C_{x}H_{y}O_{z}N_{a}S_{b} + \left(x + \frac{y}{4} - \frac{z}{2}\right) * \left[O_{2} + 3.76N_{2}\right] \to xCO_{2} + \left(\frac{y}{2}\right)H_{2}O + \left(x + \frac{y}{4} - \frac{z}{2}\right) * 3.76N_{2} + bS + Heat$$
(Eqn. 19)

The coefficients x, y, z, a, and b can be determined from a dry basis ultimate analysis of the feed, as previously described in sections preceding this one. The part of the feed that will combust will be determined using equation 20.

Feed that will combust
$$\left(\frac{kmol}{yr}\right) = Dry Feed \left(\frac{kmol}{yr}\right) * (volatile matter fraction)(Eqn. 20)$$

The volatile matter feed fraction can be determined with a feed proximate analysis. Additionally, the kmoles of feed that will combust need to be converted to kg, by using the average molecular weight of the feed.

Then, the necessary air for combustion will be determined by stoichiometrically finding the O_2 and N_2 needed to combust with the feed, and then converting the kmoles to kg.

The mass flowrate coming out of the incinerator is found by adding the mass of CO_2 , H_2O , and N_2 produced in combustion. Additionally, the mass of the solids (ash) needs to be accounted for using equation 21.

Solids Products of Incineration $\left(\frac{kg}{yr}\right) = Dry Feed\left(\frac{kg}{yr}\right) * (mass fraction of ash)$ (Eqn. 21)

2.3.2. Energy Produced on an Incineration Plant

The energy produced by the incineration of biomass will be equal to 70% of the energy content of the feed (previously estimated using the Dulong equation). Only 70% of the heating value is recovered through incineration as there are some heat losses, and the process is not 100 % efficient.

2.3.3. Incineration Economics

2.3.3.1. Capital Expenses

The capital expenses for the incineration process were modeled using the data obtained from a study done by Murphy and McKeogh titled "Technical, economic and environmental analysis of energy production from municipal solid waste" (Murphy and McKeogh 2004). This study collected economic data for incineration plants in Britain, Ireland, America, and Denmark, and the condensed data is detailed in Table 9.

Table 9. Economic Data for Fixed Capital Expenses of Incineration Plant	nts
---	-----

Capacity (thousand dry tons/yr)	Fixed Capital Investment (\$ Million)
40	\$24.6
120	\$63.6
230	\$121.8

The data from Table 9 was fit into the following equation to determine the fixed capital cost as a function of plant capacity. The resulting fitted equation is:

Fixed Capital Expenses for Incineration (\$) = 512.64*Capacity (dry tons/yr) +3E6



Figure 11. Equation to determine the fixed capital expenses of incineration based on plant capacity

2.3.3.2. Operational Expenses

The operational expenses were determined using the data collected by Murphy and McKeogh (Murphy and McKeogh 2004).

The fitted equation is: Operational Expenses for Incineration (\$) = 31.68*Capacity (dry tons/yr) + 690,476

Table 10. Economic Data for Operational Expenses of Incineration Plants

Economic Data for Operational Expenses of Incineration Plants

Capacity (thousand dry tons/yr)	Operational Expenses (Million \$)
40	\$1.8
120	\$4.8
230	\$7.9



Figure 12. Equation to determine the operational expenses of incineration based on plant capacity.

3. Biogas Purification Technologies

Biogas contains traces of impurities like hydrogen sulfide, siloxanes, and moisture. These impurities have to be removed if the biogas is to be upgraded for subsequent energy recovery. The impurities encountered in the biogas depend on the type of feed being processed. For example, feed composed of MSW has impurities such as siloxanes, since this type of feed is composed of personal hygiene and beauty products that contain it. On the other hand, digesters processing animal manure will produce biogas with higher hydrogen sulfide contents. In order to remove these impurities the use of activated carbon beds, iron sponge beds, coolers, and blowers are appropriate. The tolerated level of impurities in the biogas depends on the selected energy recovery technology, and limits are shown in Table 11.

	H ₂ S	Unit	siloxanes	Unit
Liquid Fuel Production	5 (Sun <i>et al</i> 2015)	mg/m ³ biogas	5 (Kuhn <i>et al</i> 2017)	mg/m ³ biogas
CNG	16 (Shah and Nagarseth 2015)	ppmv	2.5 (Kuhn <i>et al</i> 2017)	mg/m ³ biogas
Turbine	350 (Kuhn et al 2017)	ppmv	14 (Kuhn <i>et al</i> 2017)	mg/m ³ biogas
Internal Combustion Engine	1500 (Kuhn et al 2017)	mg/m ³ CH ₄	20 (Kuhn <i>et al</i> 2017)	mg/m ³ CH4

Table 11. Purity Requirements for Energy Recovery Technologies

To remove the amount of impurities that exceed the acceptable limits, the following purification technologies are used: activated carbon beds, iron sponge beds, coolers, and blowers. Their description follows in the sections below. These beds have different adsorption capacities and prices per pound of bed material, which are listed in Table 12 and 13, respectively.

Table 12. Adsorption Capacities of the Beds

Bed Type	Capacity
Iron Sponge Bed	2.5 kg H ₂ S/kg media (Kuhn <i>et al</i> 2017)
Activated Carbon Bed	0.216 kg Siloxanes/ kg media (Kuhn et al 2017)

Table 13. Cost of Bed Materials

Bed Material	Cost
Sulfarite	\$ 0.72 /lb (Zicari 2003)
Activated Carbon	\$ 1.5 /lb (Elwell <i>et al</i> 2018)

3.1. Activated Carbon Beds

These beds are composed of Activated Carbon (AC). This material has small pores that increases its surface area, making it a prime material for adsorption. These type of beds are used to remove organic compounds present, in this case, in biogas or LFG. They have one of the greatest breakthrough times (how long it takes before the bed is saturated and needs

replacement/regeneration) in the market. The concentration of these impurities present in the biogas are typically low; and they get adsorbed into the surface of the AC.

3.1.1. Capital Expenses

The capital expenses for activated carbon beds include equipment and installation costs. This value was estimated using the $6/10^{\text{th}}$ rule, shown in equation 7 below.

Cost 2 = Cost 1 *
$$(\frac{Q2}{Q1})^{0.6}$$
 (Eqn. 22)

where Q1 and Q2 are the capacities of the plants.

For Cost 1 the obtained literature data corresponds to 51,100 for a Q1 of 190 m³/hr (Ong *et al* 2014).

3.1.2. Operational Expenses

The operational expenses of the activated carbon beds are determined by the amount of siloxanes that need to be removed per year. Siloxanes will be present if the feed is MSW or WWTP sludge. The average amount of these impurities found in biogas can be found in Table 14.

Table 14. Average Concentration of Siloxanes in Different Feed Types

Compound	Feedstock Option			
Siloxane mg/m ³ biogas	MSW	WWTP Sludge		
	16.8 (Surita and Tansel 2015)	46 (Dewil <i>et al</i> 2006)		

Since the biogas flowrate (in m^3/yr) was previously estimated using the Buswell and Mueller equation, the amount of siloxanes produced by the digester per year can be determined. If the allowed impurity levels per year are subtracted from the total impurity mass flow rate, the amount of impurities that need to be removed per year are determined. Then, using the bed adsorption capacity it is possible to determine the mass of media needed per year to remove all the impurities. With this required mass of bed material per year known, we can determine the cost on a per year basis, using Table 13 for buying the bed materials.

3.2 Iron Sponge Beds

These beds are made out of Hydrated Iron Oxide, typically supported on wood chips. These beds purify biogas or LFG by reacting the hydrated iron oxide with hydrogen sulfide (H_2S) to produce iron sulfide and small amounts of water.

These beds work really well to remove hydrogen sulfide, and are very efficient because they can easily be regenerated by flowing oxygen through them. New bed design and technologies even allow for removal of greater H_2S concentrations, and produce even lower pressure drops across the bed. Additionally, they are non-toxic and environmentally friendly.

3.2.1 Capital Expenses

The capital expenses for iron sponge beds include equipment and installation costs. This value was estimated using the $6/10^{\text{th}}$ rule, using equation 7.

For Cost 1 the obtained literature data corresponds to 8,300 for a Q1 of 0.94 m³/min (Abatzoglou and Boivin 2009).

3.2.2 Operational Expenses

The operational expenses for iron sponge beds were determined following the same procedure as the ones for activated carbon beds, with the exception that the amount of hydrogen sulfide contained in biogas was determined using the Buswell and Mueller equation, and not from an average concentration based on feed type.

3.3 Cooler and Blower Units

This step in the biogas purification system is also called a dehumidification unit. Biogas or LFG will inevitably contain moisture (water vapor), which needs to be removed. The need to remove this moisture comes from the fact that water vapor can cause corrosion on turbines or energy recovery systems downstream in the process. Additionally, removing water increases the gas's Heating Value. This system cools down the gas, and causes the water to condense out, and be collected in a condensation tank.

3.3.1 Capital Expenses

The capital expenses for the cooler unit include equipment and installation costs. This value was estimated using the $6/10^{\text{th}}$ rule, using equation 7.

For the cooler, Cost 1 the obtained literature data corresponds to \$76,400 for a Q1 of 2,500 scfm.

For the blower, Cost 1 the obtained literature data corresponds to \$50,000 for a Q1 of 2,500 scfm.

3.3.2 Operational Expenses

The operational expensed were also determined using $6/10^{\text{th}}$ rule. For the cooler, Cost 1 is \$35,300 and Q1 is 2500 scfm. For the blower, Cost 1 is \$46,150 and Q1 is 2,500 scfm.

4. Energy Recovery Methods

4.1 Combined Heat and Power Unit Description

Combined Heat and Power units are also known as cogeneration units. They produce both electricity and heat. Typically, in power generation units alone the efficiency is estimated to be \sim 20-25%; and in heat generation the efficiency is approximately \sim 70-80%.

As it can be seen, power generation units alone are not as efficient, since there is a lot of thermal energy wasted.

In a CHP unit, power can be generated by a steam turbine. In this process, biomass or biogas are burnt, and the thermal energy resulting from this process is used to boil water to generate steam. The steam is pressurized and used to do mechanical work on a rotating shaft. This rotary motion drives an electric generator, used to produce electricity. The residual heat from the exhaust steam is recovered and utilized in the process. In a CHP unit the combined efficiency is between 80-90% (Horoloc 1987).

4.1.1 Capital Expenses

The capital expenses of a combined heat and power plant are determined by how much power is expected to be produced in the plant. Since the biogas processed has a heating value, the engine's efficiency is applied to determine how much power can be produced from the biogas fed to the engine. The efficiency of such a process is of 25%. Therefore the MW contained in the biogas are multiplied by 25% in order to find how much power the engine can produce. Then, the capital expenses are fitted using data obtained from "Cogeneration-combined Heat and power (CHP), Thermodynamics and Economics" (Horoloc 1987). This data is reflected in Figure 13, where fixed capital operational expenses are modeled as a function of power production.

The fitted equation is:

Fixed Capital Expenses for CHP Unit (\$) = -338.5*ln(Plant Capacity (dry tons/yr))+1718.4



Figure 13. Equation to determine the fixed capital expenses of a combined heat and power facility as a function of power production

4.1.2 Operational Expenses

According to "Cogeneration-combined Heat and power (CHP), Thermodynamics and Economics", the operational expenses of a combined heat and power system is \$6.31/kWh (Horoloc 1987). Assuming 25% efficiency (Horoloc 1987) and operation time of 8,000 hours/ yr , the kWh produced from the biogas fed to the system can be determined using equation 23.

Operational Expenses $\left(\frac{\$}{yr}\right) = \$6.31 * (MW \text{ in biogas}) * efficiency * operating hours (Eqn. 23)$

4.2 Liquid Fuel Production Description

Biomass has the potential to be converted into biogas or syngas, which can in turn be converted into hydrocarbon liquid fuels. The process through which this can be achieved is called Fischer-Tropsch Synthesis. This process converts gas, in the presence of a metal catalyst, into liquid hydrocarbon fuels. However, there are side products produced by this reaction like olefins, alcohols, and waxes. The steps involved in the FTS process are: synthesis gas preparation, FT synthesis, and product upgrading. FT synthesis can be carried at low temperature (220-240 °C) or high temperature (~340 °C). During the product upgrading step, the hydrocarbons can be separated or fractionated. Currently there are FTS commercial plants like Sasol in South Africa, PetroSA in South Africa, and Shell SMDS in Malaysia.

4.2.1 Capital Expenses

The capital expenses for a liquid fuel plant accounts for the following equipment: heat exchanger, compressors, drivers, towers, reforming reactor, and FTS Reactor. The cost for this equipment are discussed in the thesis "Conversion of Landfill Gas to Liquid Hydrocarbon Fuels: Design and Feasibility Study" (Kent 2016). The sum of these costs is \$9.38 Million, for a gas flowrate of 2,500 scfm.

Using the $6/10^{\text{th}}$ rule, the fixed capital expenses for plants processing different flowrates can be obtained.

Cost 2 =
$$9.38 Million * \left(\frac{Q2}{2,500 \, scfm}\right)^{0.6}$$
 (Eqn. 24)

4.2.2 Operational Expenses

The operational expenses for a liquid fuel production plant need to account for maintenance (which is estimated to be 5.5 % of FCI (Kent 2016)), labor cost for 7 operators, utilities, materials, and clean-up. The operational costs come out to be \$4.09 Million /yr, for a gas flowrate of 2,500 scfm.

Using the $6/10^{th}$ rule operational expenses for other plants can be determined.

Operational Expenses 2 =
$$4.09 \text{ Million} * \left(\frac{Q2}{2,500 \text{ scfm}}\right)^{0.6}$$
 (Eqn. 25)

4.3 Compressed Natural Gas Production Description

CNG is methane gas compressed at high pressures. The methane can come from biogas or LFG, and has to undergo a separation process to separate the CO₂ from the methane. The steps involved in making CNG are: compression, cooling, and dehydration (CNGNow 2018). During the compression step, methane is compressed to less than 1% of the volume if occupies at atmospheric pressure (CNGNow 2018). The compressed gas is stored in cylinders of up to 25 Mpa. This product can be used as transportation fuel for cars that have been modified, or specifically designed, to run on CNG. Some of the advantages of using this type of fuel is that the life of the car's oil is increased, since the combustion of CNG does not contaminate the oil. Another benefit is that the ignition temperature of the gas is around 540 °C, so the risk of flammability is less. One of the setbacks is that the transportation of such fuel is expensive, as it is a gas and not a liquid, so there are more safety considerations to take into account (CNGNow 2018).

For CNG production it is necessary to separate the CH₄ from the other components in biogas. Afterwards, CH₄ has to be pressurized to up to 1% of its original volume. This is done through a process called Pressure Swing Adsorption (PSA). A PSA column works by selectively adsorbing gas components in a microporous-mesoporous solid adsorbent at high pressures (Sircar 2002). A PSA column used to separate CO₂ will typically be ran at a pressure of 110 bar (Riboldi and Bolland 2015). This process is energy intensive, and uses approximately 100 MW. However, this technique does not rely on the use of steam for the purification and can achieve CO₂ purities of ~95% and CO₂ recoveries of ~90% (Riboldi and Bolland 2015).

4.3.1 Capital Expenses

The capital expenses with running a PSA column are modeled by the data obtained from "A techno-economic comparison of biogas upgrading technologies in Europe" (Warren 2012), and described in Figure 14.

The fitted equation is:



Fixed Capital Expensed for CNG= 1610.3 * Plant Capacity (dry tons/yr) +1E6

Figure 14. Fixed capital expenses of CNG production through PSA as a function of plant capacity

4.3.2 Operational Expenses

The operational expenses with running a PSA column to produce CNG are modeled by the data and equation described in Figure 15.

The fitted equation is:

Operational Expenses for CNG () = 550.29*ln (Plant Capacity (dry tons/yr)) + 35355



Figure 15. Operational expenses of CNG production through PSA as a function of plant capacity

5. Environmental Impact Analysis

Currently it is estimated that in the US there are 88 Waste to Energy plants that processes approximately 26.3 million tonnes of waste (Psomopoulos *et al* 2009). According to a study titled "Waste-to-energy: A review of the status and benefits in USA", choosing to process 1 metric tonne of waste in a waste to energy plant will result in $\frac{1}{4}$ less coal being mined in the US and importing 1 less barrel of oil (Psomopoulos *et al* 2009). Waste to energy technologies, compared to landfill, will produce less emissions of CH₄. A goal of WtE technologies is to reduce the emission of harmful greenhouse gasses. Methane is one such gas, which has 21 times more greenhouse gas potential than CO₂ (Psomopoulos *et al* 2009). In regular landfilling, approximately 25% of the methane produced is lost to the atmosphere, even if landfill gas collection systems are implemented. The paper by Psomopoulos et al. concluded that there is a reduction of 1 tonne of CO₂ for every tonne of waste that is processed in a waste to energy facility rather than a landfill (Psomopoulos *et al* 2009).

Another benefit of implementing these plants is that they require less area of land to build, as opposed to building a landfill. Additionally, processing waste in these facilities reduces the volume of waste that needs to be landfilled (Psomopoulos *et al* 2009).

To exemplify the environmental impact of the technologies studied in this paper, Carbon balances will be performed in Anaerobic Digestion Systems, Gasification Systems, and Incinerators. Additionally, the carbon emissions per kmol of waste fed will be determined.

5.1 Carbon Balance on an Anaerobic Digestion System

The Carbon coming into the system is totally found in the feed, and is determined using the dry basis ultimate analysis for the feed being processed.

Carbon In
$$\left(\frac{kg}{yr}\right)$$
 = Mass Dry feed $\left(\frac{kg}{yr}\right)$ * (weight fraction of Carbon in Ult. Analysis) (Eqn. 26)

The carbon coming out of the system is found in the biogas and the solid digestate. The carbon in the biogas is present in CO_2 and CH_4 . The carbon in the digestate comes from the Fixed Carbon and the 48% of the volatile matter carbon that did not convert to biogas.

Carbon Out in Digestate = Mass Dry feed $\left(\frac{kg}{yr}\right) * (wt fraction fixed carbon + (0.48 * wt fraction of Volatile matter Carbon)) (Eqn. 27)$

Carbon out in biogas
$$\left(\frac{kg}{yr}\right) = (moles of CO_2 + mol CH_4) * MW Carbon$$
 (Eqn. 28)

5.2 Carbon Balance on a Gasification System

The Carbon coming into the system is found in the feed, and is determined using the dry basis ultimate analysis for the feed being processed in combination with equation 20.

The carbon coming out of the system is found in the syngas and the tar.

Carbon in the syngas $\left(\frac{kg}{yr}\right) = (moles CO_2 + moles CH_4 + moles CO) * MW Carbon$ (Eqn. 29)

Carbon in the tar = Dry mass of feed * (wt fraction of fixed carbon) (Eqn. 30)

5.3 Comparison of CO₂ emissions

All these waste processing technologies like Anaerobic Digestion and Gasification produce less CO_2 emissions than traditional methods like landfilling or incineration. The relative amounts of CO_2 produced by each method can be found in Table 15. Additionally, the relative amounts of CH_4 produced are depicted in Table 16.

6. Excel Calculator Description

The calculator designed works to give the user techno-economic data on waste to energy plants. The user can obtain fixed capital and operational expenses for the different waste treatment methods and energy recovery technologies described in this thesis, based on the feedstock they want to process.

Method	kmol of CO2 produced / kmol of feed
Anaerobic Digestion	0.135
Gasification	0.267
Incineration	1
Landfilling	-

Table 15. Comparison of CO₂ Emissions for Various Waste Treatment Methods

Table 16. Comparison of CH4 Emissions for Various Waste Treatment Methods

Method	kmol of CH4 produced / kmol of feed
Anaerobic Digestion	0.159
Gasification	0.108
Incineration	0*
Landfilling	0.153** (Johari <i>et al</i> 2012)

*assuming complete combustion

**tons CH4/ton dry feed

6.1 Input Tab

In the input tab, the user is able to select the type of waste processed: MSW, WWTP sludge, agricultural waste, farm manure, yard waste, and food waste. After, the user is able to input the capacity, in tons of dry feed per year that the plant is going to process. Another input for the feed is the moisture content. Additionally, if Anaerobic Digestion is the selected waste processing method, the user will be able to input the percentage solids required inside the digester. The user can also select from a list of energy recovery technologies like: Combined Heat and Power, CNG, and liquid fuels.

The year the plant opens and closes, as well as the years of operation are an input. For the purposes of creating the cash flows, the user has to input the tax rate expected to pay for the project.

6.2 Output Tab

The calculator contains an output tab for anaerobic digestion, gasification, incineration, biogas purification, CHP Units, liquid fuels, and CNG. The previous sections described how the data in each tab was obtained. All technology tabs have data for economic parameters like fixed capital expenses, operational expenses, and revenues were applicable. For example, waste treatment plants will indicate production of components of interest such as biogas, syngas, digestate, and energy. Energy recovery tabs will indicate key parameters like efficiency, energy production, and hours of operation.

A tab for biogas purification will indicate the cost of purifying gases produced in waste treatment methods in order to upgrade them to the specified energy recovery technology, complying with safety standards of operation. Additionally, there is a tab labeled "Default Data" were all the default values for ultimate analysis, proximate analysis, and composition of impurities can be found. These values were set as default, but can be changed by the user if a study on the feedstock has been performed.

6.3 Report Tab

In the calculator, under the tab named Report and Cash Flows, the user can find a report detailing the waste treatment method and energy recovery technology chosen in addition to the capacity and type of feed processed in the plant. The next summary totals fixed capital expenses parameters for waste treatment, biogas purification, and energy recovery. The same parameters are also totaled for operational expenses. The revenues coming from tipping fees and sales of energy valuable products are also given.

For profitability measures, the NPW of the project is found. The discounted cash flow rate of return (DCFRR) is also found and compared to the minimum attractive rate of return that the user has specified. This measure will determine if the project is an attractive investment for the user.

7. Case Study

As a means to exemplify how the Excel calculator works, and what type of analysis can be done with is use, a case study analyzing Hillsborough County was performed. In Tampa Bay, there are four waste-to-energy facilities spread across the City of Tampa, Hillsborough, Pinellas, and Pasco counties. The authorities in the Tampa Bay Area decided to build this facility because of the landfill's capacity being reached sooner than expected. Additionally, by processing waste in these facilities, the volume of waste that is landfilled is reduced by approximately 90% (County 2018). Landfilling is becoming a less feasible option, since availability of land to construct landfills is reduced. The population in Tampa Bay is increasing at a fast rate and may reach 3 million by 2020.

One of the current waste to energy facilities in the Tampa Bay Area is the McKay Bay Waste-to-Energy facility. According to the City of Tampa website, "what cannot be recycled is burned at high temperatures in waste-fired boilers to generate steam. The steam is routed to a turbine generator to make electricity, which is purchased by Seminole Electric Cooperative".

Hillsborough county website states that 1,000 tons of residential and business waste are treated at this facility on a daily basis(County 2018). This would translate to 365,000 tons/yr processed.

The calculator was used to run the scenario of incinerating 365,000 tons/yr of MSW (dry basis; raw waste would have ~ 20% moisture in addition) and converting them to energy using combined heat and power. The results are summarized in Table 17 and Figure 16.

REPORT						
Process Parameter Inputs						
Waste Treatment	Incineration					
Energy Recovery	СНР					
Plant Capacity	365,000	Dry tons/ yr				
Feedstock Type	MSW					
Fixed Capital Expenses						
Incineration	\$257	Million				
Biogas Purification	\$01.48	Million				
СНР	\$19.71	Million				
TOTAL	\$279	Million				
Operational Expenses						
Incineration	\$17.87	Million/ yr				
Biogas Purification	\$0.85	Million/ yr				
СНР	\$2.65	Million/ yr				
TOTAL	\$21.38	Million/ yr				
Revenues						
Tipping Fee	\$12.78	Million/ yr				
Electricity Sales	\$34.07	Million/ yr				
TOTAL	\$46.85	Million/ yr				
Profitability						
Rate of Return	6%					

Table 17. Economic Report for Incineration and CHP Plant



Figure 16. Discounted cumulative cash flow diagram for an incineration and CHP plant with a life span of 25 years.

It is noted that the payback time on the project is relatively high, 11 years, and that the rate of return of 6% is not high. However, the data reported by the calculator is for the construction of an entirely new plant. In Tampa Bay, the construction of this plant started in 1970 (County 2018), which gives the county 48 years to pay off the projects and upgrade the facilities to bigger and more innovative ones. For example, in 2011, the several facilities in the county, like the South Transfer County Facility were upgraded from processing 1200 tons/day to 1800 tons/day (County 2018). The gradual upgrade and time span of the project make this a feasible waste treatment option for Tampa.

Additionally, as a means to compare scenarios the calculator simulation was done for a plant processing 365,000 tons/yr in an anaerobic digester and then producing power in a CHP unit. The results are demonstrated in Table 18 and Figure 17.

REP	ORT	
Process Parameter Inputs		
Waste Treatment	Anaerobic Digestion	
Energy Recovery	СНР	
Plant Capacity	365,000	Dry tons/ yr
Feedstock Type	MSW	
Fixed Capital Expenses		
Anaerobic Digestion	\$ 45	Million
Biogas Purification	\$1.5	Million
СНР	\$17.2	Million
TOTAL	\$63.7	Million
Operational Expenses		•
Anaerobic Digestion	\$3.4	Million/yr
Biogas Purification	\$0.9	Million/yr
СНР	\$1.6	Million/yr
TOTAL	\$5.9	Million/yr
Revenues		
Tipping Fee	\$12.8	Million/yr
Electricity Sales	\$21.0	Million/yr
TOTAL	\$33.8	Million/yr
Profitability		
Rate of Return	37 %	
Minimum Attractive Rate of Return	25 %	

Table 18. Economic Report for Anaerobic Digestion and CHP Plant



Figure 17. Discounted cumulative cash flow diagram for an anaerobic digestion and CHP plant with a life span of 25 years.

It is noted from this report that the payback time is 7 years, which is lower than the case for incineration. Additionally, the rate of return on the project is 14%. However, one of the downsides is that typically residential waste like MSW does not have a high moisture content which makes it significantly harder to run an anaerobic digester and calls for a higher utility cost as more water is needed to be fed into the digester. Even though the profitability of this project is more attractive, it might be more suitable to build it in rural areas and use it to process waste like farm manure which would maximize the profit of the project. Further analysis would be completed to assess an AD option for only the food waste portion of the waste stream as an alternative to expanding the incineration facility.

Additionally from focusing on a base case scenario where Anaerobic Digestion and CHP units are used, a comparison table with economics for all the technologies listed on the calculator is presented in Table 19.

	Anaerobic Digestion	Gasification	Incineration	Biogas Purificat ion	CHP Unit	Liquid Fuel Production	CNG
Fixed Capital Expenses (Million \$)	\$ 63.67	\$ 113	\$ 190	\$ 1.48	\$ 17	\$ 25	\$ 14
Operation al Expenses (Million \$/yr)	\$ 5.92	\$ 6.8	\$ 12.3	\$ 0.85	\$ 1.63	\$ 11	\$12

 Table 19. Economic Report for Waste to Energy Plant Treating 365,000 dry tons/yr of MSW

These numbers appear to favor AD combined with liquid fuel production. However the technology for liquid fuel production is not fully commercial yet. Incineration appears to be capital intensive even though it is one of the most commonly practiced technology. This suggests that more accurate economic data is needed to evaluate alternative technologies. The results and conclusions drawn are only accurate as the data employed. This combined with the rapid advances in the technology employed in recent years suggests a more thorough economic evaluation with detailed process models is necessary. We are currently undertaking such studies to enhance the capabilities of the tool developed.

8. Conclusion

In conclusion waste to energy projects have a significant benefit to both the environment and the communities where they are implemented. Implementing these projects reduces the amount of greenhouse emissions, makes the project more carbon neutral, and reduces the amount and volume of waste that is landfilled. Inevitably, landfills will reach their maximum capacity sooner than they can expand, as population grow and more waste is generated.

To target this problem facilities like anaerobic digestion, gasification, and incineration facilities can be built. These can be combined with energy recovery facilities like Combined Heat and Power, diesel production from liquid fuels, and compressed natural gas. Some of these facilities are more suitable for urban waste, for example, anaerobic digesters. MSW can be processed in incinerators or gasifiers.

The technology which is the most capital cost intensive is incineration, mainly because laws like Clean Air Act of 1990 monitors the emissions of such plants, requiring them to have state of that air flue gas clean-up systems (County 2018). Anaerobic Digester and gasifiers have similar costs. Additionally, all the gas produced by these technologies has to be cleaned and upgraded, and the costs for that will depend on how contaminated the gas is. As a last step, the gas will be converted into energy. The least capital intensive technology is producing power in a CHP unit, but the

revenues from this source are the least. Up next in capital costs is CNG production, but care needs to be accounted for the fact that using this product might require a fleet upgrade to engines that support CNG as fuel or the construction of pipes for delivery or fueling stations. This will in turn mean that the revenues from this stream will be reduced by these parameters. At last, producing diesel has the highest capital cost, but also yields a higher revenue.

Lastly, all of these technologies are fairly new, and several analysis of technology combinations should be done to determine which one would be more feasible to apply given feed processed and rate of return desired, in combination with what the county or organization needs in terms of energy at that point.

9. Recommendations

More accurate and current cost estimates for the various technologies are necessary to enhance the capabilities of the Calculator. Detailed techno-economic studies using process models will also help increase the accuracy of the results obtained. Efforts are underway to do such detailed studies.

It would be recommended, in order to make the Excel calculator more complete, to add the costs of doing single-stream recycling of the waste delivered to the facility. Another improvement would be to determine revenue of sales of electricity or costs of tipping fees by region to expand for scenarios outside of Florida. Additionally, for the purposes of determining depreciation the salvage value of the facility is assumed to be zero, but to make a better estimation it is recommended to have the user input their estimated salvage value.

In order to make the calculator more user-friendly, VBA macros should be done to automatically execute calculations involving Excel Solver. This will reduce the chances of introducing human error into the calculations. Once the calculator is finalized, it should be password protected to avoid users from altering the code. Also, a web application can be made out of the application in the future.

The calculator provides a powerful tool for municipalities and private entities to make preliminary estimations for projects and feasibility of building plants of this nature, however it can be greatly improved to make it an even better and more user friendly tool.

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11. Appendices

Appendix A. Default Ultimate and Proximate Analysis for Calculator Feedstock Options

Compound	Feedstock Options									
Compound	Agricultural Waste	Farm Manure	MSW/Yard Trimmings	WWTP	Food Waste					
Carbon	47.3	51.5	51.81	31.79	45.6					
Hydrogen	5.1	4.9	5.76	4.36	6.2					
Oxygen	40.6	39.5	35.88	20.57	36.2					
Nitrogen	0.8	2.9	0.26	4.88	2.3					
Sulfur	0.2	0.6	0.36	1.67	0					
Ash	6	0	0	36.37	9.7					

 Table A.1 Ultimate Analysis (wt%, dry basis)

Table A. 1 Proximate Analysis (wt%, dry basis)

Compound	Feedstock Options				
Compound	Agricultural Waste	Farm Manure	MSW/Yard Trimmings	WWTP	Food Waste
Ash	6	0	5.93	21.5	9.7
FC	23.6	25.8	11.79	10.7	13.6
VM	70.4	74.2	82.28	67.8	76.7

Appendix B. Visual Representation of the Tabs in the Excel calculator

The following tables and figures assume that the user inputted the data shown in Table B.1 and subsequent figures show calculations assuming this basis and scenario.

General Inputs	
Facility Inputs	Input Data
Type of waste to be processed	MSW
Capacity of the facility (dry tons/yr)	365,000
% Moisture Content in the Feed	20%
Project Start Year	2019
Project End Year	2039
Expected Facility Life (years)	20
Waste Treatment Method Inputs	
Type of waste treatment method	Anaerobic Digestion
% Solids in Anaerobic Digester	20%
Energy Recovery Inputs	
Type of energy recovery method	СНР
Profitability Inputs	
Tax Rate	20%
Minimum attractive rate of return	15%

Table B. 1 Input Tab

PROCESS PARAMETER INPUTS				ECONOMIC PARAMETER OUT	ECONOMIC PARAMETER OUTPUTS			
Parameter		Unit		Parameter				
Project Start Year	2019							
Project End Year	2039			Fixed Capital Investment		\$112	Million	
Expected Facility Life	20	years						
Plant Capacity	365,000.00	dry tons	of feed/yr	Operational Expenses		\$8.6	Million/yr	
Feedstock Type	MSW			Operational Expenses per ton	-\$	30	dry ton of feed/yr	
% Moisture Content in Feed	20%							
% Solids in Anaerobic Digester	20%			Tipping Fee	\$	35	/ton	
Type of Anaerobic Digester	High-Solids (Dry)			Revenue from tipping fee		\$12.78	Million/yr	

					BIOGAS OUTPUT COMPOSIT	ON (million kg/yr)	ULTIMATE ANALYSIS FEED (wt%, o		/ basis)
PROCESS PARAMETER OUTPUTS					CH4	50.02	C	51.81	
					CO2	114.93	н	5.76	
Digestate Production rate	1481.5	million kg	g of digestate /yr		H2S	.67	0	35.88	
Solid Digestate Production rate	217.6	million kg	g of solid digestat	æ/yr	H2O	19.22	N	0.26	
Liquid Digestate Production rate	1263.9	million kg	g of liquid digesta	te/yr	NH3	.66	S	0.36	
Biogas Production rate	351	m^3/mir	า				Ash	0	
% Energy Recovery	57%								
					BIOGAS OUTPUT COMPOSIT	ON (million kmol/yr)	PROXIMATE ANA	YLIS FEED (wt%, dr	y basis)
					CH4	3.118	Ash	5.93	
					CO2	2.612	FC	11.79	
					H2S	.019	VM	82.28	
					H2O	1.067			
					NH3	.039			

Figure B.1.Anaerobic Digestion tab calculations

		ΕΓΩΝΟΜΙΟ ΡΑΒΑΜΕΤΕΒ ΟΙ ΙΤΡΙ ΙΤΣ		
	Unit	Parameter		
2019				
2039		Fixed Capital Investment	\$113.5	million
20	years			
365,000.00	dry tons of feed/yr	Operational Expenses	\$6.8	million/yr
MSW				
20%		Tipping Fee	\$35	/ton
		Revenue from tipping fee	\$12.78	Million/yr
		SYNGAS OUTPUT COMPOSITION (milli	on kmol/yr)	
463.8	million kg/yr	СО	06.92	
58.7	million kg/yr	H2	04.63	
86.8	million kg/yr	CO2	02.97	
3.82		N2	2.37	
		H20	02.49	
		CH4	01.19	
	2019 2039 20 365,000.00 MSW 20% 463.8 58.7 86.8 3.82	AAUnitI2019I2039I2030I365,000.00dry tons of feed/yrMSWI20%I20%I365,000.01I401I20%I20%I365,000.02I401I20%I365,000.02I401I20%I365,000.02I365,000.02I365,000.02I365,000.02I365,000.02I365,000.02I362,000.02I363,000I363,000I363,000I363,000I363,000I363,000I363,000I363,000I363,000I363,000I363,000I363,000I363,000I363,000I363,000I364,000I365,000I365,000I365,000I365,000I365,000I365,000I365,000I365,000I365,000I365,000I365,000I365,000I37,000I37,000I38,000I39,000I39,000	Image: section of the section of th	Image: section of the section of th

Figure B. 2 Gasification tab calculations



Figure B. 3 Mole percent composition of syngas produced by gasification.

PROCESS PARAMETER INPUTS				ECONOMIC PARAMETER C	OUTPUTS	
Parameter		Unit		Parameter		
Project Start Year	2019					
Project End Year	2039			Fixed Capital Investment	\$257.43	Million
Expected Facility Life	20	years				
Plant Capacity	365,000.00	dry tons of fee	d/yr	Operational Expenses	\$17.87	Milion/yr
Feedstock Type	MSW					
% Moisture Content in Feed	20%			Tipping Fee	\$35	/ton
				Revenue from tipping fee	\$12.78	Million/yr
PROCESS PARAMETER OUTPUTS				PRODUCTS OF INCINERAT	ION (million kmol/	/r)
Stoichiometric Air Flowrate	236.81	million kmol/yr		CO2	45.6	
				H20	39.1	
				N2	187.3	
				S	.153	

Figure B. 4 Incineration tab calculations

PRODUCTS OF INCINERATION



Figure B. 5 Mole percent of incineration products

PROCESS PARAMETER INPUTS				ECONOMIC PARAMETER OUTPUT	rs					
Barameter		Unit			Cani	tal Exponsion			Operational Expone	
Parameter		Unit			Capi	tai expenses			Operational Expense	es .
Project Start Year	2019			Activated Carbon Beds	\$	862,181		Activated Carbon Beds	7,600	\$/yr
Project End Year	2039			Iron Sponge Beds	\$	289,000		Iron Sponge Beds	365,700	\$/yr
Expected Facility Life	20	years		Cooler Unit	\$	200,000		Cooler Unit	174,900	\$/yr
Plant Capacity	365,000	dry tons	; /yr	Water Scrubbing	\$			Water Scrubbing		\$/yr
Feedstock Type	MSW			Blower	\$	131,000		Blower	228,800	\$/yr
Energy Recovery Method	CHP									
				total biogas purification capital in	ivestr	nent		total biogas purification	operational expense	s
				1,482,000	\$				851,000	\$/yr
BIOGAS IMPURITY LEVELS				BIOGAS PURITY REQUIREMENTS E	BASED	ON ENERGY	CONV TECH	IMPURITIES TO BE REMO	OVED BY PURIFICATIO	N
Siloxane in Biogas at the Inlet	3100	kg/yr		Siloxane Purity Required		2,600	kg/yr	Siloxane	500	kg/yr
H2S in Biogas at the Inlet	665,000	kg/yr		H2S Purity Requirement		87,900	kg/yr	H2S	577,100	kg/yr
CO2 in Biogas at the Inlet	114,930,000	kg/yr		CO2 Purity Requirement	nor	ne	kg/yr	CO2	none	kg/yr

Figure B. 6 Biogas Purification Tab calculations

PROCESS PARAMETER INPUTS			ECONOMIC PARAMETER	OUTPUTS	
Parameter		Unit	Parameter		
Project Start Year	2019				
Project End Year	2039		Fixed Capital Investment	\$ 17.19	million
Expected Facility Life	20	years			
Plant Capacity	365,000	dry tons of feed/yr	Operational Expenses	\$ 1633	thousand/yr
Feedstock Type	MSW				
% Moisture Content in Feed	20%		Price of Electricity	\$ 0.08	/kWh
Type of waste treatment method	Anaerobic Digestion				
Hours of Operation	8,400	hr/yr	Revenue from Electricity	\$20.96	Million/ yr
GAS PRODUCTION OUTPUTS					
Parameter					
CHP Efficiency	85%				
Gas Type	Biogas				
Gas Flowrate	185	Million m^3/yr			
Energy in the gas	88	MW			
Power plant can generate (with eff)	31	MW			
	30,800	kW			
	258,720,000	kWh/ yr			
Equivalent Energy to Power	24,000	Houses			

Figure B. 7 CHP Unit tab calculations

PROCESS PARAMETER INPUTS					ECONOMIC PARAMETER OU	JTPUTS			
Parameter		Unit			Parameter				
Project Start Year	2019								
Project End Year	2039				Fixed Capital Investment	\$24.51	Million		
Expected Facility Life	20	years							
Plant Capacity	365,000.00	dry tons of fee	ed/yr		Operational Expenses	\$10.69	Million/yr		
Feedstock Type	MSW								
					Price of Diesel	\$3.00	/ gal diesel	with RIN inc	entive
PROCESS OUTPUTS					Revenue from Diesel Sales	\$39.42	Million/yr		
Liquid fuel Avg Production	36	gal diesel/ton	dry feed						
Diesel Production	13.14	Million gal die	sel/yr						

Figure B. 8 Liquid fuel production tab calculations

PROCESS PARAMETER INPUTS					ECONOMIC PARAMETER OUTPUTS		
Parameter		Unit			Parameter		
Project Start Year	2019						
Project End Year	2039				Fixed Capital Investment	\$14.5	Million
Expected Facility Life	20	years					
Plant Capacity	365,000	dry tons of f	eed/yr		Operational Expenses	\$12.13	Million/yr
Feedstock Type	MSW						
					Price of CNG	\$2.20	/gallon CNG
PROCESS OUTPUTS					Revenue from CNG Sales	\$78.27	Million/yr
CNG Avg Production	0.012	gallons CNG	/ ft^3 CH4				
CH4 Production from AD	2965	Million ft^3	CH4/yr				
CNG produced	35.58	Million Gallo	ons CNG/yr				
Hours of Operation	8,400	hr/yr					
Biogas Flowrate	184.6	Million m^3	/yr				
	21.97	thousand m ⁴	^3/hr				

Figure B. 9 CNG production tab calculations

REPORT		
Process Parameter Inputs		
Waste Treatment	Anaerobic Digestio	n
Energy Recovery	CHP	
Plant Capacity	365,000	
Feedstock Type	MSW	
Fixed Capital Expenses		
Anaerobic Digestion	\$112	Million
Biogas Purifitcation	\$01.48	Million
CHP	\$17.19	Million
TOTAL	\$131	Million
Operational Expenses		
Anaeropic Digestion	\$8.6	MillionAr
Biogas Purification	\$0.85	Million/yr
СНР	\$1.63	Million/yr
	Ş1.05	IVIIIIOII/ ¥I
TOTAL	\$11.08	Million/yr
Tinning Foo	¢10.70	Million for
Tipping Fee	\$12.78	Million/yr
Electrcity Sales	\$20.96	willion/yr
TOTAL	\$33.73	Million/yr
Profitability		
Rate of Return	14%	
Minimum Attractive Rate of Return	15%	

Figure B. 10 Expense summary and report for a waste

processing and energy recovery plant of specific capacity

CASH FLOWS					
	N	Description	Cash Flaur	Discounted Cook Flore	Consultation Const. Floor
	Year	Depreciation		Discounted Cash Flow	Cumulative Cash Flow
	0	\$13,087,413.73	(\$130,874,137.35)	(\$130,874,137.35)	(\$130,874,137.35)
	1	\$13,087,413.73	\$20,735,720.19	\$ 18,019,155.72	\$ (110,138,417.16)
	2	\$13,087,413.73	\$20,735,720.19	\$ 15,658,485.45	\$ (89,402,696.97)
	3	\$13,087,413.73	\$20,735,720.19	\$ 13,607,084.06	\$ (68,666,976.78)
	4	\$13,087,413.73	\$20,735,720.19	\$ 11,824,434.57	\$ (47,931,256.60)
	5	\$13,087,413.73	\$20,735,720.19	\$ 10,275,328.08	\$ (27,195,536.41)
	6	\$13,087,413.73	\$20,735,720.19	\$ 8,929,168.37	\$ (6,459,816.22)
	7	\$13,087,413.73	\$20,735,720.19	\$ 7,759,367.59	\$ 14,275,903.96
	8	\$13,087,413.73	\$20,735,720.19	\$ 6,742,821.17	\$ 35,011,624.15
	9	\$13,087,413.73	\$20,735,720.19	\$ 5,859,451.39	\$ 55,747,344.34
	10	\$13,087,413.73	\$20,735,720.19	\$ 5,091,810.95	\$ 76,483,064.52
	11	\$-	\$18,118,237.44	\$ 3,866,200.82	\$ 94,601,301.96
	12	\$-	\$18,118,237.44	\$ 3,359,694.00	\$ 112,719,539.40
	13	\$-	\$18,118,237.44	\$ 2,919,544.09	\$ 130,837,776.84
	14	\$-	\$18,118,237.44	\$ 2,537,057.75	\$ 148,956,014.28
	15	\$-	\$18,118,237.44	\$ 2,204,680.53	\$ 167,074,251.72
	16	\$-	\$18,118,237.44	\$ 1,915,847.70	\$ 185,192,489.16
	17	\$ -	\$18,118,237.44	\$ 1,664,854.55	\$ 203,310,726.60
	18	\$-	\$18,118,237.44	\$ 1,446,743.74	\$ 221,428,964.04
i	19	\$ -	\$18,118,237.44	\$ 1,257,207.39	\$ 239,547,201.48
i	20	\$ -	\$22,647,796.80	\$ 1,365,627.50	\$ 262,194,998.28
	21	\$ -	\$22,647,796.80	\$ 1,186,718.11	\$ 284,842,795.08
	22	\$ -	\$22,647,796.80	\$ 1,031,247.44	\$ 307,490,591.88
	23	\$ -	\$22,647,796.80	\$ 896,144.82	\$ 330,138,388.68
	24	\$ -	\$22,647,796.80	\$ 778,741.85	\$ 352,786,185.48
	25	\$ -	\$22,647,796.80	\$ 676,719.71	\$ 375,433,982.28
	NPW	-\$ 0.00			

Figure B. 11 Cash Flows and project Net Present Worth (NPW)



Figure B. 12 Discounted cumulative cash flow diagram