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Food Waste to Bio-Products

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Food Waste to Bio-Products

Abstract

The goal of this project was to design and evaluate a project for the collection and processing of food waste and spent oil in Philadelphia. The project was designed to handle 5% of the total commercial waste generated in Philadelphia. This amounted to approximately 9,700 tons/year of food waste and 73,000 gallons/year of spent oil. The process was designed to utilize a BIOFerm™ Dry Fermentation Digestion System. Following the digestion, the biogas produced is passed through a Caterpillar CG132-12 Generator Set, producing electricity to be sold back to the local grid. The digestate from the anaerobic digestion is used to produce compost, providing an additional revenue stream. In addition to handling the solid food waste, the project is designed to convert the collected spent oil into biodiesel using prepackaged processing units by Springboard Biodiesel. The facility is anticipated to annually produce 2,541 tons of biogas, 5,184,000 kWh of electricity, 14,756 tons of compost, and 59,616 gallons of biodiesel. A rigorous profitability analysis was conducted in order to project cash flows for fifteen years. The total capital investment of the plant is $5.6MM and the expected NPV of the project is -($682,000). The estimated IRR of the project is 12% and the 3-year ROI is 7%. Given the project's negative NPV, our recommendation is to adopt such a process solely for environmentally beneficial waste management purposes. A key takeaway is that in order for such a project to be profitable it would need to target more than just 5% of the total commercial food waste produced.

Disciplines

Biochemical and Biomolecular Engineering | Chemical Engineering | Engineering

University of Pennsylvania
School of Engineering and Applied Science
Chemical and Biomolecular Engineering

April 2017

Dear Dr. Shieh and Mr. Vrana,

As requested by our assigned Senior Design Project, we have designed and evaluated a project for the collection and processing of food waste and spent oil in Philadelphia. The process handles the solid food waste through anaerobic digestion in a BIOFerm Dry Fermentation Digestion System. Following the digestion, the biogas produced is passed through a Caterpillar CG132-12 Generator Set, producing electricity to be sold back to the local grid. The digestate from the anaerobic digestion is used to produce compost, an additional revenue stream. In addition to handling the solid food waste, the project is designed to convert collected spent oil into biodiesel. The processing is performed using prepackaged units by Springboard Biodiesel. The project was designed to handle waste from one-hundred large institutions, with a total solid waste of approximately 9,700 tons/year and a spent oil volume of roughly 73,000 gallons/year. These figures amount to roughly 5% of the total commercial waste produced in Philadelphia.

The plant was designed assuming a 360-day year with operations running 24/7. The facility is anticipated to annually produce 2,541 tons of biogas, 5,184,000 kWh of electricity, 14,756 tons of compost, and 59,616 gallons of biodiesel.

A rigorous profitability analysis was conducted in order to project cash flows for fifteen years. The total capital investment of the plant is $5.6MM and the expected NPV of the project is -($682,000). The estimated IRR of the project is 12% and the 3-year ROI is 7%. Given the project's negative NPV, our recommendation is to adopt such a process solely for environmentally beneficial waste management purposes. The project does show sustainability in that it is able to generate positive cash flows, however the high capital costs do not make it a lucrative project at this capacity. Our recommendation would be to target more than the 5% of commercial waste produced in Philadelphia in order to increase revenues and generate a positive NPV.

Sincerely,

Elizabeth Handen	Mauricio Diaz Padilla	Hannah Rears	Lyle Rodgers

Food Waste to Bio-Products

Elizabeth Handen | Mauricio Diaz Padilla | Hannah Rears | Lyle Rodgers

Project submitted to:	Dr. Warren Seider Prof. Bruce Vrana
Project proposed by:	Dr. Wen K. Shieh Dr. Miriam Wattenbarger

Department of Chemical and Biomolecular Engineering
School of Engineering and Applied Science
University of Pennsylvania
April 18, 2017

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Section 1: Abstract

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Section 2: Background Information

2.1 Introduction

Food waste is the second largest category of solid waste sent to landfills in the United States. Much is being done to look at alternative means of handling these large quantities of waste. Anaerobic digestion (AD) is a biological process that converts organic waste into different, potentially useful products, using microbes. The process is carried out in the absence of oxygen and the final products are biogas and the remainder of the digested food waste, known as digestate. The composition of biogas differ and depend mainly on the digestion process, however the main constituents are methane (55-70%) and carbon dioxide (30-45%) with trace amounts of hydrogen sulfide and other impurities, which can be troublesome for certain applications. The digestate produced has potential applications in composting and fertilizer production. The digestate is rich in nitrogen, phosphorus, and potassium, making it an ideal substitute to chemical fertilizers. The exact concentrations can be determined by carrying out tests on the digestate. This is necessary in order to determine applications and pricing, as these often depend on compost's levels of nutrients.

There are a number of commonly used applications for the biogas produced during anaerobic digestion. One popular option is to upgrade the biogas to biomethane by removing the impurities. This allows it to be injected into the natural gas grid and utilized that way. Another alternative is to convert the biogas to electricity, which can be accomplished with either combustion engines or gas turbines. When biogas is combusted, it produces renewable energy which can be substituted for fossil fuels, thus reducing the greenhouse gas emissions associated with energy production. This is because the only carbon emissions associated with energy produced from food waste result from the carbon that was absorbed by the food when it was being grown. There is also the added bonus of reducing the methane—a greenhouse gas—that would be produced if the food waste was to openly decompose in landfills.

Another environmentally-friendly method for minimizing food waste is to convert spent cooking oil into biodiesel. Biodiesel is a biodegradable fuel considered to be a “green” replacement for fossil fuels. It can be easily manufactured from spent oil and has the advantage of reducing both waste and carbon emissions. Renewability, biodegradability, and the potential minimization of the greenhouse effect have all encouraged agencies and individuals to look at carrying out the process of collecting and converting spent cooking oil to biodiesel.

This project proposes a process to collect food waste from large institutions around Philadelphia for conversion into useful products via anaerobic digestion. Specifically, the project focuses on the conversion of the collected food waste into biogas, which can be used to generate electricity to sell back to the local grid. There is also the possibility of using the leftover digestate to produce compost. Finally, the project also looks at collecting the spent cooking oil produced by the institutions for conversion into biodiesel, which can be sold or used by our facility to reduce the operating costs associated with the collection vehicles.

2.2 Objective-Time Chart

The goal of this project was to develop a process to collect and convert food waste and spent cooking oil from around Philadelphia to economical products. The project's scope included estimating the amount of food waste and oils generated in the area, identifying the best way to process this waste, designing the process, performing the mass and energy balances, calculating the required utilities, and performing financial analysis to gauge the feasibility of the project. A timeline of the deliverables, their descriptions, and their dates accomplished is shown below.

Table 1. Timeline for project deliverables.

Deliverable	**Description**	**Date Accomplished**
Food Waste & Spent Oil Market Sizing	Determined how much food waste and spent oil would be collected and processed.	January 24th
Product Selection	Determined which of the possible products--biomethane, electricity, fertilizer, compost, biodiesel--had the most economic potential.	February 21st
Initial Process Designs & Mass Balances	Alternative processes developed to convert food waste to electricity. Equipment sizing and selection for biodiesel production.	February 23rd
Energy Balances & Final Process Design	Compared energy balances and utility requirements of alternative processes to choose the final design for electricity production.	February 27th
Utility Requirements	Finalized utility requirements of plant, and for food waste & oil collection.	March 27th
Financial Analysis	Finalized capital cost and profitability analysis	April 8th
Complete Report		April 18th

2.3 Innovation Map

An innovation map for this project can be seen below (Figure 1). This project is motivated by the economic and environmental benefits of using anaerobic digestion to manage the large quantities of food waste produced by institutions around Philadelphia. The project also includes the collection and conversion of spent cooking oil to biodiesel, which carries its own economic and environmental benefits. The economic motivation of the project is focused around the ability to use anaerobic digestion to produce biogas which, via a gas generator set, can be used to produce electricity for inclusion in the local grid. Such a process has the advantage of generating revenue streams due to the incentivization of renewable energy production. Since this project is working with creating renewable energy from municipal solid waste, it falls under the United States Treasury 1603 Program. This program covers up to 30% of the total eligible cost of the project, which is beneficial in the profitability analysis of the project. In addition, the production of electricity by renewable means generates Renewable Energy Credits (RECs). One REC represents 1 MWh of renewable electricity produced, and can be used to demonstrate the environmental benefit of the electricity being sold. On top of that, RECs can be sold on the market to consumers who need to meet renewable energy quotas, thus increasing the potential profit for this project.

The use of anaerobic digestion to manage the food waste also has the advantage of reducing greenhouse gas emissions, whether using products as fossil fuel alternatives, or merely looking at the reduction in methane produced from decomposing food waste in landfills. The process provides a renewable and clean source of energy. The conversion of spent oil to biodiesel has similar benefits as it is able to provide a "green" fuel with lower carbon emissions that can be used in place of traditional fuel. These lower carbon emissions, on top of being extremely beneficial to the environment, also provide a lucrative economic opportunity in the form of carbon offsets. By creating electricity and fuel in a process with lower carbon emissions, carbon offsets are generated. This is a voluntary system in which carbon emissions are lowered in one location to compensate for emissions elsewhere. The offsets are then bought and sold on the market, which provides an increased economic opportunity for this project. The process of converting spent oil to biodiesel also generates a glycerin waste product that can be added to the anaerobic digester and used to produce biogas, a more valuable product. Due to the “green” nature of the fuel produced from this process, Renewable Identification Numbers (RINs) are produced in proportion with gallons of fuel. These RINs help to ensure that certain percentages of environmentally friendly energy are being used per year. These RINs, like the RECs, can be sold for a profit to those who have renewable energy quotas to satisfy. For this project, the biodiesel produced will be sold bundled with the RIN, increasing the value of the biodiesel and increasing the benefit to the environment since more green energy is being produced.

Finally, the digestate produced during the digestion can be collected and used to produce compost, a low cost alternative to chemical fertilizers. While this adds economic value to our project, it also adds environmental value. Chemical fertilizers increase the risk of nitrogen leaching into groundwater; this risk is reduced when the fertilizer or compost is derived from food and organic waste instead.

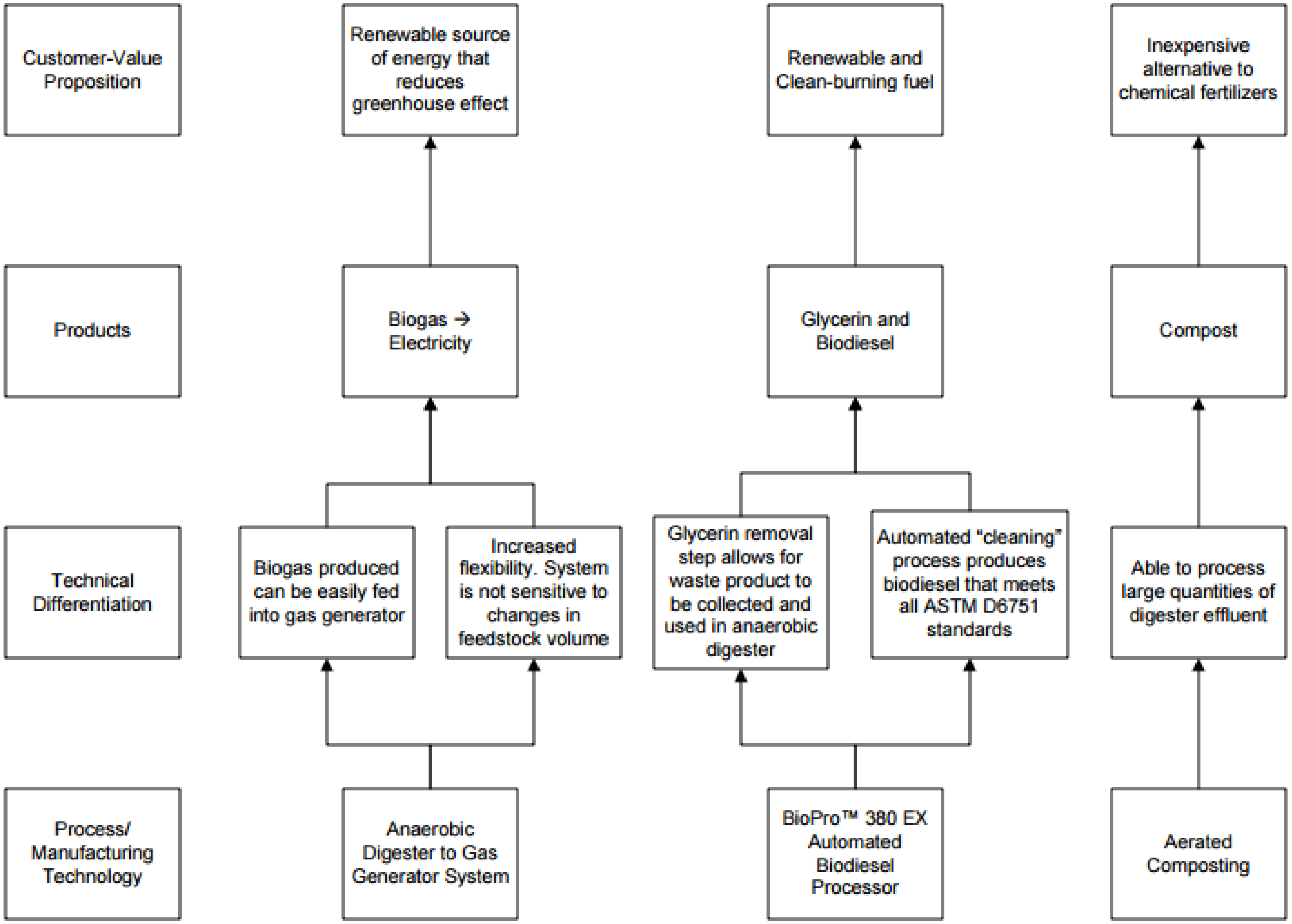


Figure 1. Innovation Map for Production of Bio-Products from Food Waste and Spent Oils.

Section 3: Preliminary Analysis

3.1 Market and Competitive Analysis

Renewable Energy Market

World production of renewable energy has grown significantly over the last few years, with solid biofuels remaining one of the most used forms of renewable energy. Renewable energy technologies have enormous potential in the United States and are able to be pursued at a reasonable cost. Market research has even shown that consumers are becoming more and more willing to purchase renewable power, even if it costs more than the conventional power sources (UCS, 1999). An example of this is seen in the U.S. Information and Communication Technology (ICT) Industry. The industry is a large user of electricity, with figures from 2013 showing data centers alone representing 2.4% of the total U.S. electricity consumption. In addition, the growth in electricity consumption for the industry was shown to be larger than that of the growth in the entire market (Miller, 2015). A number of large ICT companies are making commitments to reduce their electricity consumption and to invest in clean and renewable energy resources. In many cases, these commitments have been substantial, and certain companies have even set goals to have 100% of their electricity procured from renewable sources by 2020. The growing number of ICT companies pursuing renewable energy are able to do so in a number of ways, with power purchasing agreements (PPAs) being one of the major facilitators. PPAs are contracts between a power producer and the company in which the company agrees to purchase a fixed amount of renewable electricity at a predetermined price for the duration of the contract. However, there are many competitors to provide renewable energy for these PPA contracts, including companies using wind, solar, and hydropower to create renewable electricity. According to the U.S. Energy Information Administration, renewable energy provides about 13% of U.S. electricity, with these three types dominating the majority of the market. Hydropower provides 6% of U.S. electricity, while wind power provides 5% and solar provides 1%. Although these kinds of projects are very popular for producing renewable energy, they generally take up a lot of space. This poses a problem for a project in Philadelphia as land is a valuable commodity and there are not large areas which could accommodate a wind, solar, or hydropower project. Power derived from biomass, including municipal solid waste, accounts for 2% of all electricity produced in the United States. This lower percentage means that there are not many companies with processing similar to the processing proposed in this project. This provides a large advantage in this competitive market for renewable energy. In addition, this project is small enough that the processing can be done in Philadelphia, which makes it competitive compared to other forms of renewable energy (i.e. solar, wind, hydropower, etc.). Accompanying the sale of renewable electricity is also the sale of the renewable energy certificates (RECs) which, when "bundled" with the electricity contracts, pass on the environmental attributes of renewable energy generation to the purchasing company. Figure 2 shows the U.S energy consumption by energy source in 2015. The current renewable energy contribution is around 10%, but after analyzing the increasing demand for renewable energy in the ICT industry alone, the projected growth in the renewable energy market is substantial.

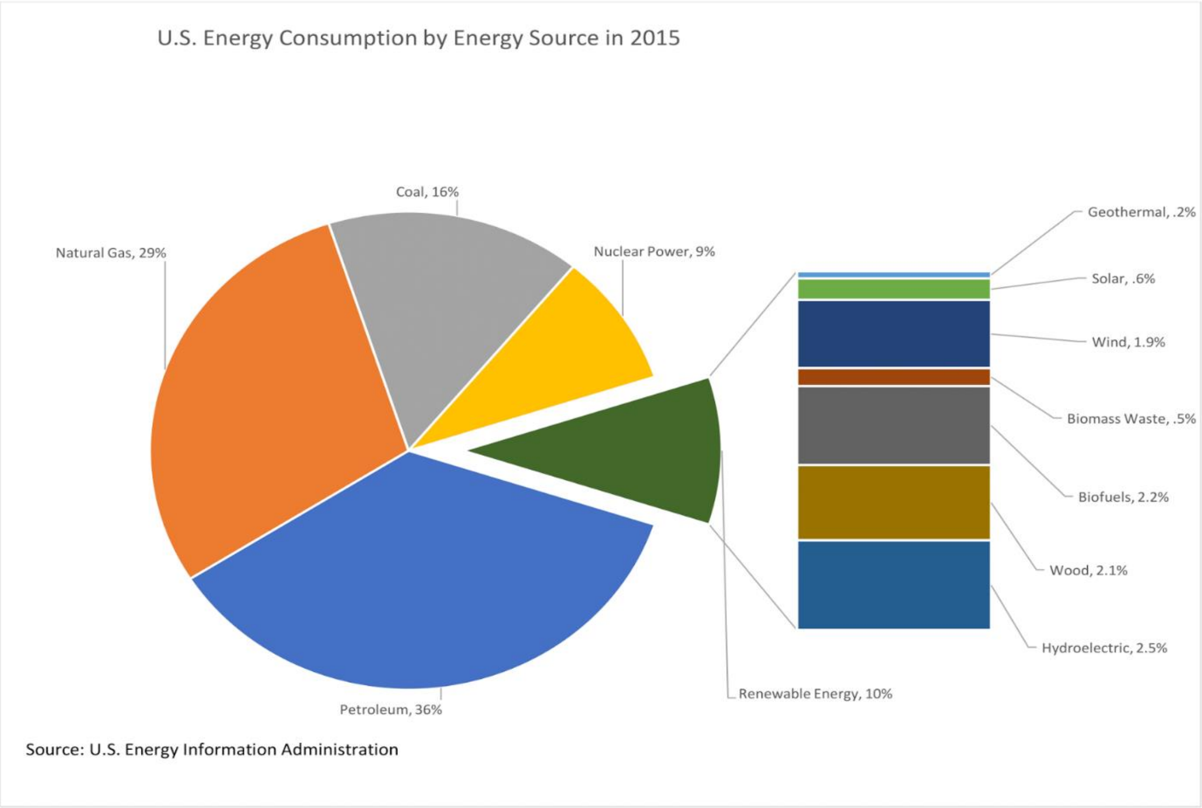


Figure 2. United States Energy Consumption by Energy Source. Note that renewable energy accounts for 10% of energy consumption.

Biodiesel Market

The biodiesel industry is still a relatively small industry when compared to the corn ethanol industry. However, the biodiesel market reached $33 billion in 2015 and is expected to see significant growth with projections of about $41 billion by 2021. Despite the surge in biodiesel production, the U.S. has been a net importer of biodiesel since 2010. This is likely due to a number of reasons, including a higher demand to satisfy the "advanced biofuel and total renewable fuels standards, the biodiesel tax credit, growing access to foreign biodiesel, and favorable blending economics" (AgMRC). The total U.S. biodiesel imports reached approximately 260 million gallons towards the end of 2015. Figure 3 shows the total U.S. biodiesel production and net import figures from 2005-2015.

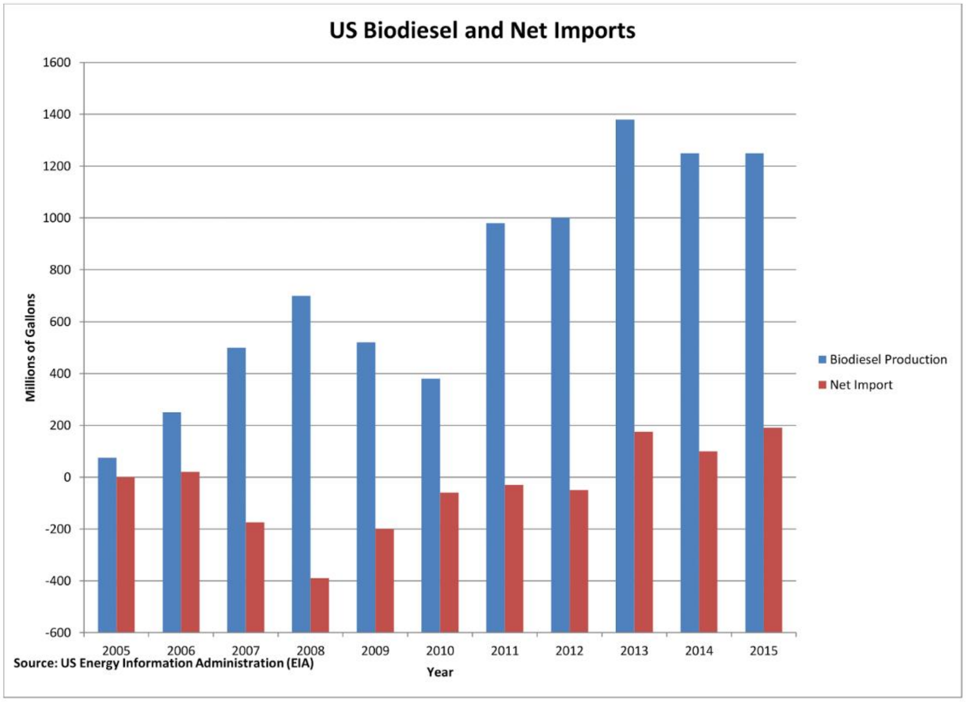


Figure 3. United States Biodiesel Production and Net Imports.

Another reason for increased interest in the biodiesel industry is due to the increasing world and U.S. oil prices, which are expected to increase over the next decade as a recovery occurs in the global economy. According to a report by the Agricultural Marketing Resource Center the price of crude oil is expected to increase at a faster rate than the general inflation rate through 2010-2019, at the end of which crude oil prices are projected to be back at around $100 a barrel. This price increase is a major driver for innovation and demand in other energy supply sectors, such as biodiesel. These projections, as well as the other benefits associated with biodiesel, emphasize the potential for strong growth in the biodiesel market. The primary competitor for biodiesel specifically is cellulosic biofuel, which is produced primarily in the Midwest. Currently, only 5% of the biodiesel in the United States is produced on the East Coast, which means there is an opportunity to break into the market in Philadelphia (USDA). In 2014, 1.28 billion gallons of biodiesel were produced and this number continues to grow (AgMRC). While the corn ethanol industry is very large and has been a force for a long time, the biodiesel industry is still relatively young. Consequently, there is opportunity to increase the biodiesel market size, as well as the market share this project would own.

Compost Market

Compost is a valuable product derived from organic matter that has decomposed and been recycled as a fertilizer. It is able to improve the physical, chemical (nutritional), and biological properties of soil and plant growth media. The specific characteristics of the compost, controlled by a number of factors, determine which applications it is best suited for. In this market, the main competitors are other fertilizer and compost companies. There is no major advantage that this project has over other companies since all of the projects are fairly similar. The main point of differentiation is the chemical makeup of the fertilizer; fertilizer with higher levels of key nutrients tends to be more sought-after and sells for a higher price. This project, since it uses food waste as the feedstock, is likely to produce a fertilizer rich in nitrogen, potassium, and phosphorus, which is ideal. As a result, this fertilizer is expected to be competitive in the market and sell for a profit.

The main suppliers of fertilizer and compost are chemical product manufacturing companies and oxygen and hydrogen gas manufacturing companies (IBIS World). A complicated aspect of compost market analysis and development is that it is not controlled by market demand, but by the economics of waste management, as well as environmental regulation. However, the fact that composting is an economically viable solution for waste management has led to an overall increase in volumes of compost being produced. An important use of compost is as biofertilizer, which acts as a substitute for chemical-based fertilizers. The biofertilizer market size was estimated to be about $540 million in 2014. Governments have made significant efforts to promote the use of biofertilizers. For example, India introduced national initiatives to promote the production, distribution, and use of biofertilizers. Figure 4 shows the estimated growth in biofertilizer market revenue from 2012-2022 (Grand View Research). The environmental benefits of biofertilizers over traditional chemical-based fertilizers, as well the large global push towards their use, could translate to an increased demand for compost, making it a potentially lucrative product.

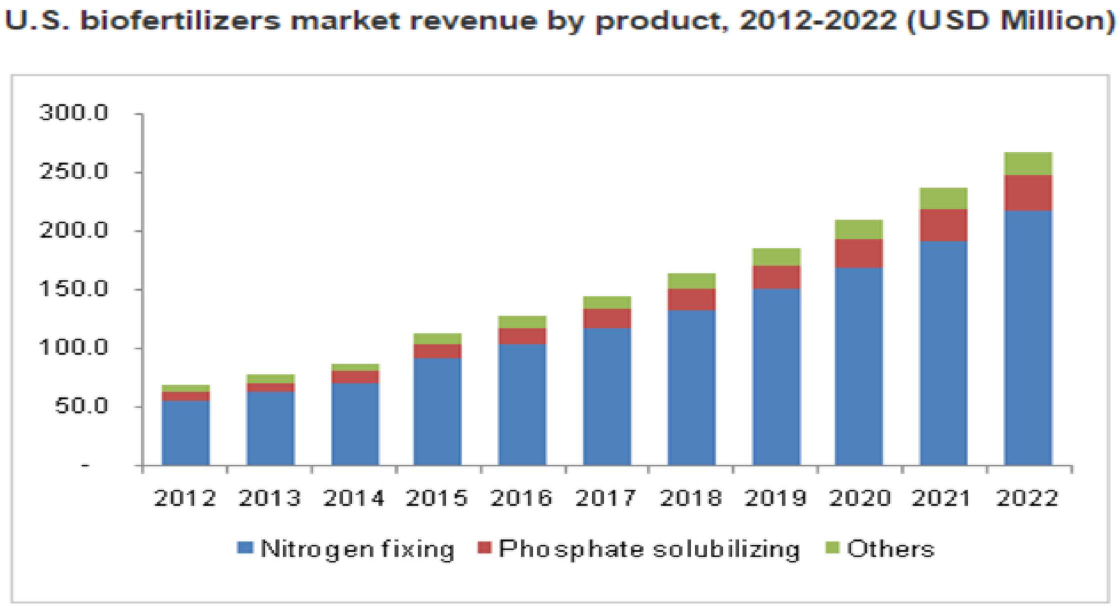


Figure 4. Estimated Biofertilizer Market Growth.

Tipping Fees Market

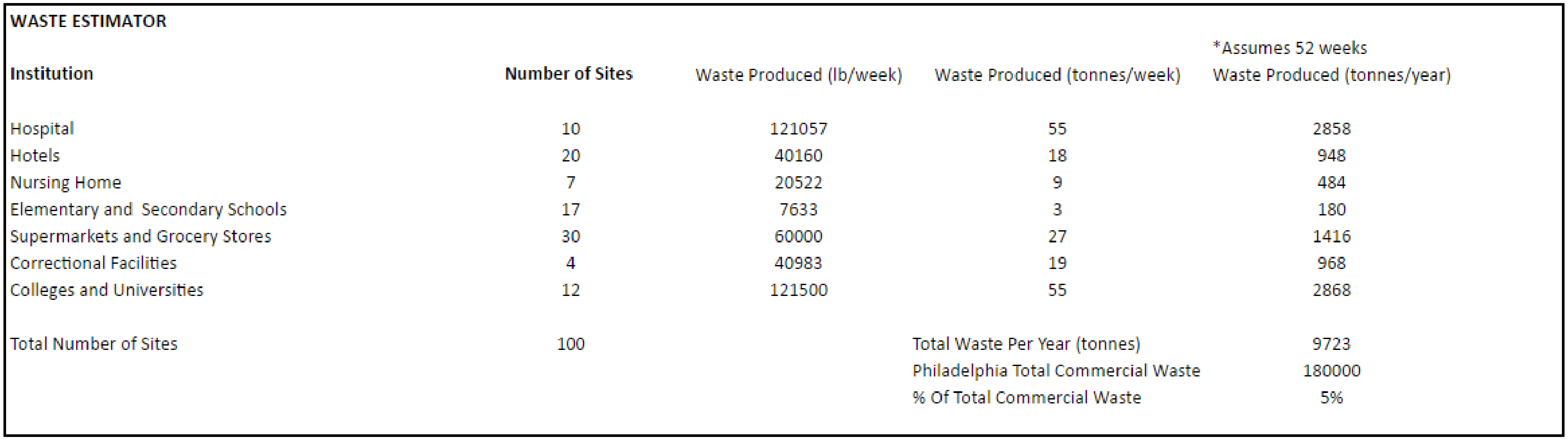
Food waste can be used by and/or sold to several different consumers—including this project— for processing into compost, biodiesel, and renewable energy. One of the perks of this project is that collecting raw materials can generate a profit on its own through tipping fees, which are defined as fees paid to anyone collecting waste for disposal at a landfill (WM). In this market where waste is collected to create products, tipping fees can also be collected even though the waste is not being taken to a landfill. While this is beneficial for this project, it also means that this project has to be competitive with other food waste collectors regarding the tipping fees. The main competitors for waste and tipping fees are disposal and waste management companies. The companies collect garbage and dispose of it at landfills. These disposal companies are not able to claim green processing and the production of renewable energy, which provides a large advantage for this project from a marketing standpoint. On the other hand, the waste management companies may have lower tipping fees and thus be the more attractive option to potential customers. The other competitors for tipping fees are fertilizer companies. Fertilizer companies collect waste to use in composting to create fertilizer. This project does something similar by taking the leftover digestate from anaerobic digestion to create compost. These fertilizer companies may have more competitive rates for tipping fees, which is something to consider when determining the optimal price to charge institutions for collecting their waste.

3.2 Preliminary Process Synthesis

Attainable Food Waste and Spent Oil

Before deciding on a process and possible products for the project, the amount of attainable food waste and spent oil needed to be determined. With a focus on the commercial sector, institutions with large dining facilities were chosen as sources of food waste. These included hospitals, hotels, nursing homes, elementary and secondary schools, supermarkets and grocery stores, correctional facilities and colleges and universities. The amount of food waste produced by each institution was determined using data from a study conducted in Massachusetts by Recycling Works. The company was able to come up with a set of standards for the amount of food waste produced per institution over the course of a year. This model was applied to one-hundred chosen institutions in Philadelphia, yielding a total of 9,700 tons of food waste, approximately 5% of the total food waste produced by commercial institutions according to the ARI estimate. Table 2 shows the total food waste per institutional group. Research has shown the average spent oil produced per institution to be around 230L per month. When applying this to the same one-hundred commercial institutions, a total of 276,000 L of attainable spent oil per year was calculated.

Table 2. Waste estimator for 100 large institutions around Philadelphia. The total estimated food waste for these 100 institutions is approximately 9700 tons per year, roughly 5% of the total commercial food waste produced in Philadelphia.



WASTE ESTIMATOR

Institution	**Number of Sites**	Waste Produced (lb/week)	Waste Produced (tonnes/week)	*Assumes 52 weeks Waste Produced (tonnes/year)
Hospital	10	121057	55	2858
Hotels	20	40160	18	948
Nursing Home	7	20522	9	484
Elementary and Secondary Schools	17	7633	3	180
Supermarkets and Grocery Stores	30	60000	27	1416
Correctional Facilities	4	40983	19	968
Colleges and Universities	12	121500	55	2868
Total Number of Sites	100		Total Waste Per Year (tonnes)	9723
			Philadelphia Total Commercial Waste	180000
			% Of Total Commercial Waste	5%

Food Waste Processing

Once we determined how much food waste from Philadelphia we could feasibly collect, the next step was to evaluate a list of feasible products, determine which ones we should pursue based on their economic value and cost of manufacturing, and consider alternative processes to produce the chosen products.

Two of the main uses for collected food waste are production of biogas through anaerobic digestion and composting. Anaerobic digestion is a technology that has existed for years, and is therefore well-documented. However, unlike other chemical processes, it is almost entirely regulated by the bacteria within that carry out the biochemical reactions. Anaerobic digestion is facilitated with an inoculum of bacteria. There are two types which can be used for the process, mesophilic and thermophilic. Whether the bacteria carrying out the reactions are thermophilic or mesophilic is determined by the operating temperature of the digester. Mesophilic bacteria are active at approximately 35 C, while thermophilic bacteria are active between 120-140°C ("Biogas from Manure," Homan et. al.). Thermophilic digesters tend to produce slightly more biogas than mesophilic digesters; however, this slight increase in biogas does not usually outweigh the greater amount of utilities required to heat it to a higher temperature.

Regardless of which type of bacteria is active, digestion occurs in four distinct stages. During hydrolysis, the bacteria break down the food waste into amino acids, monosaccharides, and fatty acids. In the next stage, acidogenesis, the products of hydrolysis are converted into acids, ketones, alcohols, hydrogen, and carbon dioxide. Afterwards, these products are transformed into acetic acid and more hydrogen and carbon dioxide in the acetogenesis stage. In the final stage of methanogenesis, a gaseous mixture of methane, carbon dioxide, and hydrogen sulfide is generated. This mixture is referred to as biogas, and it is the main financially lucrative product of anaerobic digestion. However, during the process, not all of the initial solid waste is converted to biogas. The remainder of this waste is referred to as the digestate, and has a higher percentage of available nitrogen than the initial food waste. The composition of biogas varies with the feedstock used, and often times the percentage volume of a component is given as a range. For the purpose of this project, we decided to assume the following percentages for the components of biogas, seen below in Table 3. These percentages were determined through discussion with Dr. Shieh and external sources.

Table 3. Biogas Composition by Volume.

Biogas Component	Percentage by Volume
Methane	67%
Carbon Dioxide	26%
Nitrogen	6%
Hydrogen Sulfide	<1%

We decided to pursue anaerobic digestion as our primary way of processing the food waste for a few different reasons. The first was the flexibility of such a system. Anaerobic digesters can be set up as either batch or continuous systems, which is decided based on the amount and frequency of waste being processed, the percentage of solids in the feedstock, and the desired biogas production. In addition, because a digester is essentially a sealed tank maintained at a constant temperature, it is not sensitive to changes in the volume of feedstock as long as the volume of feed does not exceed capacity. Because the quantity of food waste we are processing is based on past annual estimates and future projections, there is a strong likelihood that the actual amount of waste processed each week would fluctuate (both in quantity and quality). As a result, we needed a system that was not extremely sensitive to variation in the feed flow rates and composition of the feed.

The other reason for choosing an anaerobic digester was the ability to minimize waste from production. While biogas is typically seen as the main product of anaerobic digestion, we determined that the leftover digestate waste also has economic potential. Digestate from the digestion of organic matter—in particular food—has a high percentage of available nitrogen. The high temperature of digestion also ensures that the digestate is essentially pathogen-free by the end of the process. This is advantageous for turning it into either organic fertilizer or compost, which are often preferred to chemical fertilizers due to the minimized risk of nitrogen leaching into groundwater. By adding a bulking agent (e.g. woodchips or sawdust) to the leftover digestate, it can be converted to compost (and is no longer a waste stream that must be disposed). In this way, we are able to harness the financial benefits of both anaerobic digestion and composting in one streamlined process.

Another source of waste from our proposed facility is the crude glycerin and excess base reagent generated from the conversion of cooking oil to biodiesel. Because crude glycerin is a common byproduct of other industrial processes, including other, larger-scale biodiesel production facilities, the market is oversaturated with suppliers. However, glycerin can be processed in an anaerobic digester to produce biogas. Therefore, using an anaerobic digester allows us to reduce our waste from the biodiesel production process, and convert the crude glycerin into a more lucrative product. In addition, digesters must operate within a basic pH range (at least 7.5 or higher) for the bacteria to facilitate the process. The addition of the base reagent remaining from the biodiesel process to our feedstock will allow us to ensure our feedstock is basic enough for the bacteria to break it down.

The final reason for choosing anaerobic digestion is that the only alternative process—other than composting—was to directly combust the food for electricity generation. This process was unideal for a number of reasons—potential community resistance to an industrial incinerator nearby, the utilities associated with an incinerator of that size, and the disposal necessary for ash produced during combustion. For this reason, and the others previously discussed, we decided to use an anaerobic digestion system for the process.

Next, we faced the decision of how to process the biogas, since it cannot be directly injected into the natural gas grid due to impurities. Two main options were considered: upgrade the biogas to biomethane, or convert it to electricity to sell to the local power grid. Upgrading biogas to biomethane has recently taken a public spotlight, with BP set to purchase Clean Energy's biomethane production facilities for $155M. However, while this is a financially lucrative option for large scale organic waste processing and biogas production, few cost-effective biogas upgrading technologies exist for smaller-scale operations.

Once the potential revenues for biomethane versus electricity were calculated and shown to be relatively similar, we decided to pursue electricity production since the infrastructure has a lower capital cost and would be more economical for the amount of waste being processed. After this, the next step was to identify the best process to convert the biogas to electricity for our facility. Once again, two main options were considered: a gas turbine system and a Caterpillar biogas generator set. A simulation of a gas turbine system was created in Aspen (see Appendix C), and the cost was analyzed using the Aspen Process Economic Analyzer function. A gas turbine for our scale of operation was anticipated to be roughly $4M in capital cost, and $245, 000 for annual utilities. A Caterpillar biogas generator set, on the other hand, was anticipated to be much cheaper, with some generators available on the market for roughly $55,000. The models available also had a higher electrical efficiency than the gas turbine, and more options were available to easily add an additional unit to harness the thermal energy produced via cogeneration.

In addition to the capital cost differences, we also had to consider the nature of biogas. Biogas often has impurities, such as hydrogen sulfide, that are present in trace amounts. However, these impurities can affect the lifespan of the equipment used to process the gas due to their corrosive nature. The CAT biogas generators are specifically designed to withstand such impurities, which would likely increase their lifespans compared to systems with components that are not hardened to corrosive gases. The choice of a CAT generator set was also greatly influenced by logistics. The biogas generators are specifically designed to be easily connected to the local power grid to sell renewable energy, which is included within the installation costs and available CAT technical support. If we were to design and implement a gas turbine system, connecting it to the power grid would be much more cumbersome than the generator units specifically designed for such a purpose.

In summary, our solid food waste process decisions were heavily influenced by the existing technologies available, their benefits and downsides, the products they could be used to produce, as well as which options were suitable and logical for the scale of our operations. Figure 5, seen on the following page, displays a flowchart for the different decisions made in designing the initial process.

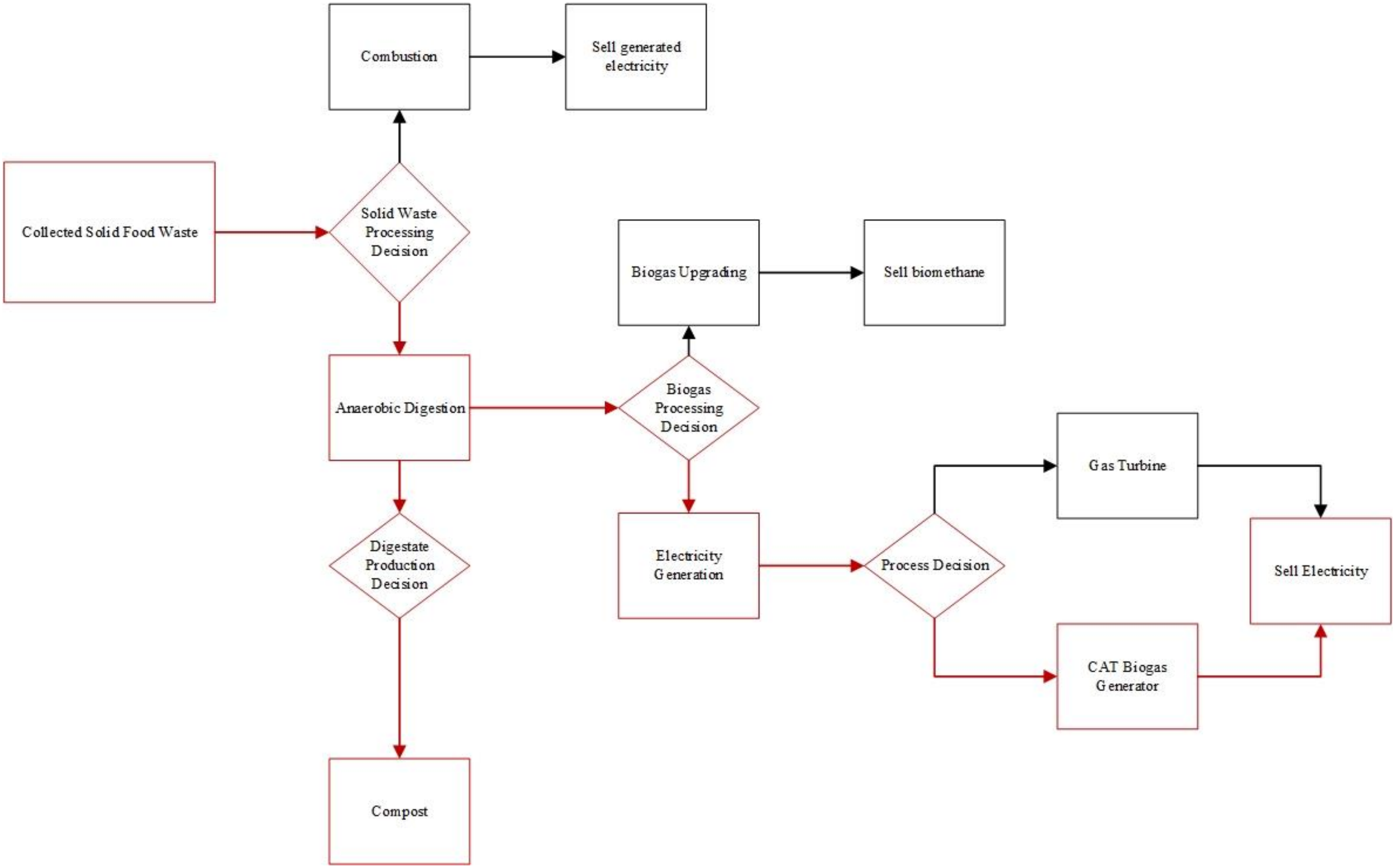


Figure 5. Flowchart for initial solid waste processing decisions. The boxes and arrows in red display the chosen options.

Spent Oil Processing

After deciding to focus on 276,000 L of attainable spent cooking oil produced by the one-hundred large institutions, the next step was to determine the most cost efficient way to convert the oil to biodiesel. Given that the conversion of oil to biodiesel is a relatively cheap and simple process, there are a number of prepackaged systems to carry out this process available on the market. However, because we are processing a large amount of oil each year, we also wanted to consider designing a larger-scale industrial process for our facility. Before choosing one of these processes, we needed to analyze the capital cost of a custom industrial design and compare this to the cost of processing the same amount of oil with a prepackaged unit.

The conversion of oil to biodiesel is carried out via an acid/base catalyzation. The reagents for this process are methanol, sulfuric acid, and a base catalyst. The first reaction is the esterification, or "acid" stage, which involves the mixing of sulfuric acid and a portion of the methanol into the oil. This reaction generates the biodiesel. The second reaction is the transesterification, or "base" stage, which involves the catalyst—usually sodium or potassium hydroxide—breaking up the oil molecules into glycerol and fatty acid chains. Finally, methanol reacts with the fatty acid chains, which causes glycerin drops to form. The process involves a settling period in which the glycerin falls to the bottom of the reactor and is separated away from the biodiesel. Finally, the system is drained and washed before it is run again. As mentioned before, a benefit of running anaerobic digestion as well as carrying out biodiesel production is that the glycerin produced during the oil conversion and the remaining base can easily be added to the digester, thus reducing disposal costs and improving the anaerobic process.

The conversion of spent oil to biodiesel has become a commonly used process. Due to the low cost and relatively easy reaction process, a number of prepackaged units have been developed that can be used to carry out the reaction without the need to design a system from scratch. One such unit is the BioPro™ 380EX Automated Biodiesel Processor developed by Springboard Biodiesel, which costs approximately $21,000 per unit. With a total annual capacity of 37,400 gallons each, two such processors are capable of handling our annual 72,864 gallons of collected spent oil. In addition, we found that prepackaged units have relatively small installation costs, since these units are designed for the average consumer to set up in their home.

The alternative to a prepackaged unit would be to design and build a process from scratch that can handle the capacity of collected spent oil. Figure 6 shows the ASPEN flowsheet for a proposed continuous design alternative. In order to conduct a capital cost analysis, the method outlined in Chapter 16 of *Product and Process Design Principles: Synthesis, Analysis and Evaluation* (Seider et. al.) was used (see Appendix A). The two reactors needed for the process, seen below in Figure 6, were costed at approximately $60,000 total. Without accounting for the cost of other equipment needed for the process, such as pumps and separators, it can be seen that the cost of the prepackaged units is significantly lower than that of the alternative design from scratch.

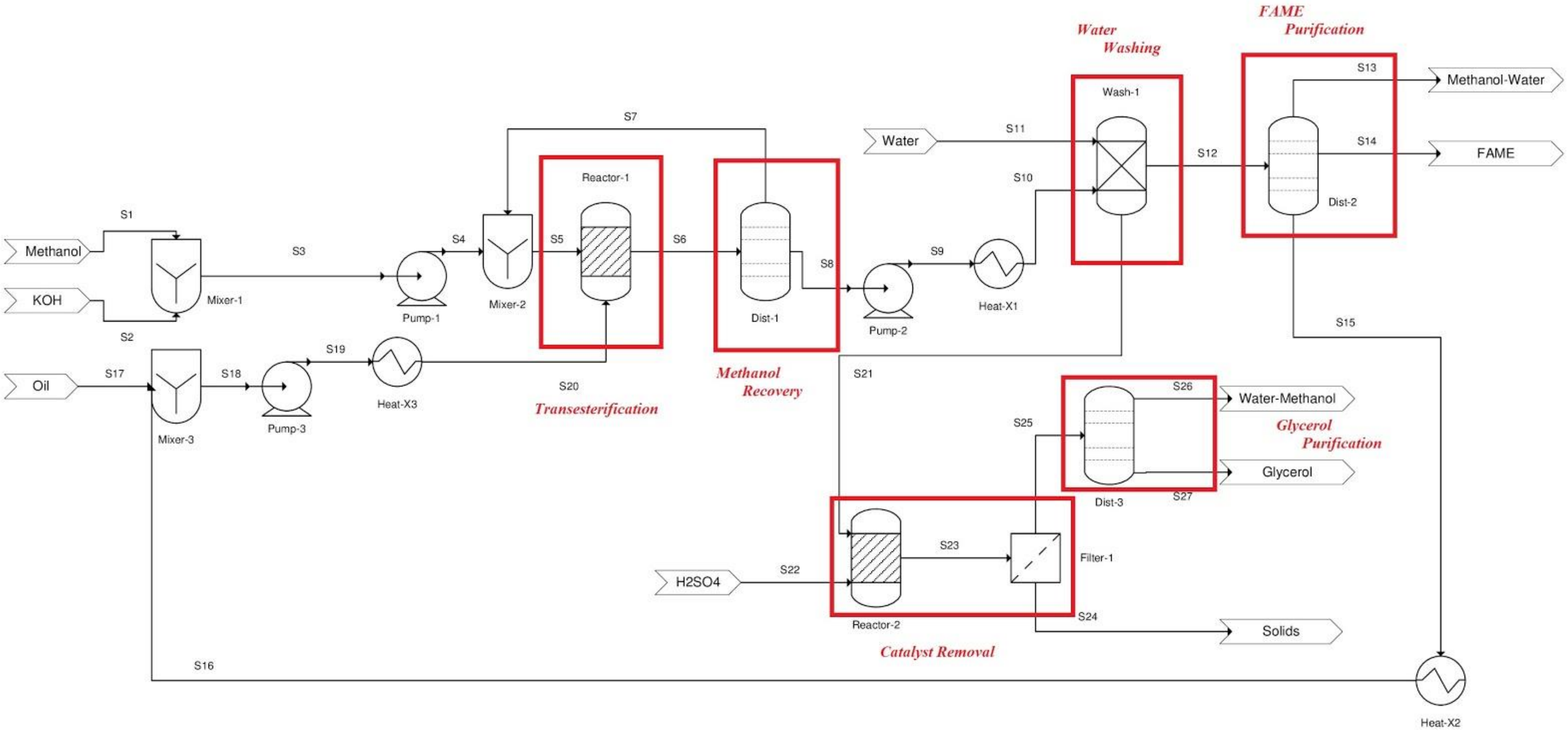


Figure 6. ASPEN Plus Simulation for Large-Scale Biodiesel Production. Note that the red boxes represent the major steps of the biodiesel production process.

After considering these two options, we decided to design our process with a prepackaged processing unit for a couple of reasons. Firstly, given the relatively small amount of oil that would need to be processed, two such units would be sufficient. Secondly, the installation and operation of these units are significantly cheaper and easier than those of a full-blown industrial process.

Compost Processing

As mentioned before, the digestate produced during anaerobic digestion has the potential to be used in composting, thus providing another income stream for our facility. There are a number of different techniques that are used in composting. The two most common techniques used for composting are aerated (turned) windrow composting and in-vessel composting. In-vessel composting can handle a diverse supply of food waste and involves the waste being fed into large drums or concrete-lined trenches. The waste is then mechanically turned, aerating the matter, producing compost in just a few weeks. The other alternative is the aerated (turned) windrow composting method which is capable of handling large quantities of waste. The process involves the addition of a composting agent, such as sawdust, and the piling of compost into mounds called “windrows” out in the open. The windrows are periodically turned, either manually or with machinery.

For the purpose of this project, the aerated composting system was chosen as it requires little initial investment and is ideal for handling large quantities of food waste. The process can also work in cold climates as the compost generates temperatures as high as 140°F, killing any pathogens in the process. Managing the compost is fairly simple and requires little work besides the occasional turning. There is, however, the need to add a bulking agent (in this case sawdust) in a ratio of 1:1 in terms of bulking agent to digestate.

Solid Food Waste Collection Process

The total projected food waste to be collected for this project is approximately 9,700 tons from 100 large institutions. Assuming a 52 week year and a 5 day collection week with each site being visited once per week, the total amount of waste that would be handled is approximately 37 tons and 20 sites collections made per day. The collection process is to be carried out using waste collection trucks designed by Mack®, which have a maximum capacity of approximately 30 tons and cost approximately $200,000 per truck. This process will include the purchase of three of these collection vehicles, two of which are capable of handling the daily waste collection with the third being used as a backup in case of breakdowns. The average fuel consumption estimated for these vehicles is 4 mpg. With an average distance travelled of about 25 miles per vehicle, the total mileage covered by the fleet per day is 50 miles, with fuel a consumption of about 12.5 gallons per day. At a diesel cost of approximately $2.69 as of March 24, 2017, the total weekly cost is approximately $170, giving an annual fuel cost for a two vehicle fleet managing 100 sites of approximately $8,700.

Spent Oil Collection Process

The spent oil collection process is able to be performed using a simple pick-up truck and collection drums. Each institution will be provided with a 30 gallon drum to collect the spent oil produced over the course of the week. Every week, the 30 gallon drum will be collected and replaced with an empty one for the next week. Each drum costs approximately $80. Servicing 100 institutions, 200 drums are required, with a total cost of $16,000. The pickup schedule can be kept the same as that for the solid food waste as the process will involve the same institutions. As with the solid food waste system, three collection vehicles will be purchased, each with an approximate cost of $30,000. The fuel consumption for such vehicles is approximately 12 mpg, giving an annual fuel cost of approximately $3,000. This was calculated using the current diesel cost of $2.69 and a daily truck mileage of 25 miles, as was used with the solid food waste collection calculations.

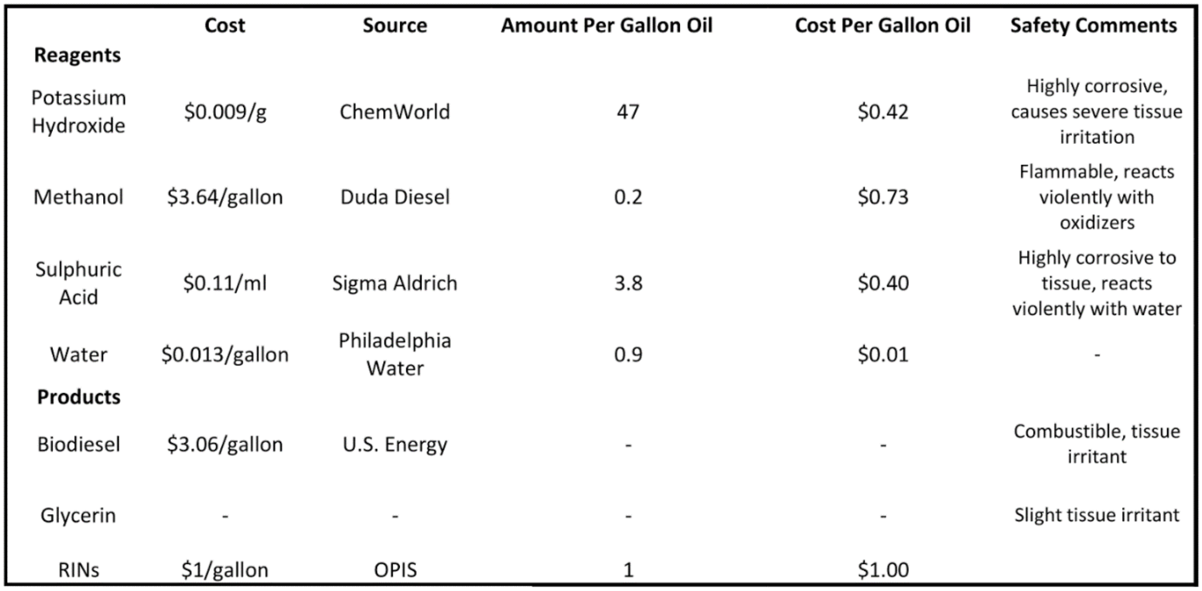
3.3 Assembly of Database

Biodiesel Processing

The costs of reagents used in the biodiesel processing were estimated using quotes from vendors. Table 4 shows the estimated prices and sources for the materials. Another important “product” from the spent oil processing is the renewable identification numbers (RINs) which are generated along with the biodiesel. The biodiesel production process generates 1.5 RINs per gallon of biodiesel. This means that our spent oil processing generates approximately 89,424 RINs annually, which are able to be sold together with the biodiesel. The price of the RINs is approximately $1/RIN according to OPIS, an ethanol and biodiesel information service. In analyzing the glycerin produced, the cost is not taken into account as it is simply added to the anaerobic digester and is not directly used to generate an income stream.

Table 4 also displays comments regarding the safety of each reagent. For more detailed safety information, the Safety Data Sheets for these reagents can be found in Appendix B.

Table 4. Cost of materials used in biodiesel processing.



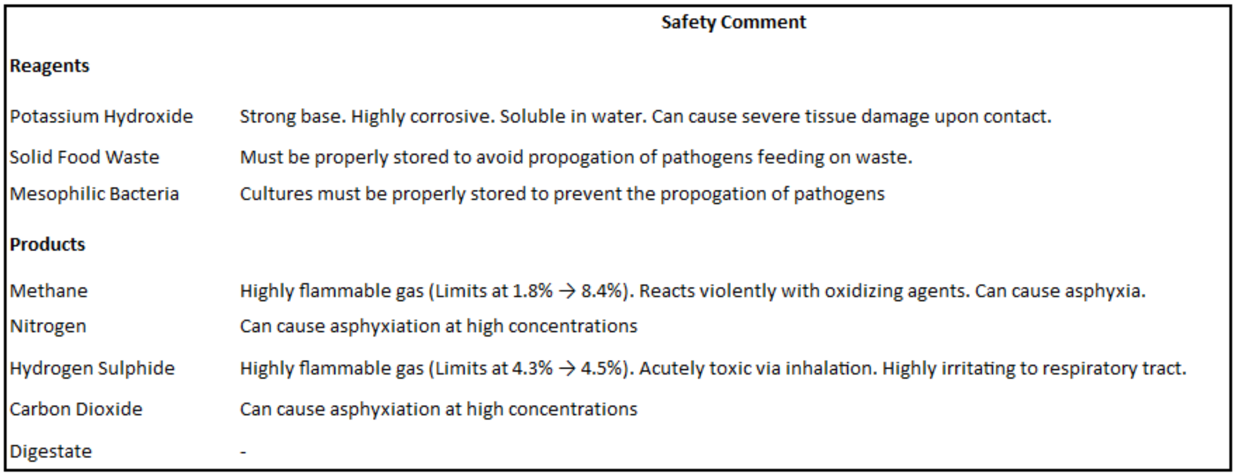
	Cost	Source	Amount Per Gallon Oil	Cost Per Gallon Oil	Safety Comments
Reagents					
Potassium Hydroxide	$0.009/g	ChemWorld	47	$0.42	Highly corrosive, causes severe tissue irritation
Methanol	$3.64/gallon	Duda Diesel	0.2	$0.73	Flammable, reacts violently with oxidizers
Sulphuric Acid	$0.11/ml	Sigma Aldrich	3.8	$0.40	Highly corrosive to tissue, reacts violently with water
Water	$0.013/gallon	Philadelphia Water	0.9	$0.01	-
Products					
Biodiesel	$3.06/gallon	U.S. Energy	-	-	Combustible, tissue irritant
Glycerin	-	-	-	-	Slight tissue irritant
RINs	$1/gallon	OPIS	1	$1.00	

Anaerobic Digester

The anaerobic digester requires two main reagents: food waste and a bacteria inoculum, both of which have no anticipated cost of purchase. The solid food waste is collected from food institutions where a tipping fee is collected from the institution. The bacteria inoculum is typically obtained from waste water or manure sludge, which can be obtained from the local water treatment facility or dairy farm. A third reagent, potassium hydroxide, can also be added to the anaerobic digester to reduce the acidity of the feedstock. Potassium hydroxide is a waste product from the biodiesel processing unit, so there is not any cost associated with it.

The biogas produced from the digestion is composed mainly of methane and carbon dioxide, with smaller amounts of nitrogen and hydrogen sulfide. Table 5 contains brief comments on the safety and toxicity of these compounds; the full Safety Data Sheets can be found in Appendix B.

Table 5. Safety and Toxicity of Anaerobic Digestion Reagents and Products.



	Safety Comment
Reagents	
Potassium Hydroxide	Strong base. Highly corrosive. Soluble in water. Can cause severe tissue damage upon contact.
Solid Food Waste	Must be properly stored to avoid propogation of pathogens feeding on waste.
Mesophilic Bacteria	Cultures must be properly stored to prevent the propogation of pathogens
Products	
Methane	Highly flammable gas (Limits at 1.8% → 8.4%). Reacts violently with oxidizing agents. Can cause asphyxia.
Nitrogen	Can cause asphyxiation at high concentrations
Hydrogen Sulphide	Highly flammable gas (Limits at 4.3% → 4.5%). Acutely toxic via inhalation. Highly irritating to respiratory tract.
Carbon Dioxide	Can cause asphyxiation at high concentrations
Digestate	-

Composting

Materials involved in the composting process include digestate from the digestion process and bulking agent. The cost of bulking agent, in this case sawdust, is estimated to be approximately $0.20 per ton. The sawdust is a waste product from other processes and given its production in large quantities and the small market demand, it is relatively cheap. However, the major cost associated with the bulking agent is from the transportation. Using Freight Center shipping cost estimates, the cost of shipping is approximately $20/ton of sawdust. The compost product has an estimated selling price of $65/ton. This is based off of the national compost prices data, and is on the lower end of the scale. Once testing and research is performed on our compost to determine its nutrient content, the compost's value could be found to be significantly higher. Table 6 shows the price estimates for material used in the composting process.

Table 6. Cost of materials used in composting processing.

	Cost	**Source**	**Cost per Tonne Compost**	**Safety Comments**
Bulking Agent	$0.2/tonne	Independent Suppliers	$ 0.10	May Cause Allergic Respiratory Symptoms
Compost	$65.0/tonne	National Compost Prices	-	-

Section 4: Process Flow Diagrams and Material Balances

4.1 Process Design and Descriptions

Before presenting the process flow diagrams and mass balances, it is important for us to discuss the different equipment options we faced for the three major processes: biogas production, electricity generation, and biodiesel production. In particular, we want to highlight the logistical and financial factors that influenced us to choose the units that we did.

Biogas Production

The most important equipment decision we faced for the biogas production process was the digester system. Before we could choose a specific system, we first had to decide whether wet or dry anaerobic digestion was the more suitable choice. Wet digestion is typically used for feedstock with a moisture content greater than 75%, while dry digestion is used for feedstock with a moisture content less than that (“Dry Fermentation vs. Wet Fermentation”). With food waste typically having a moisture content of roughly 70% (Hogg), our feedstock was on the border between the two options. Consequently, we examined the major process differences between the two to identify which was better for our proposed facility. When performing wet digestion, additional water is used to dilute the biomass to ensure it can easily flow through the system. In addition, the food waste must be pre-treated to ensure its homogeneity. Both dry and wet anaerobic digestion must be carried out at 40 C (in the mesophilic range). As a result, a significantly larger amount of energy would be required for wet digestion, since the feedstock would have a higher moisture content and therefore a higher heat capacity. In addition, energy would be needed for the mechanical pre-processing of the food. Wet fermentation also produces a greater amount of waste water, and a smaller amount of solid digestate. This would be detrimental to the project, since it would both increase the cost of wastewater disposal and decrease the amount of compost that could be produced from the digestate.

Dry digestion, on the other hand, eliminates the need for pre-processing of the food waste and the addition of water to the process. As a result, the amount of waste water produced is minimal and the digestate has a higher solids content, which is ideal for producing compost. Compared to a wet digestion facility, the dry digestion facility would have decreased utility and waste disposal costs, as well as higher production of compost.

Despite these benefits, we had initial concerns about using a dry system, since food waste does have a high moisture content, and dry systems are traditionally used for feedstocks such as grain, straw, and manure. However, after researching case studies of other projects that used dry digestion of food waste for renewable energy production—including the University of Wisconsin Oshkosh Campus ("Urban Anaerobic Dry Biogas Systems"), the Monterey Peninsula region of California (Beane), and others—we discovered that dry fermentation has proven to work very well for projects similar to ours. For these reasons, we decided to design our process with dry fermentation, even though it is a slightly unorthodox choice.

Once this decision was made, we focused on identifying a system and vendor appropriate for the size of our annual feedstock, as well as for our goal to sell electricity back to the local grid. We ultimately chose the Wisconsin-based vendor BIOFerm™ Energy Systems, a subsidiary of the Viessmann Group, and their Dry Fermentation Digester. In addition to them being a leader in the dry anaerobic digestion industry with over 400 installations in North America, there were a few distinct reasons why their system appealed to us. These included the similarities between their past projects and ours, the customizability of their system, and the standard design of the system, which can be seen below in Figure 7. A picture inside of one of their existing facilities can be seen in Figure 8.

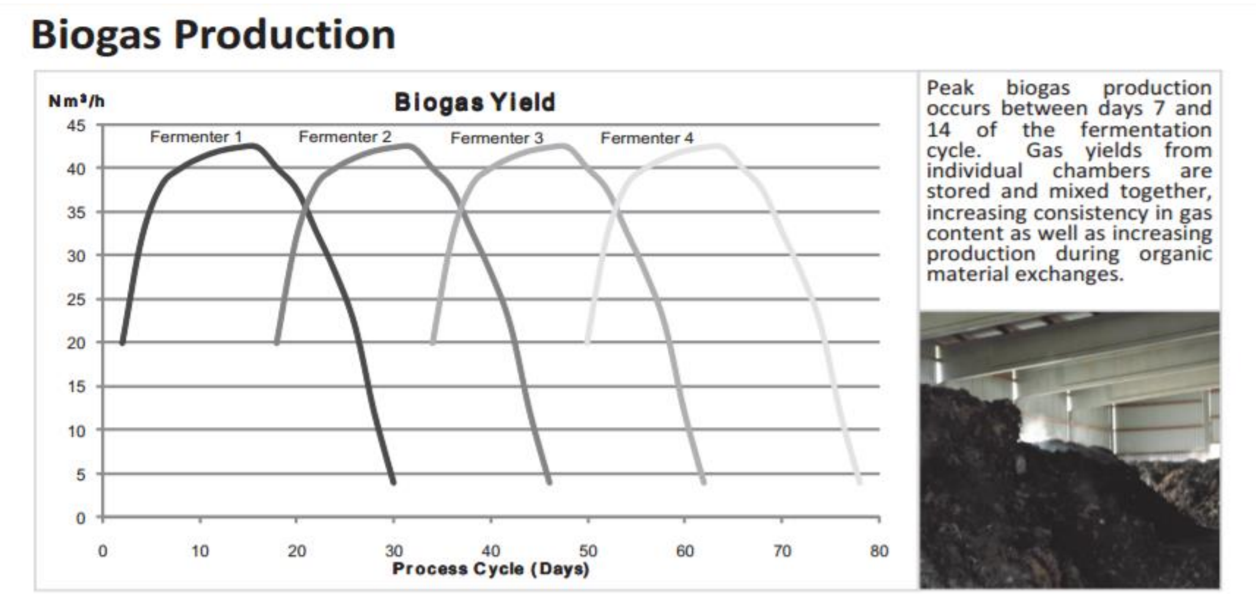
Figure 7. Vendor’s rendering of a standard BIOFerm™ Dry Fermentation Digester. Note the multiple fermentation chambers. In our case, the mixing station, fermenting chambers, biomass, and combined heat and power module would all be contained within the facility. This type of indoor facility has been designed by the vendor in past projects.

Figure 8. Interior of a BIOFerm Dry Fermentation System.

The BIOFerm™ Dry Fermentation Digester differed from similar systems on the market based on its annual processing capacity. Other digesters on the market were either designed for smaller-scale operations (i.e. 6000 tons per year or less), or much large-scale projects, on the scale of tens of thousands of tons per year. In addition, the BIOFerm system is designed to operate in the mesophilic temperature range at roughly 40 C. As mentioned in the Preliminary Analysis section, this is preferred over operating in the thermophilic range (approx. 120 C) since the slight increase in biogas production at a higher temperature does not outweigh the increased heating utilities. One of the main competitors to BIOFerm is Zero Waste Energy with their SMARTFerm system. This system is very similar to the Bioferm Dry Fermentation Digester; however, it is designed to operate in the thermophilic range. For this reason, we chose the BIOFerm system for our facility over one of the competing SMARTFerm options.

BIOFerm™ Digester Design Considerations

BIOFerm Dry Fermentation Digestion systems are composed of multiple concrete chambers, into which food waste is placed. When a chamber is in use, it is sealed shut for 28 days, during which time the food waste breaks down into biogas and digestate. Afterwards, operators can remove the digestate from the chamber and prepare a new batch for processing. These systems are highly customizable; that is, the number of chambers of each system is determined based on the amount of food waste the facility intends on processing per year. Each chamber can process roughly 150-200 tons of fresh feed per batch. To appropriately calculate our capital cost and determine a feasible production schedule, we first had to determine the optimal number of chambers for the amount of food the facility is processing each year. This was determined by assuming a new chamber would be loaded each week (to reduce the amount of food waste lying around after pickup to improve odor control), such that the individual batches are run in series to simulate a continuous process. Based on this, the optimal number of chambers to process the amount of food was determined to be six. This was done by using information about the biogas production of individual chambers provided by the vendor, which can be seen in Figure 9. The figure provided by the vendor only shows four fermenting chambers in series; we were able to recreate these biogas production curves in Excel to extrapolate to a six chamber system, seen in Figure 10. As you can see, a six figure system allows for a relatively consistent flow of biogas. By creating the figure, we were also able to confirm that there is a sufficient number of fermenting chambers for a batch frequency of 7 days; that is, we were able to show that Fermenter 1 would be complete and ready for a new batch the week after Fermenter 6 is loaded with a batch.



Biogas Production

Peak biogas production occurs between days 7 and 14 of the fermentation cycle. Gas yields from individual chambers are stored and mixed together, increasing consistency in gas content as well as increasing production during organic material exchanges.

Figure 9. Biogas production rates for individual fermenters over 28-day batch time. This plot is provided by the vendor. Note that the units of biogas production are normal cubic meters per hour, not cubic nanometers per hour.

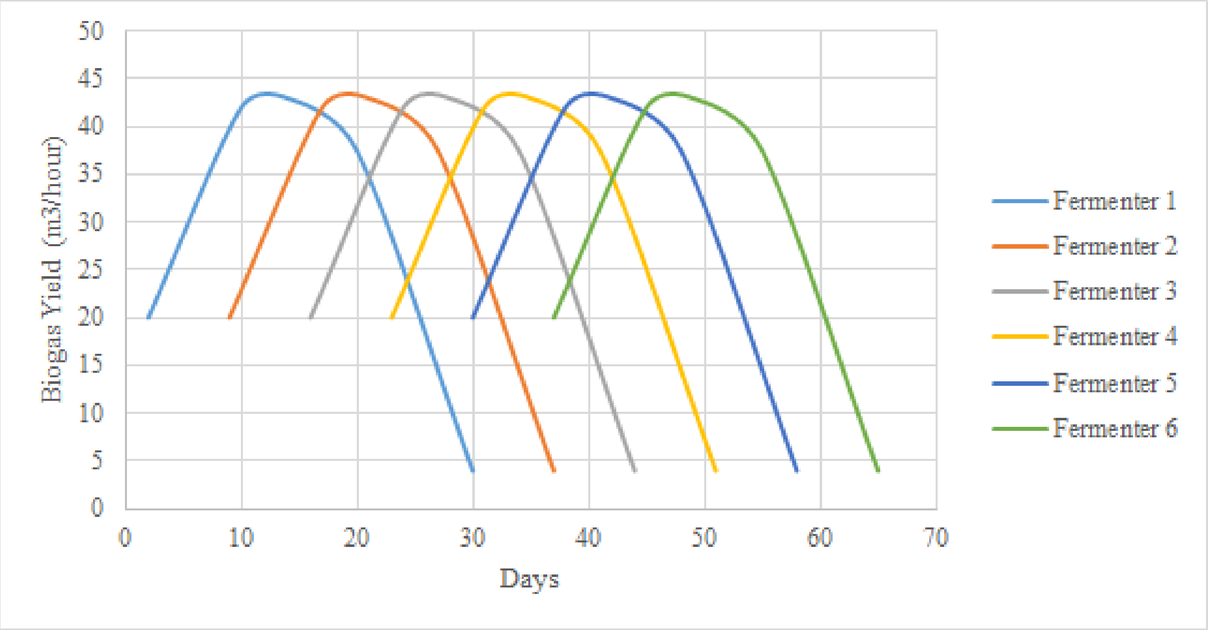


Figure 10. Plot of Biogas Yield of Six Fermenters in Series versus Number of Days. Note that there is no overlap between the cycles of Fermenter 1 and Fermenter 6, which means 6 fermenters is a sufficient amount for a 7-day period between starting batches.

Electricity Generation

When it came to choosing a generator set, it was important to consider the nature of biogas. Biogas contains trace amounts of impurities, such as hydrogen sulfide, that can corrode the engine of a generator and decrease its overall lifespan. Biogas also has a greater moisture content than natural gas, which can also decrease the lifespan of the generator. For this reason, we decided to look into generator sets specifically designed to process biogas, as opposed to using a generator designed for natural gas. We discovered that Caterpillar has a line of gas generator sets that are specifically designed to take biogas as an input. The engine components of these generators are specifically hardened to handle impurities to increase lifespan. In addition, Caterpillar provides comprehensive support for installing these generators and connecting them to the local power grid to sell the renewable electricity that is produced. Given that this is exactly what our project is focused on, we decided to choose one of their biogas generator sets for our electricity generation process.

Caterpillar Gas Generator Set Design Considerations

To choose the appropriate CAT gas generator set for our process, we worked with a power systems engineer at Ransome Cat, which is the supplier for the Philadelphia region. In order for him to recommend which set we use, we had to provide him with a list of specifications, which are shown below in Table 7. With this information, he recommended that we use the Caterpillar CG132-12 Generator set (Figure 10), which is rated 600 kW, and has an electrical efficiency of 41.4%, a thermal efficiency of 43.7%, and an overall efficiency of 85.1%. More information regarding this generator set can be found in the Equipment List section, and the technical data sheet from Caterpillar can be found in Appendix B. The calculations for the energy value of our biogas stream can be found in Appendix A.

When operating at 100% load of the generator (i.e. 600 kWh electricity output), the energy requirement of the stream is 1449 kWh. This is slightly less than the total energy available from our biogas per hour (1556 kWh). The reason for this is that we wanted to leave a buffer of available biogas for processing. With anaerobic digestion, biogas production rates can often be inconsistent. We designed the digester to operate as a series of batch processes to mimic a continuous process and therefore hopefully have uniform production of biogas. However, this is not a guarantee. Therefore, by planning to use less of the biogas than we're producing on average per hour, we leave ourselves a comfortable buffer if for some reason the biogas production rates are lower than expected at a given time.

Table 7. A list of specifications provided to Caterpillar for generator selection. The calculations for the energy value of biogas can be found in Appendix A. The voltage requirement was given as 277 volts per PECO recommendation.

Specification	Value
Energy Value of Biogas	1556 kWh
Installation Location	Indoors
Paralleled with Grid?	Yes
Voltage Requirement	277 V

Figure 10. Caterpillar CG132-12 Biogas Generator Set.

Biodiesel Production

The conversion from spent cooking oil to biodiesel is a well-investigated reaction pathway. Thermodynamic and kinetic data for this conversion is abundant and thorough. Using this data, the pathway that most fit our needs was determined. The conversion requires an esterification reaction followed by a transesterification reaction. Both reactions require catalysts.

An esterification reaction requires an acid catalyst. Typically for the conversion from spent cooking oil to biodiesel, either phosphoric acid or sulfuric acid is used. On the market, phosphoric acid tends to be cheaper but less concentrated. On the other hand, sulfuric acid is more expensive, but also more concentrated. Sulfuric acid has a higher pKa value, which means it would result in better conversion of the oil, thus justifying the higher cost.

A transesterification reaction requires a base catalyst. The recommended catalysts based on the kinetic data are potassium hydroxide and sodium hydroxide. Unlike the acid catalysts for the esterification process, neither offers a clear kinetic advantage over the other. Since they are nearly kinetically identically in regards to this reaction, potassium hydroxide was chosen as the catalyst due to its lower cost.

As mentioned in the Preliminary Synthesis, we decided to purchase a prepackaged reactor unit rather than designing one from known thermodynamic and kinetic data. Through careful consideration, the BioPro™ 380 EX unit was selected (Figure 12). The company that produces this unit sells it with a SpringPro™ T76 unit. This unit is a drying tower designed to purify the biodiesel produced by the BioPro unit to ASTM D6751 standards.

Another appealing aspect of the BioPro unit is the integrated automation. Once the operator loads the reagents and starts the batch, his only other job is to manually drain the solid glycerin from the tank during the separation stage. Otherwise, the unit is essentially autonomous, which reduces the number of operators needed each shift.

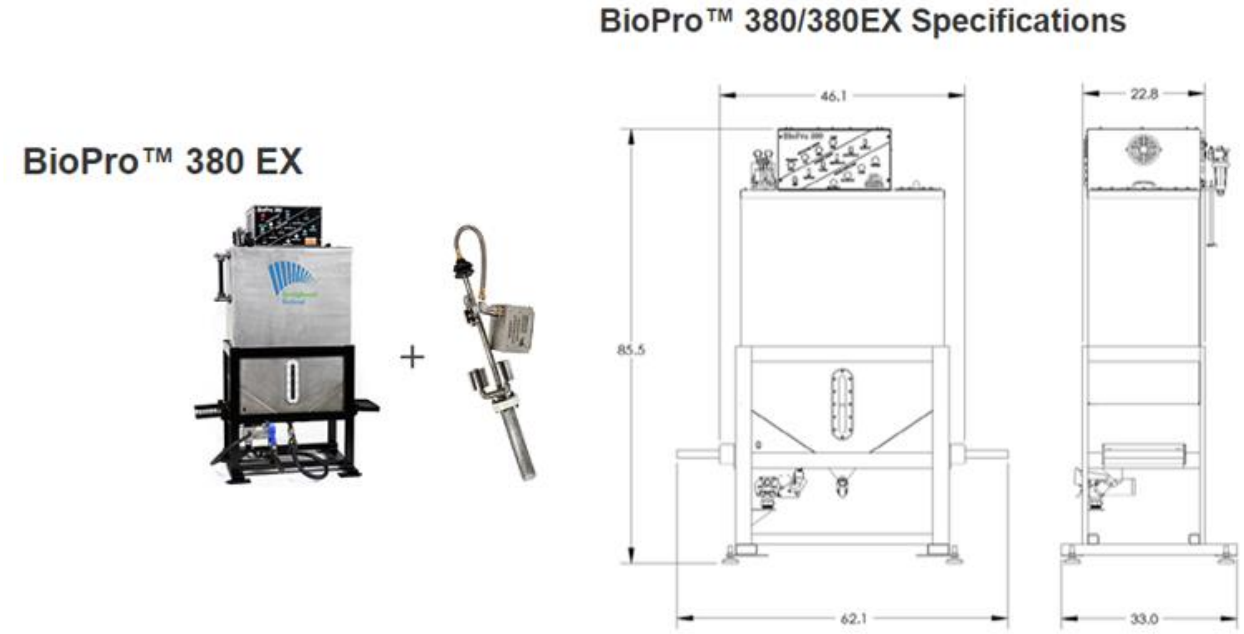


Figure 12. Vendor's Picture of BioPro™ 380EX.

Section 4.2 Process Flow Diagrams and Mass Balances

The process flow diagrams and stream tables are shown below for the two main sections of the plant. Section 100 is the anaerobic digestion of solid waste to produce biogas and digestate, and the subsequent production of electricity from the biogas and compost from the digestate. The digestion is carried out as multiple batch processes in series to give a relatively continuous flow of biogas to the generator set. Figure 13 shows the process flow diagram for Section 100. Table 8 displays the mass balance information for this section and Table 9 displays information about the energy streams. The conversion of spent oil to biodiesel is shown in Section 200; this is also a batch process. Figure 14 shows the process diagram and Table 10 shows the mass balance information for this section.

Section 100

Food waste enters the BIOFerm Dry Fermentation Anaerobic Digestion System (R-100) at 25 C and 1.013 bar. The system is maintained at 40 C via heat produced from the generator set. Digestate leaves the fermentation chambers at 40 C and 1.013 bar and is sent to the composting area within the system (V-100). The digestate is mixed with bulking material, in this case sawdust, to produce compost. During the composting process, the mixture is expected to reach internal temperatures of 40-65 C while at 1.013 bar.

Biogas also leaves the fermentation chambers and enters a storage vessel (R-100) before being processed in the Caterpillar CG13-12 Gas Generator Set (G-100) to produce electricity to sell back to the grid and heat to maintain the temperature of the BIOFerm system. Before the gas is fed to the generator set, impurities are removed via proprietary systems within the BIOFerm facility. These include a proprietary biological desulfurization system within this storage vessel to remove hydrogen sulfide from the gas, and a carbon filter/iron sponge system to remove other impurities. A more in depth description about what is included in this facility can be referenced in Section 4.4.

Because of the inconsistent nature of anaerobic digestion, and the fact that it is a batch process with inhomogeneous feeds, it is important to note that the numbers in Table 8 for the temperature, pressure, and stream compositions are approximations. In reality, these numbers would be adjusted once the facility begins operating, when lab tests can be completed to check the composition and purity of the biogas, digestate, and compost. Because the process is batch, it should also be noted the flow rates listed below are hourly averages based on expected yearly production, and an operating year of 360 days.

It should be noted in the PFD below, that streams 106 and 108 represent the electricity produced to be sold back to the grid, and the heat produced to maintain the digester temperature. While these are not actual mass flows, we felt that it was important to understanding our process to have them represented. Information about them can be found in Table 9.

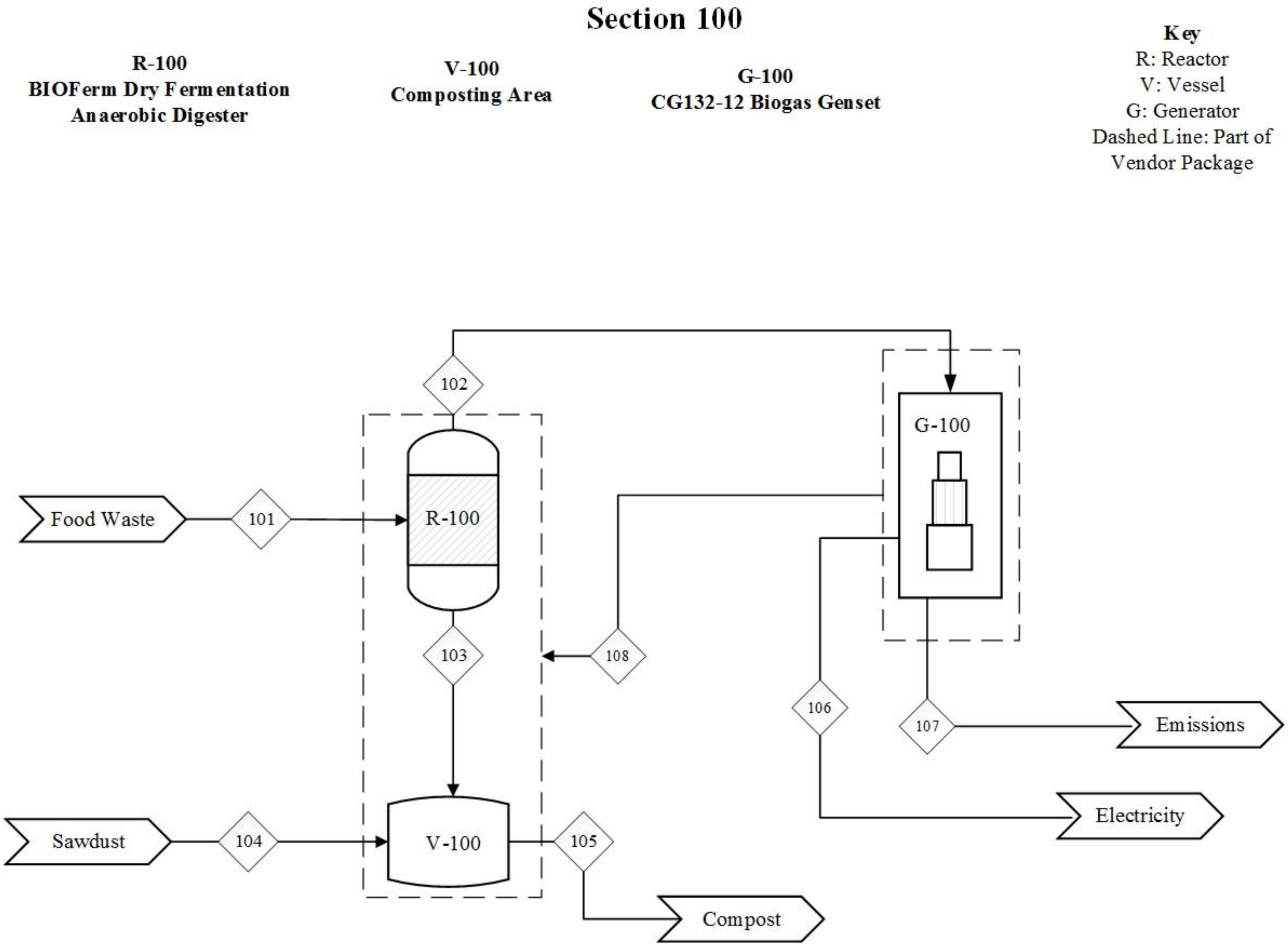


Figure 13. Process flow diagram for anaerobic digestion of food waste. Biogas is subsequently processed by a generator set to produce electricity and heat.

Table 8. Section 100 Mass Stream Summary Table. Numbers are approximations based on pre-existing facilities and case studies; these would be confirmed with process monitoring and lab testing once the facility is operational. Stream 102 represents the biogas flowing to the generator; this flow also includes the air needed for combustion in the engine, the value of which was taken from vendor's spec sheet. The values for this stream are approximations, and would be confirmed with additional testing.

STREAM ID:	**101**	**102**	**103**	**104**	**105**	**107**
Temperature (C)	25	40	40	25	30	475
Pressure (bar)	1.013	1.013	1.013	1.013	1.013	1.013
Total flows (kg/hr)	1025	3250	762	762	1524	3250
Component flows (kg/hr)						
Methane	0	113	0	0	0	trace
Carbon Dioxide	0	121	0	0	0	432
Nitrogen	0	16	0	0	0	1515
Hydrogen Sulfide	0	trace	0	0	0	0
CO	0	0	0	0	0	trace
NOx	0	0	0	0	0	trace
Air	0	3000	0	0	0	1048
Digestate	0	0	762	0	0	0
Compost	0	0	0	0	1524	0
Food Waste	1025	0	0	0	0	0
Sawdust	0	0	0	762	0	0
Water	0	0	0	0	0	255

Table 9. Section 100 Energy Stream Summary Table. Stream 106 is the electricity produced from the generator, and stream 108 is the thermal heat produced from the generator fed back to the facility.

STREAM ID:	**106**	**108**
Energy Type	Electricity	Thermal Heat
Total Flow (kWh)	600	633

Section 200

To begin the process of converting oil to biodiesel, the BioPro™ 380 is charged with the collected spent oil (Reactor). This oil enters the reactor at 25 C and 14.7 psi. In addition, methanol, sulfuric acid, and potassium hydroxide are loaded into their specific compartments (Reactor). The reactor is maintained at 14.7 psi and is heated to about 60°C to facilitate the reactions. Once the reactions are complete, the effluent from the reactor is flushed with water to separate the biodiesel from the other products (Separator and Mixer). After removing the solid glycerin (S10) and draining the aqueous solution (S9), the remaining biodiesel is allowed to dry to remove any remaining moisture. This drying is achieved by heating the biodiesel and keeping it well ventilated. A process flow diagram for these steps can be seen below in Figure 14. Table 10 displays the information for the feed and product streams per batch.

Although the chemical nature of spent vegetable oil can vary from institution to institution, the rigorous automation of the esterification process eliminates the need to apply a complex control system. Consequently, every batch of biodiesel produced may vary very slightly, but will always fall within the ASTM D6751 standards for biodiesel.

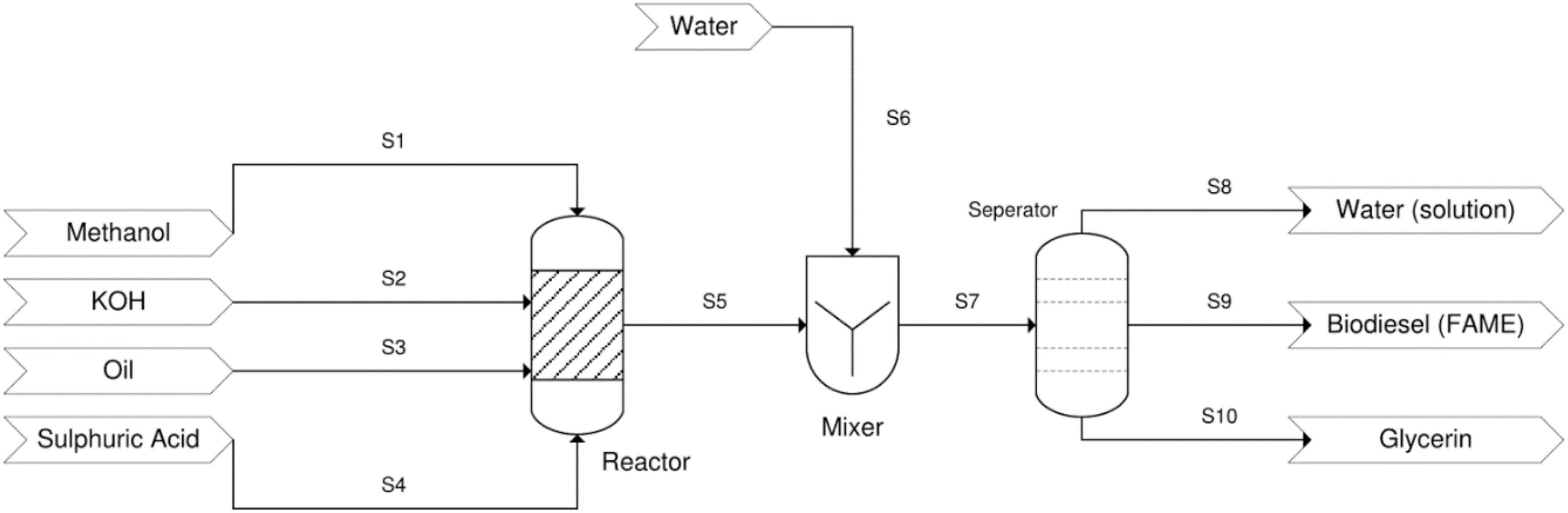


Figure 14. The process flow diagram for the BioPro™ 380EX biodiesel unit. Although these units are modeled as if they were separate, the reaction, washing, and separation all occur in the same module.

Table 10. Section 200 Stream Summary Table. Even though the above PFD in Figure displays multiple streams and units, the actual biodiesel unit has one feed stream and one product stream.

STREAM ID:	**Feed**	**Product**
Temperature (C)	25	25
Pressure (psi)	14.7	14.7
Total Flows (kg/batch)	754	754
Component Flows (kg/batch)		
Spent Oil	348	0
Methanol	59.96	5.41
Potassium Hydroxide	4.70	4.70
Sulfuric Acid	0.70	0.70
Water	340.65	340.65
Biodiesel	0	272.45
Glycerin	0	130.09

Section 5: Energy Balance and Utility Requirements

Due to the nature of our facility producing green heat and electricity, we decided early on to use the heat and electricity produced from the biogas to power the facility. Because the design of the dry fermentation digester system was approximated based on past projects, and is customized by the vendor for each new project, the utilities were calculated based on their approximations and our own calculations. Biodiesel production requirements were determined from the specification sheets provided from the vendor.

Section 100

BIOFerm™ approximates that roughly 5% of the total energy produced from the biogas is required to power the facility. In order to determine if this was applicable to our facility, we created a heat transfer model to approximate the amount of energy required to maintain the chambers at 40 C. The full extent of these calculations can be seen in Appendix A. Based on this model, the total amount of utilities required to heat the six fermenting chambers is roughly 658,500 kWh per year. This is roughly 6% of the total energy produced by the facility, which is slightly higher than BIOFerm's estimate. However, this is expected since these calculations were performed assuming the outdoor temperature was the Philadelphia average winter low (roughly 30 F) year-round.

A breakdown of the electricity and thermal energy produced by the generator set on an hourly basis can be seen below in Table 11. These values were calculated based on the energy value of the entering biogas stream, the electrical efficiency of the generator, and the thermal efficiency of the generator.

Table 11. Energy balance for generator set on an hourly basis.

Energy Value of Entering Biogas (kWh)	Electricity Output (kWh)	Thermal Output (kWh)	Energy Requirement of Generator/Heat Losses (kWh)
1449	600	633	216

Section 200

The two main utilities for biodiesel production are electricity to run the unit and water to clean the unit. Since the biodiesel production is being carried out with consumer units, the annual electrical utilities for operating two of these units were calculated via the power requirements on the vendor's specification sheet. In total, these utilities came out to be 36,400 kWh annually. The electricity cost for processing the spent oil was estimated to be $0.07/kWh and was obtained by averaging the price of electricity from local providers such as PECO and Frontier Utilities.

The cost of water used for the cleaning stages during the process was estimated to be $0.01/gallon and assuming an annual biodiesel production of 59,616 gallons. This price was obtained from The Philadelphia Water, Sewer and Stormwater Rate Board.

Table 12: Utility costing for biodiesel processer. This is assuming an annual biodiesel production of 59,313 gallons

Utility	Requirement/Gallon Biodiesel	Cost	Total Cost
Electricity	1.2kWh	$0.07/kWh	$5,000
Water	0.9 gal	$0.01/gal	$540

Section 6: Equipment Lists and Unit Descriptions

6.1 Equipment List

BIOFerm™ Dry Fermentation Digester

A BIOFerm™ Dry Fermentation Digester will be used for solid food waste processing. The system will consist of six 70’ x 23’ x 16.7’ concrete fermentation chambers, each which can process 150-200 tons of fresh feed per cycle. Each chamber is maintained at 40 C during the fermentation cycle. Each chamber is connected to a balloon-like flexible storage unit that contains the biogas produced; the gas is stored at low pressure (<1 psi). A biological desulfurization system within the roof of the storage unit is used to remove the trace amounts of hydrogen sulfide, while a carbon filter/iron sponge system is used to remove other toxic impurities. Percolate sprinkler systems are installed within each of the fermentation chambers, to allow percolate to be continuously circulated through the feedstock. Liquid percolate generated during the process will escape via a drain system and enter the percolate storage tank before re-entering the fermentation chambers. The percolate storage tank is estimated to be 675 m^3 (based on the University of Wisconsin Oshkosh facility). The tank also operates under anaerobic conditions and generates biogas, which will be sent to the generator set. A biofilter system is included in the mixing room where the food will be stored before being processed to ensure odor control.

Caterpillar CG132-12-B-60 Gas Generator Set

A Caterpillar CG132-12 generator set will be used to convert biogas to electricity and heat. The generator is rated 600 kWel. The engine has a speed of 1800 1/min, 12 cylinders, a compression ratio of 15, and a frequency of 60 Hz. At 100% load, the fuel consumption is 4944 MBTU/hr. The electrical efficiency is 41.4%, the thermal efficiency is 43.7%, and the overall efficiency is 85.1% at 100% load. The cooling system for the generator consists of an intercooler with 35% volume glycol and a water cooling jacket. The CHP add-on unit for the generator will be designed for steam heating at 1.1 bar.

2015 Mack Granite, 25 Yd McNeilus Rear Loader

Mack Granite™ garbage trucks will be used to collect the solid food waste from various institutions and transport them to the processing facility. The truck's load capacity is 40,000 – 46,000 lbs. The collection system is rear-loading, with compression hydraulics in the rear to maximize the volume available for waste collection. There will be three waste collection trucks, one of which will be kept as a contingency in case one of the other trucks requires maintenance. Each truck will be manned by one person and will visit ten institutions per day, traversing an average of 25 miles daily. Assuming an average of 4 miles per gallon, annual fuel costs for the fleet of waste collection trucks are estimated at $8,743.

Ford F-150 Waste Vegetable Oil Collection Vehicle

Two Ford-F150 XL pickup trucks will be used to collect the waste vegetable oil from various institutions and transport them to the processing facility. Each truck's towing capacity is 10,000 lbs. The trucks will each visit ten institutions each day and traverse about 25 miles daily. The trucks will collect oil drums and transport them to the processing facility. This will be done by having each truck manned by one person. Assuming an average of 18 miles to the gallon, annual fuel costs for the waste oil collection vehicles are estimated at $1,943.

Toyota Electric Pneumatic Forklift

A Toyota Electric Pneumatic forklift will be used to move around the drums of reagents, waste to be processed, and reactor effluent around the facility. The forklift has a load capacity of 5,000 pounds. From the loading dock, the forklift will move oil drums of waste vegetable oil to the biodiesel reactor.

John Deere 4066R Compact Utility Tractor

To move digester input and output, a small John Deere™ front loader will be used. The front loader will move the solid food waste from the loading dock to the fermentation digester and will then move the digestate to the composting area outside. The front loader has a 65.9 horsepower engine that yields a lift capacity of 54 horsepower. Diesel is the fuel for the engine, and the engine can produce 131.3 lb-ft of torque.

Carbon Steel Drums

To store waste vegetable oil and transport it to the facility safely, 200 55-gallon steel drums will be used. The drums are made of carbon steel and are sealed with an EPDM rubber gasket and a bolt closure. The inside of the drum has an epoxy phenolic lining. The steel gauge of the top, body, and bottom of the drum is 18, 20, and 18, respectively. Internally, the drum has a 23.5-inch diameter and a 33-inch height. The drums have a UN liquid rating of UN1A2/Y1.5/150. Each of the 100 institutions will be given a steel drum. At each collection visit, the institutions' drums will be switched out with a fresh, empty one, and this will be done on a weekly basis.

BioPro™ 380EX

The BioPro™ 380EX prepackaged unit by Springboard Biodiesel was selected for conversion of spent cooking oil to biodiesel. Two units are needed to meet the required capacity and process approximately 200 gallons per day. Each unit is 85.5''x 46''x 33" and is manufactured from 304 stainless steel. The units are capable of processing 100 gallons of spent oil each and run via a fully automated system. Predetermined amounts of spent oil and reagents are easily added to the unit which is then left to carry out the necessary reactions. Eight hours after beginning the process, the operator is able to return to the unit and carry out a glycerin removal stage through a large drain valve. The system then enters into the washing stages where all remaining resins and contaminants are stripped from the biodiesel. The unit performs three wash cycles using approximately 90 gallons of freshwater per 100 gallon oil batch. The water is pumped out of another drainage valve and the remaining biodiesel is dried to evaporate off any remaining water. At that point, the BioPro™ is full of ASTM D6751 standard biodiesel that can be drawn, stored, and sold.

6.2 Specification Sheets

BIOFerm™ Dry Fermentation Anaerobic Digester System

Identification:	**Item**	*Dry Anaerobic Digestion System*	
	Item No.	R-*100*	Date: *28 March 2017*
	No. Required	1	By: BIOFerm™

Function: Facilitate dry anaerobic digestion of food waste and glycerin byproduct to produce biogas and compost.

Operation: Batch

Materials Handled:	Feed	Biogas	Digestate
Quantity (tons/batch):	1800	232.5	1567.5
Composition:			
Food Waste	0.4955	--	--
Glycerin	0.0045	--	--
Digestate	0.5000	--	1
Hydrogen Sulfide	--	0.05	--
Methane	--	0.43	--
Nitrogen	--	0.06	--
Carbon Dioxide	--	0.46	--
Temperature (°C):	25	40	40

Design Data:

Number of digestion chambers: 6

Pressure: 1 atm

Material of construction: Concrete

Chamber height: 16.7’

Chamber width: 23’

Chamber length: 70’

Mixing area (approx.): 7,800 sq. ft.

Storage area (approx.): 2,000 sq. ft.

Percolate Tank Volume (approx.): 675 m^3

Batch Cycle: 28 days

Batches/year: 13

Capital Cost: $3, 344, 580
Anticipated Operating & Maintenance Costs: $147, 555
Utilities: In-floor heating powered by CHP uses approx. 658,432 kWh/year operation
Comments and drawings: See Process Flow Diagram
Design based off of BIOFerm’s University of Wisconsin Oshkosh System (See Appendix B)

CG132-12-B-60-00480-M-S Gas Generator

Identification:	**Item**	*Biogas Generator Set*	
	Item No.	G-*100*	Date: *3 April 2017*
	No. Required	1	By: *Caterpillar*

Function: Converts chemical energy of biogas to electricity to feed back to the local grid and heat for use in the rest of the facility.

Operation: Continuous

Energy Balance:	Biogas Input	Electricity Output	Thermal Output	Energy req/lost by Genset
Quantity (kWh):	1448.94	599.86	633.19	215.89
Temperature (°C):	25	--	--	--

Design Data:

Electrical power COP: 600 kW	Exhaust Temperature: 887 F
Engine: CG132-12	Electrical Efficiency: 41.4 %
Speed: 1800 1/min	Thermal Efficiency: 43.7 %
Frequency: 60 Hz	Total Efficiency: 85.1 %
Number of cylinders: 12	
Voltage: 277 V	

Capital Cost: $55,000 (Approximated based on current market)
Comments and drawings: Assumes operation at 100% load. See Caterpillar Technical Data Sheet for more information.

BioPro™ 380EX Biodiesel Processing Unit

Identification: **Item** *Biodiesel Processing Unit*
Item No. Date: *28 March 2017*
No. Required 2 By: Springboard Biodiesel

Function: Convert spent oil into biodiesel by utilizing two chemical processes – acid catalyzed esterification and base catalyzed transesterification.

Operation: Batch

Materials Handled:	Reagents	Products
Quantity/batch:		
Spent Oil (gal)	100	--
Methanol (gal)	20	--
Potassium Hydroxide (g)	4700	--
Sulfuric Acid (ml)	*380*	--
Water (gal)	*90*	*90*
Biodiesel (gal)	--	*90*
Glycerin (gal)	--	*30*
Temperature (°C):	25	25

Design Data: Batch Cycle: 23 hrs
Pressure: 1 atm
Material of construction: 304 Stainless Steel
Chamber height: 85.5’’
Chamber width: 33’’
Chamber length: 46’’
Reaction Method: Acid-catalyzed esterification/base-catalyzed transesterification.
INCOSEPTM Acceleration Module: All EX models use proprietary technology that accelerates all processes without loss of fuel quality.

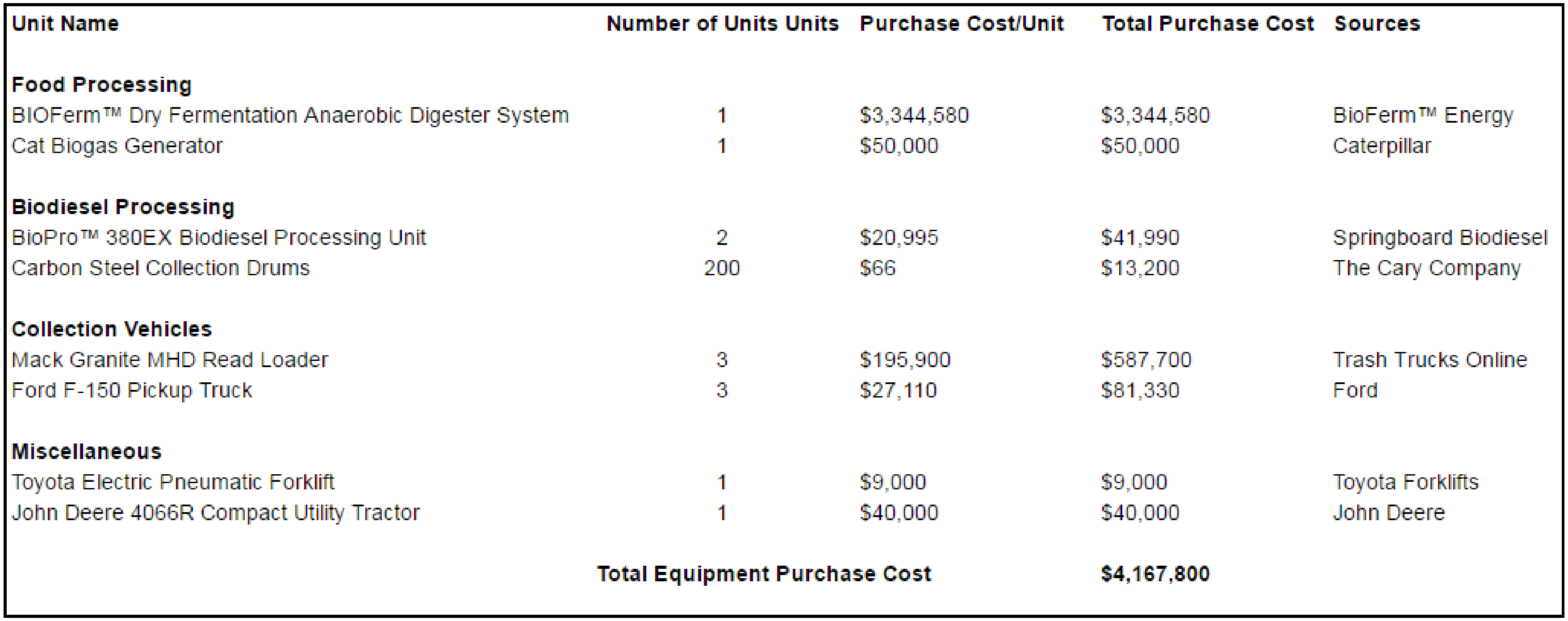
Capital Cost: $20,995
Anticipated Annual Operating & Maintenance Costs: $2,500
Power Requirements: Standard, single phase 220V DC power (20 amp maximum draw) (36,400 kWh/year operation)
Comments and drawings: See Figure 11.

Section 7: Costing Analysis

7.1 Equipment Cost Summary

Shown below in Table 13 is the description of the equipment.

Table 13. Equipment Costs.



Unit Name	Number of Units Units	Purchase Cost/Unit	Total Purchase Cost	Sources
Food Processing				
BIOFerm™ Dry Fermentation Anaerobic Digester System	1	$3,344,580	$3,344,580	BioFerm™ Energy
Cat Biogas Generator	1	$50,000	$50,000	Caterpillar
Biodiesel Processing				
BioPro™ 380EX Biodiesel Processing Unit	2	$20,995	$41,990	Springboard Biodiesel
Carbon Steel Collection Drums	200	$66	$13,200	The Cary Company
Collection Vehicles				
Mack Granite MHD Read Loader	3	$195,900	$587,700	Trash Trucks Online
Ford F-150 Pickup Truck	3	$27,110	$81,330	Ford
Miscellaneous				
Toyota Electric Pneumatic Forklift	1	$9,000	$9,000	Toyota Forklifts
John Deere 4066R Compact Utility Tractor	1	$40,000	$40,000	John Deere
	Total Equipment Purchase Cost		**$4,167,800**	

7.2 Fixed-capital Investment Summary

A rigorous cash flow analysis was generated with help from Brian K. Downey. The total permanent investment of the plant is approximately \$5.6MM with fixed costs of approximately \$721,000. As shown in Figure 15, operations accounts for the largest portion, 60%, of the fixed costs.

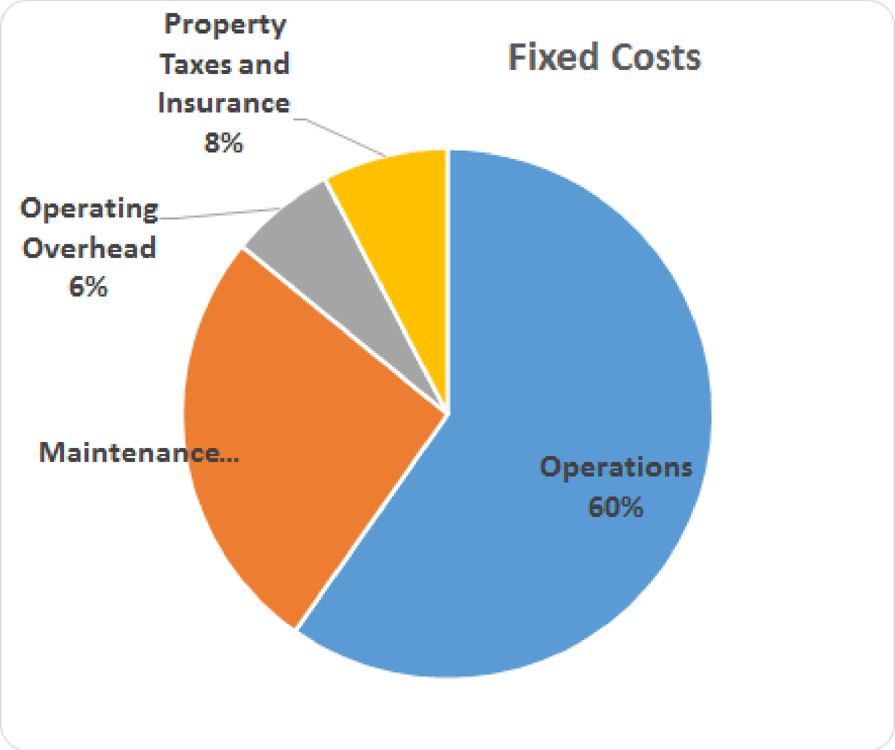
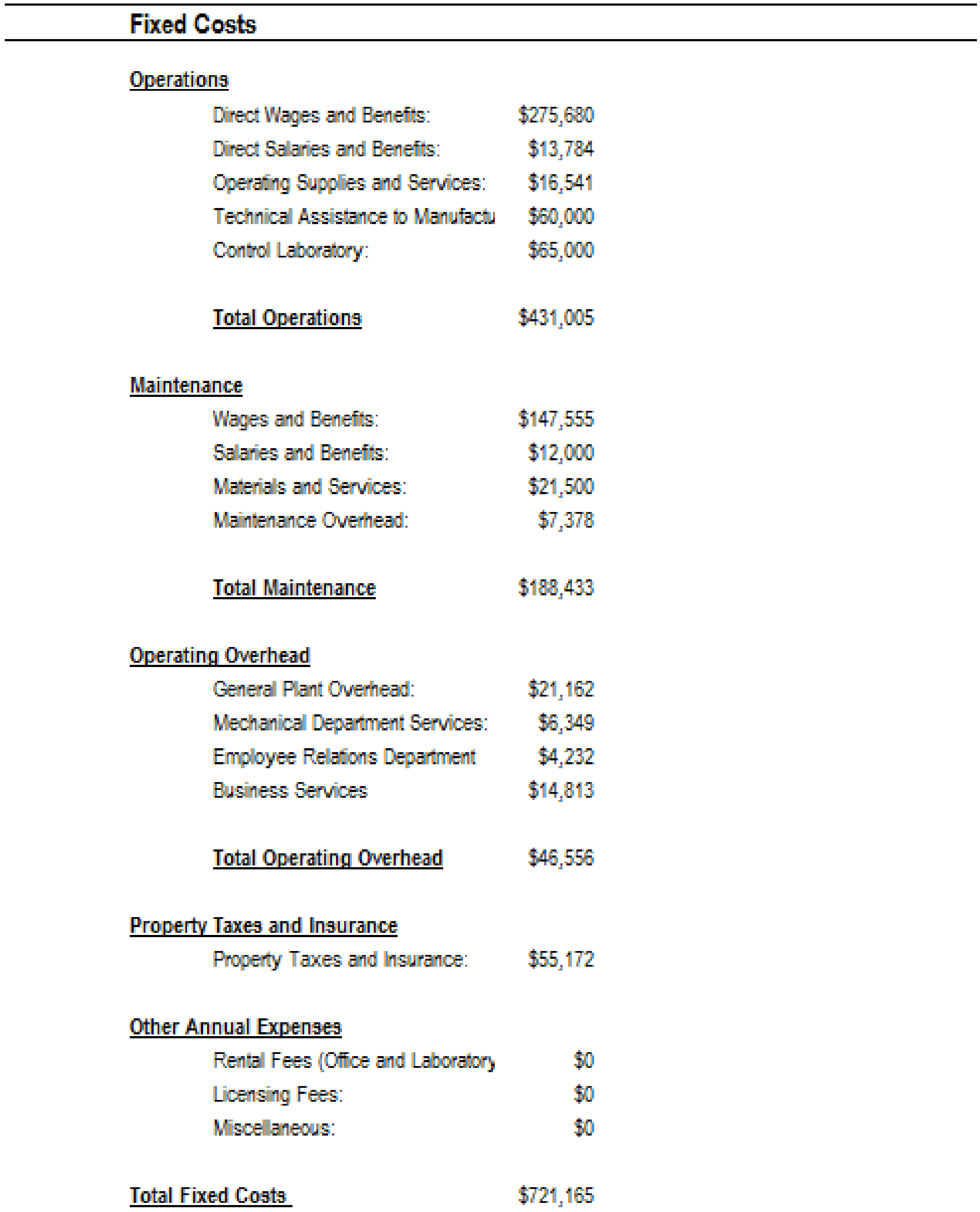


Figure 15. Fixed Costs. Note that Operations accounts for the largest portion of the fixed costs for this project.

The fixed costs and fixed capital investment for the plant were estimated based on correlations from Seider et al. However, the bare module cost was estimated using different multiplying factors than those suggested in the text. The reason for this is due to the fact that the plant equipment is prepackaged and incurs significantly lower installation costs than what would be experienced for a facility built from scratch. In addition to this, the total equipment cost includes the cost of vehicles that will be needed and these require little to no engineering work during the plant startup. They do, however, incur costs associated with storage and spares, hence the reduced bare module factors. The capacity of the plant is also relatively small compared to the size of plants that these factors were intended for, and for this reason, smaller values were discussed with consultants and advisors and chosen for calculating the total bare module cost.

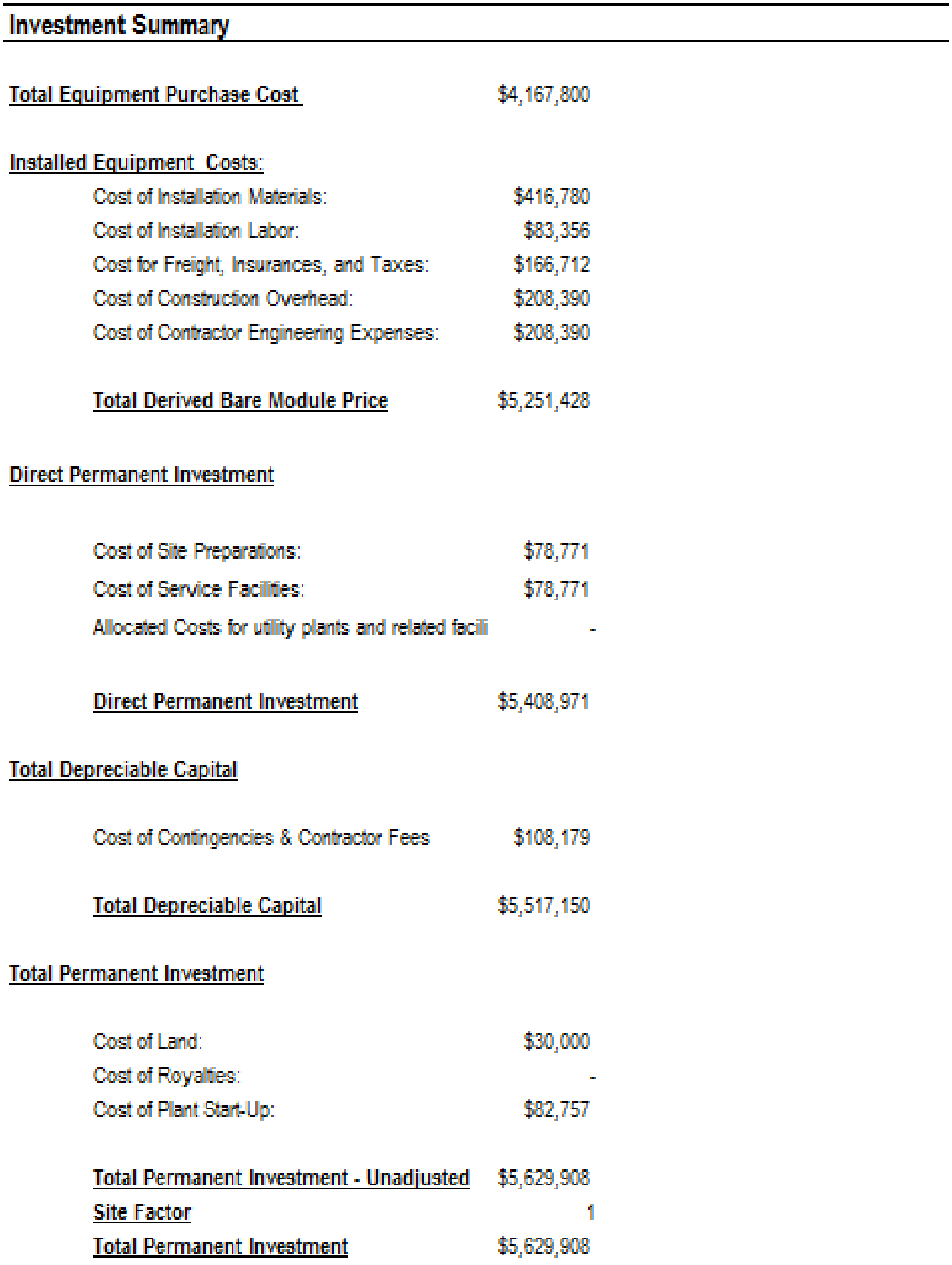
Other factors were used in determining the fixed costs. The cost of site preparations and the cost of service facilities were estimated at 1.5% of the total bare module equipment costs each. The cost of contingencies and contractor fees were estimated at 2% of the direct permanent investment and the cost of land and cost of plant startup were estimated at $30,000 and 1.5% of the total depreciable capital, respectively. Costs of wages and salaries were estimated based on 6 employees per day shift: two engineers and four waste and spent oil collectors. The evening, night, and weekend shifts have a single employee to oversee the site. There will be no collections during the evening, night, or weekend shifts. Maintenance costs were estimated using recommendations from vendors. The largest unit contributing to maintenance is the anaerobic digester, which had a maintenance cost of about $14/ton of food processed according to the vendor. Using this figure, the total maintenance costs were estimated and shown in Figure 16.

A detailed line-item breakdown of the fixed costs and the permanent investment can be found in Figure 16 and Figure 17, respectively. The purchase cost of equipment can be found in the previous equipment pricing section. Most of the equipment purchase costs were taken directly from vendor quotes and websites.



Fixed Costs		
Operations		
	Direct Wages and Benefits:	$275,680
	Direct Salaries and Benefits:	$13,784
	Operating Supplies and Services:	$16,541
	Technical Assistance to Manufactu	$60,000
	Control Laboratory:	$65,000
	Total Operations	$431,005
Maintenance		
	Wages and Benefits:	$147,555
	Salaries and Benefits:	$12,000
	Materials and Services:	$21,500
	Maintenance Overhead:	$7,378
	Total Maintenance	$188,433
Operating Overhead		
	General Plant Overhead:	$21,162
	Mechanical Department Services:	$6,349
	Employee Relations Department	$4,232
	Business Services	$14,813
	Total Operating Overhead	$46,556
Property Taxes and Insurance		
	Property Taxes and Insurance:	$55,172
Other Annual Expenses		
	Rental Fees (Office and Laboratory	$0
	Licensing Fees:	$0
	Miscellaneous:	$0
Total Fixed Costs		$721,165

Figure 16. Fixed Costs Summary.



Investment Summary	
Total Equipment Purchase Cost	$4,167,800
Installed Equipment Costs:	
Cost of Installation Materials:	$416,780
Cost of Installation Labor:	$83,356
Cost for Freight, Insurances, and Taxes:	$166,712
Cost of Construction Overhead:	$208,390
Cost of Contractor Engineering Expenses:	$208,390
Total Derived Bare Module Price	$5,251,428
Direct Permanent Investment	
Cost of Site Preparations:	$78,771
Cost of Service Facilities:	$78,771
Allocated Costs for utility plants and related facili	-
Direct Permanent Investment	$5,408,971
Total Depreciable Capital	
Cost of Contingencies & Contractor Fees	$108,179
Total Depreciable Capital	$5,517,150
Total Permanent Investment	
Cost of Land:	$30,000
Cost of Royalties:	-
Cost of Plant Start-Up:	$82,757
Total Permanent Investment - Unadjusted	$5,629,908
Site Factor	1
Total Permanent Investment	$5,629,908

Figure 17. Investment Summary.

7.3 Operating Cost - Cost of Manufacture

Variable costs were estimated to be -$188,000 annually when the plant is operating at 100% capacity. The negative variable cost represents a net inflow of money when taking into account the sale of byproducts. This process is able to generate a revenue stream from "tipping fees," as we are able to collect approximately $45/ton of waste collected on average. This, coupled with the relatively low raw material and utility costs, which were estimated using vendor spec sheets and recommendations, results in a net cash inflow from operating costs. A chart showing the cost breakdown can be found in Figure 18 below. It shows that 48% of the variable costs come from general expenses. Figure 19 gives a summary of the variable costs. The general expense figures were based off of a total sales figure of about $1.8MM. The multiplying factors were discussed with consultants and advisors and were adjusted from those used in Downey's profitability spreadsheet to better model this particular project.

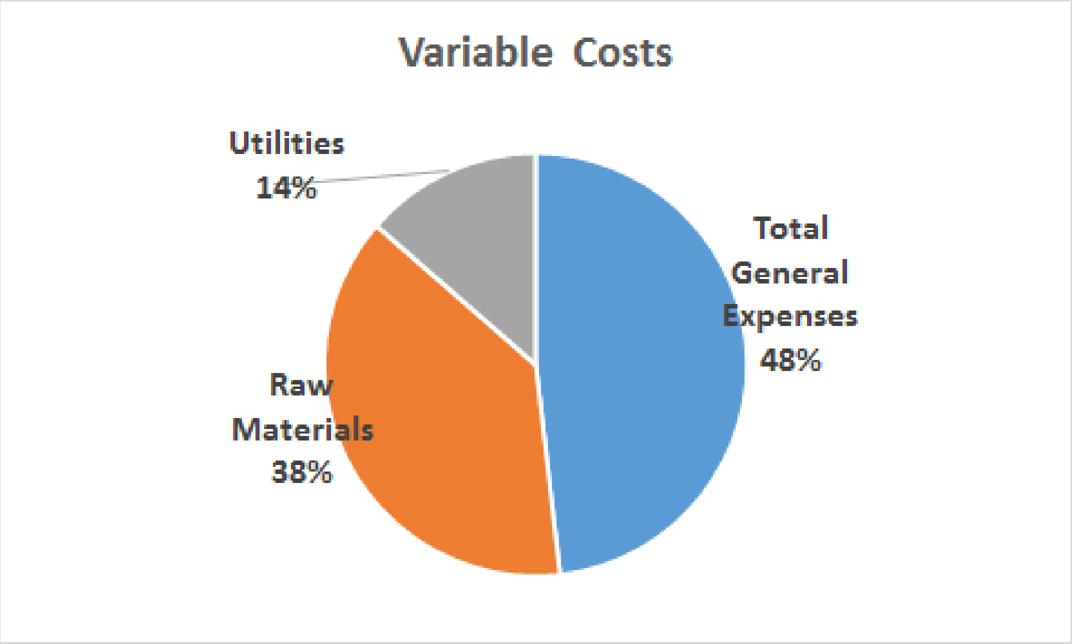
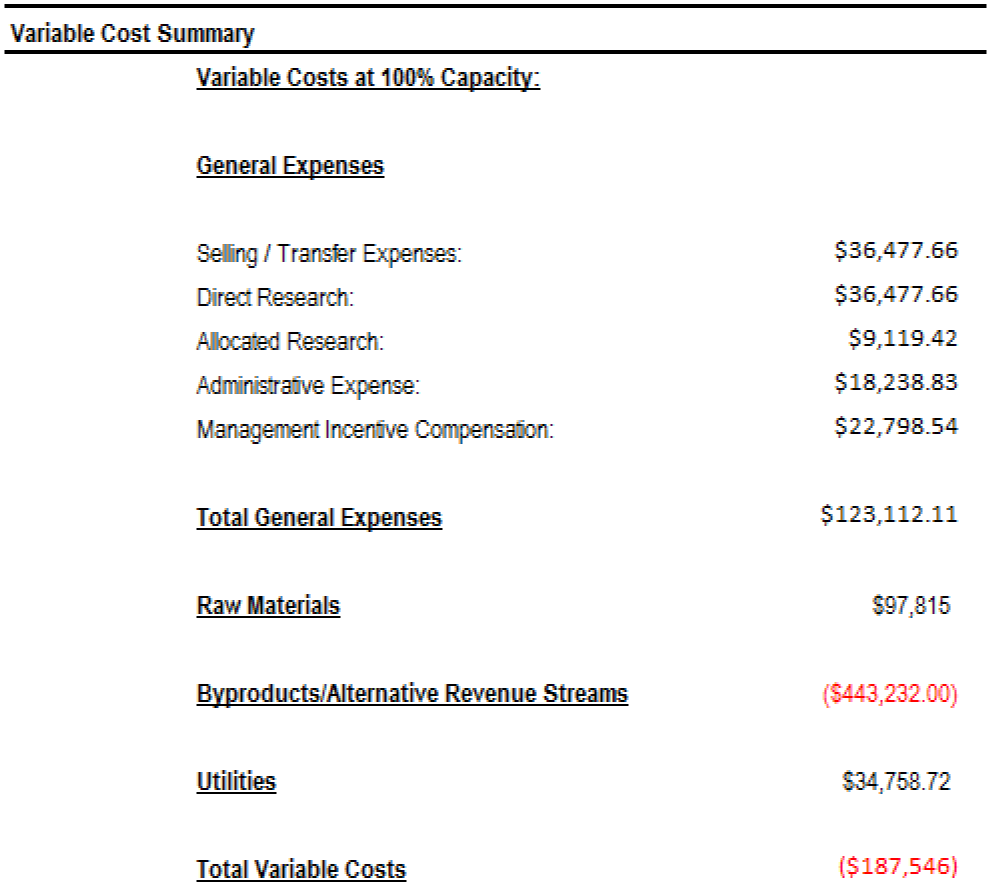


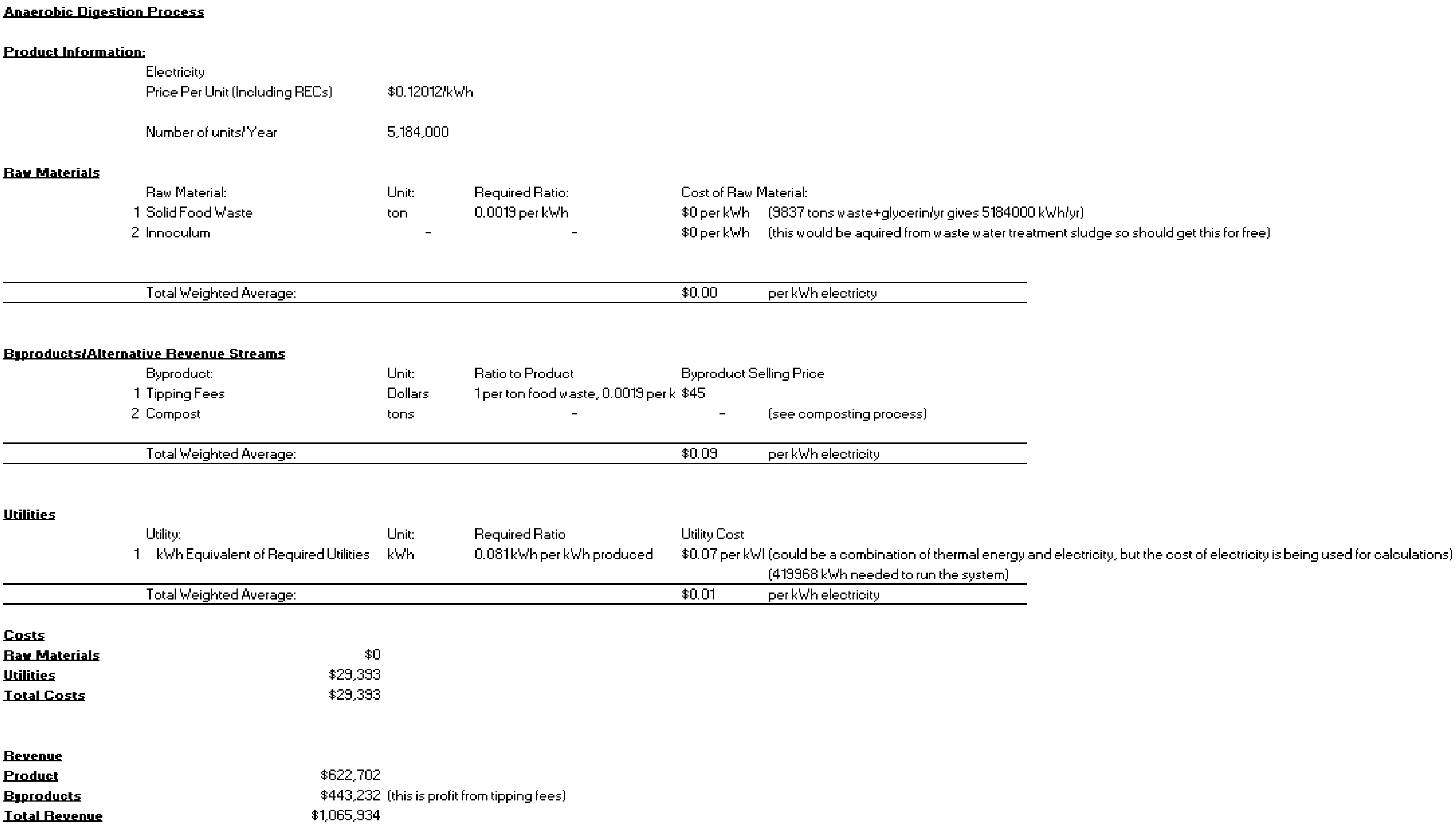
Figure 18. Variable Costs



Variable Cost Summary	
Variable Costs at 100% Capacity:	
General Expenses	
Selling / Transfer Expenses:	$36,477.66
Direct Research:	$36,477.66
Allocated Research:	$9,119.42
Administrative Expense:	$18,238.83
Management Incentive Compensation:	$22,798.54
Total General Expenses	$123,112.11
Raw Materials	$97,815
Byproducts/Alternative Revenue Streams	($443,232.00)
Utilities	$34,758.72
Total Variable Costs	($187,546)

Figure 19. Variable Costs Summary

Prices and quantities for raw materials and utilities can be found in Figures 20, 21, and 22 for the digester, biodiesel, and composting processes respectively. Prices of raw materials were based on prices provided by vendors. These are shown in the Assembly of Database section. The price of waste tipping fees was taken to be $45/ton of waste collected. This is based on the average tipping fee in the Philadelphia region. Finally, the utility cost of the electricity used in the costing was taken to be $0.07 per kWh, an average value for industrial electricity provided by local electricity providers.



Anaerobic Digestion Process

Product Information:

	Electricity	
	Price Per Unit (Including RECs)	$0.12012/kWh
	Number of units/Year	5,184,000

Raw Materials

	Raw Material:	Unit:	Required Ratio:	Cost of Raw Material:	
1	Solid Food Waste	ton	0.0019 per kWh	$0 per kWh	(9837 tons waste+glycerin/yr gives 5184000 kWh/yr)
2	Innoculum	-	-	$0 per kWh	(this would be aquired from waste water treatment sludge so should get this for free)
	Total Weighted Average:			$0.00	per kWh electricty

Byproducts/Alternative Revenue Streams

	Byproduct:	Unit:	Ratio to Product	Byproduct Selling Price	
1	Tipping Fees	Dollars	1 per ton food waste, 0.0019 per k	$45	
2	Compost	tons	-	-	(see composting process)
	Total Weighted Average:			$0.09	per kWh electricity

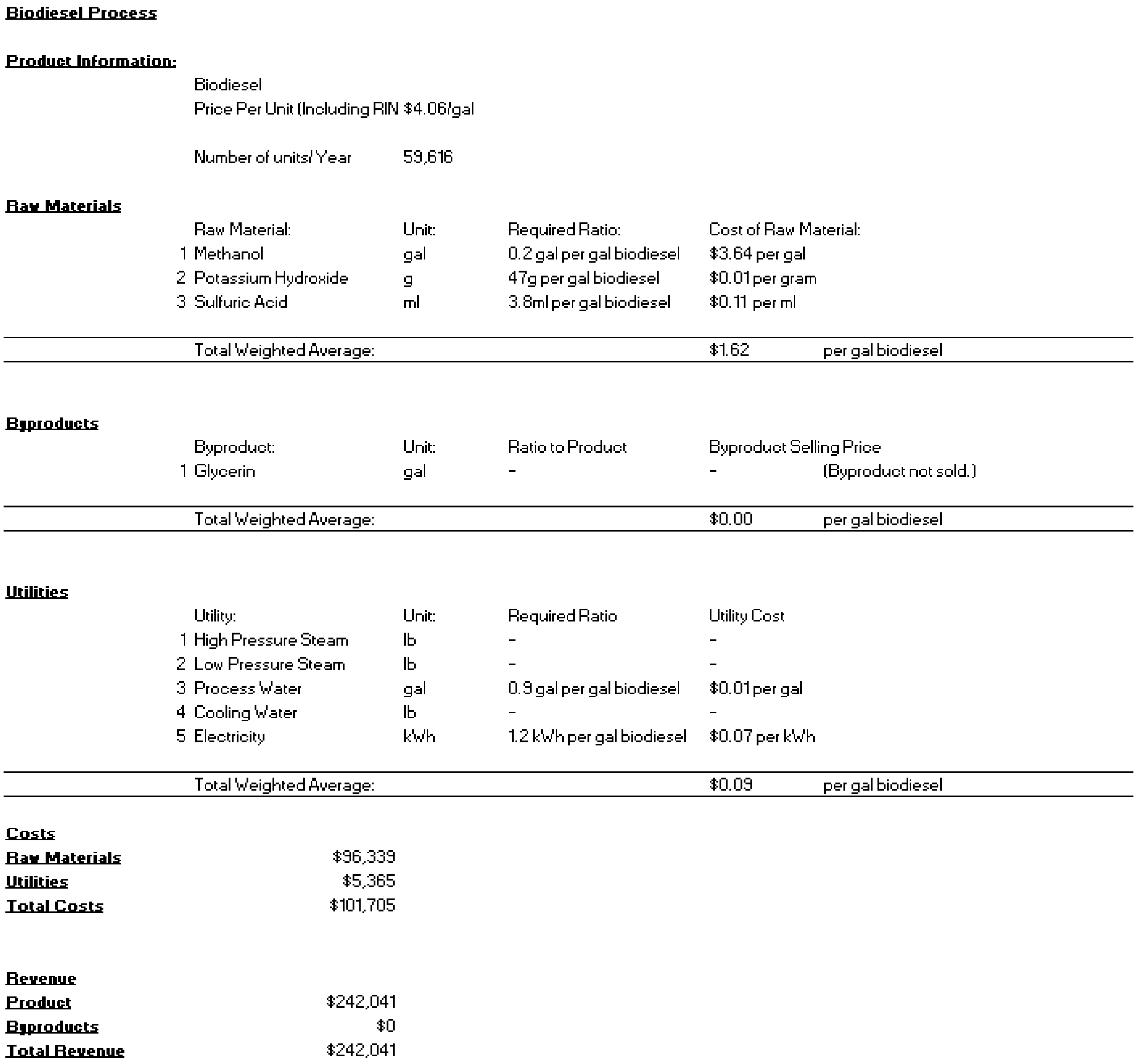
Utilities

	Utility:	Unit:	Required Ratio	Utility Cost	
1	kWh Equivalent of Required Utilities	kWh	0.081 kWh per kWh produced	$0.07 per kW	(could be a combination of thermal energy and electricity, but the cost of electricity is being used for calculations) (419968 kWh needed to run the system)
	Total Weighted Average:			$0.01	per kWh electricity

Costs	
Raw Materials	$0
Utilities	$29,393
Total Costs	$29,393

Revenue		
Product	$622,702	
Byproducts	$443,232	(this is profit from tipping fees)
Total Revenue	$1,065,934	

Figure 20. Anaerobic Digester Operating Costs.



Biodiesel Process

Product Information:

Biodiesel	
Price Per Unit (Including RIN	$4.06/gal
Number of units/Year	59,616

Raw Materials

	Raw Material:	Unit:	Required Ratio:	Cost of Raw Material:	
1	Methanol	gal	0.2 gal per gal biodiesel	$3.64 per gal	
2	Potassium Hydroxide	g	47g per gal biodiesel	$0.01 per gram	
3	Sulfuric Acid	ml	3.8ml per gal biodiesel	$0.11 per ml	
	Total Weighted Average:			$1.62	per gal biodiesel

Byproducts

	Byproduct:	Unit:	Ratio to Product	Byproduct Selling Price	
1	Glycerin	gal	-	-	(Byproduct not sold.)
	Total Weighted Average:			$0.00	per gal biodiesel

Utilities

	Utility:	Unit:	Required Ratio	Utility Cost	
1	High Pressure Steam	lb	-	-	
2	Low Pressure Steam	lb	-	-	
3	Process Water	gal	0.9 gal per gal biodiesel	$0.01 per gal	
4	Cooling Water	lb	-	-	
5	Electricity	kWh	1.2 kWh per gal biodiesel	$0.07 per kWh	
	Total Weighted Average:			$0.09	per gal biodiesel

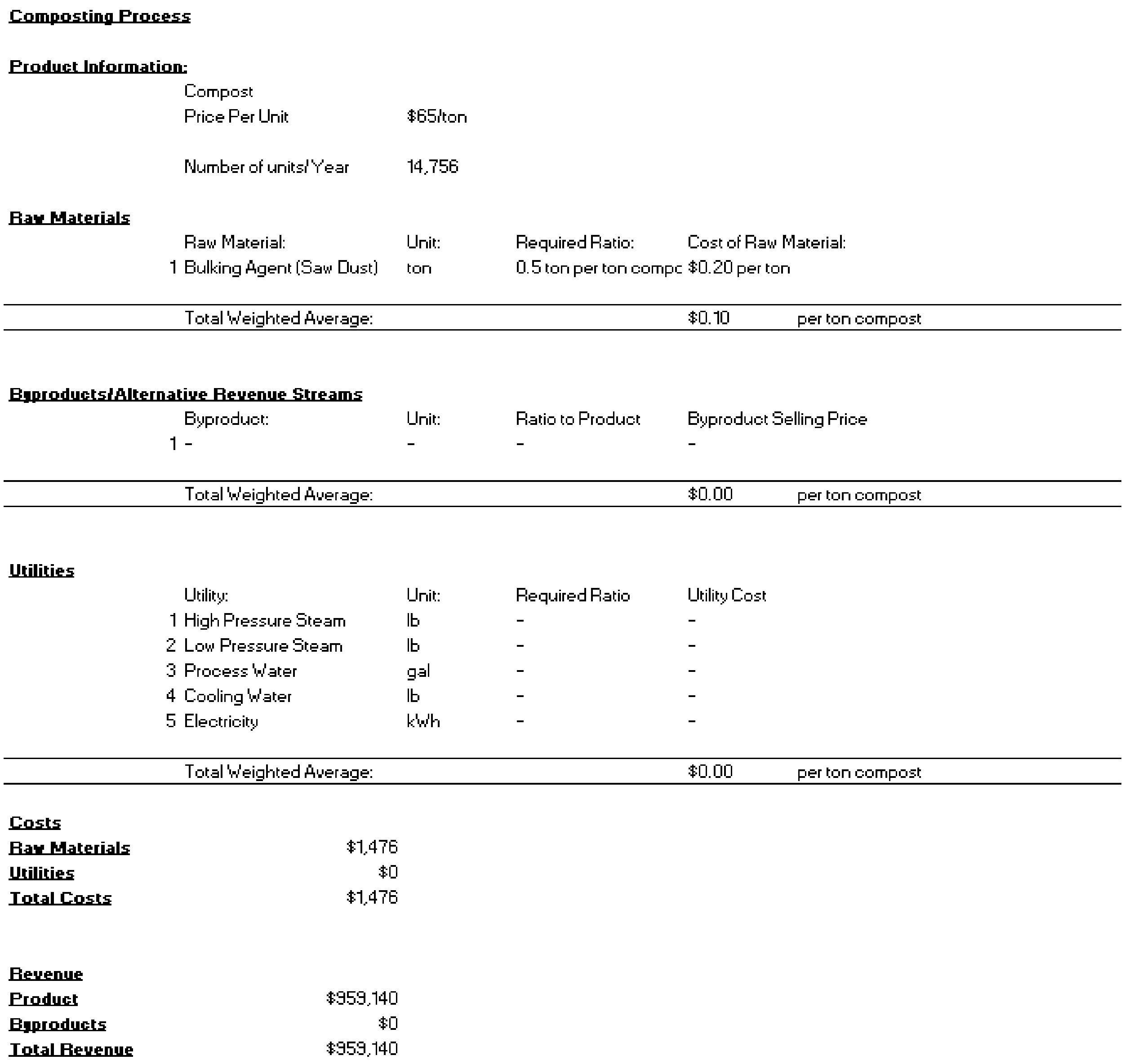
Costs

Raw Materials	$96,339
Utilities	$5,365
Total Costs	$101,705

Revenue

Product	$242,041
Byproducts	$0
Total Revenue	$242,041

Figure 21. Biodiesel Process Operating Costs.



Composting Process

Product Information:

Compost	
Price Per Unit	$65/ton
Number of units/Year	14,756

Raw Materials

	Raw Material:	Unit:	Required Ratio:	Cost of Raw Material:	
1	Bulking Agent (Saw Dust)	ton	0.5 ton per ton compc	$0.20 per ton	
	Total Weighted Average:			$0.10	per ton compost

Byproducts/Alternative Revenue Streams

	Byproduct:	Unit:	Ratio to Product	Byproduct Selling Price	
1	-	-	-	-	
	Total Weighted Average:			$0.00	per ton compost

Utilities

	Utility:	Unit:	Required Ratio	Utility Cost	
1	High Pressure Steam	lb	-	-	
2	Low Pressure Steam	lb	-	-	
3	Process Water	gal	-	-	
4	Cooling Water	lb	-	-	
5	Electricity	kWh	-	-	
	Total Weighted Average:			$0.00	per ton compost

Costs	
Raw Materials	$1,476
Utilities	$0
Total Costs	$1,476

Revenue	
Product	$959,140
Byproducts	$0
Total Revenue	$959,140

Figure 22. Composting Process Operating Costs.

Section 8: Other Important Considerations

8.1 Environmental Considerations

Biogas Production

Using biogas to generate electricity and heat provides environmental protection because the combustion of biogas only releases the amount of CO_2 which the substrates used in production absorbed during their growth. This leaves a net neutral amount of carbon dioxide in the atmosphere rather than emitting more CO_2, which can harm the environment. In addition, creating electricity from biogas prevents emissions which otherwise would be released by fossil fuels (Caterpillar Electric Power Division). Creating electricity from food waste results in a carbon-neutral cycle which does not increase the concentration of greenhouse gases in the atmosphere. In addition, by using food waste that would otherwise end up in a landfill as a raw material in the process, fewer greenhouse gases are being emitted. When food waste is sent to landfills to decompose it can pollute groundwater and it produces high amounts of methane, which has 20 times the global warming potential of carbon dioxide (Garcia). Therefore, this process is better for the environment since it removes food waste which would contribute to methane emissions and global warming and instead uses it in a carbon-neutral cycle to create a renewable source of electricity. Collecting this methane in a controlled environment in which it can be turned into useful energy is much more productive and environmentally beneficial than releasing it to the atmosphere, where it could contribute to global warming.

The other environmental benefit of using anaerobic digestion of food waste to produce electricity is that this does not rely on or take away from food crops. This process solely relies on food which is wasted and can no longer be used for human consumption. There is no land competition for crops being produced for food versus those being produced for energy. There is only so much land available in the country, especially near urban areas like Philadelphia, and being able to use it for food crops alone, rather than overworking the soil due to competition from energy crops, is desirable for sustained food production (Graunke).

There are no real safety concerns during the processing of food waste to electricity as the process is fairly self-contained. Dry fermentation only requires food waste and an inoculum of bacteria to run properly. The largest byproduct of the anaerobic digestion process is the leftover digestate, which can be used in composting to create fertilizer. Composting the digestate has no environmental concerns as it is created purely of safe, natural materials. There may be water coming out of the process which needs to be disposed of properly. However, there are likely very few contaminants in the water which is removed from the food waste in this process and therefore it poses little risk to the environment, especially when the water is sent directly to the wastewater treatment plant. In this case, we believe the wastewater will be relatively negligible, since dry fermentation reduces the amount of wastewater, and recycles water from the feedstock back into the process via percolate sprinklers.

Biodiesel Production

Biodiesel production also has environmental benefits. Biodiesel contains virtually no sulfur or aromatics, and the use of biodiesel in a conventional diesel engine results in a substantial reduction of unburned hydrocarbons, carbon monoxide, and particulate matter. A U.S. Department of Energy study showed that the production and use of biodiesel, compared to petroleum diesel, resulted in a 78.5% reduction in carbon dioxide emissions. Moreover, biodiesel has a positive energy balance. For every unit of energy needed to produce a gallon of biodiesel, at least 4.5 units of energy are gained (National Biodiesel Board). The process also reduces the accumulation of spent oil in landfills as well as in drainage and sewer systems. In assessing the reduction of greenhouse gases (GHG) brought about from burning the biodiesel produced from this process, instead of using traditional diesel, the level of GHG reduction can be calculated based on the known amount of waste grease converted.

According to the U.S. Environmental Protection Agency (EPA420-F- 05-001, Feb 2005.): CO_2 produced from combustion of 1 gallon of petroleum-based diesel = 22.2lbs GHG emissions. Reduction from replacing petroleum-based diesel with biodiesel = 86% GHG emissions, giving a total reduction in GHG emission from this project of 696 tons/year. The calculations to achieve this result are shown in Appendix A.

According to data published by the U.S. Environmental Protection Agency, our process of converting spent oil to biodiesel has the potential to reduce greenhouse gas emissions by 696 tons/year. This assumes the biodiesel is burnt in place of traditional diesel and does not take into account any potential benefits from the potential GHG emissions from waste accumulating in landfills.

With regards to environmental considerations during the process itself, the main concern involves the disposal of the wastewater used during the “cleaning” stages. This water is used to strip the and clean the biodiesel by removing any reagent residue. At this point in the reaction, very little reagent remains and the resulting wastewater contains very dilute amounts of contaminants. This is largely due to the controlled addition of reagents into the BioPro™ during specific times of the process. This reduces the likelihood of residue and excess reagent. Due to the low traces of contaminants, the wastewater is able to be safely disposed of into the municipal drainage system. The KOH catalyst is removed in the glycerin and only trace amounts are found in the wastewater. The glycerin is added to the anaerobic digester where the KOH helps to maintain basic operating conditions.

Another concern associated with the burning of biodiesel is the level of nitrogen oxides. These gases contribute to ground-level ozone, acid rain, and visibility impairment. Over half of human made NOx emissions come from fuel combustion in motor vehicles. The trend of NOx emissions from use of biodiesel is still uncertain. Several studies show an increase in NOx emissions, while others show a decrease. Further research is still needed on NOx emissions from engines burning biodiesel (U.S. Environmental Protection Agency).

8.2 Process Controllability and Instrumentation

Anaerobic Digestion Process Controllability

While the technology to run an anaerobic digester in a dry fermentation process is well developed and understood, it is difficult to implement control tools to monitor and optimize the system. This difficulty stems from the complexity of fermenting municipal solid waste due to the different reactions and microorganisms needed for the process to function correctly. The system is unable to quantify the majority of these parameters using process control software since there are not many control tools available for this type of processing. Currently, the only parameter which can be measured is the methane levels (Weiland). Better process control is important for the future and can help to increase biogas yield. As only a few sensors are currently available to monitor biogas production online, increasing the available control systems that can monitor the process online would help to increase yield and quality of the biogas (Weiland). Although the selection of control equipment is small, most plants operate using a programmable logic controller. This controller includes a processing unit and a piece for visualization (Wellinger). The specific modular units are selected based on the needs of the plant. The majority of the control is done through automation, but the option for manual control must be built in for possible cases of plant breakdown (Wellinger).

In this project, the BIOFerm digester has control technology for measuring methane levels to ensure that the fermentation chambers do not open until the biogas has been appropriately flushed out, so that the chambers are safe for operators to enter.

Biodiesel Process Controllability

As mentioned previously, the BioPro™ 380EX is a fully automated system that has been optimized for the reactions that it will conduct. Once charged with the reactants, the user does not interact in any way with the reactions taking place.

8.3 Safety and Health Concerns

Safety Concerns with Anaerobic Digestion

One of the biggest safety concerns in the anaerobic digestion process is the high levels of methane produced. Operators cannot open the chambers until the methane levels are low enough that the methane itself won't harm them and there is no possibility of a fire or explosion. The sensors in the processing chambers must be extremely sensitive in order to ensure the safety of all those working near the plant. The release of this gas also has the potential to harm the environment, which is undesirable (Garcia). Important safety features to be included in the plant are vents which would allow for gas to escape rather than causing an explosion. The most critical concerns are that there are no explosions, fires, or release of toxic gas, such as hydrogen which is generated during processing (Elsdon). In order to do this, the chamber remains sealed to prevent oxygen from entering the environment and causing an explosion or fire. This seal also ensures all of the gas does not leak out prevents any potential harm. Other than these few, controllable hazards there are no safety concerns with regards to the operation of the anaerobic digester (Elsdon).

Safety Concerns with Biodiesel Processing

Biodiesel causes far less damage than petroleum diesel if spilled or released to the environment. It is safer than petroleum diesel because it is less combustible. The flashpoint for biodiesel is higher than 130°C, compared with about 52°C for petroleum diesel. Biodiesel is safe to handle, store, and transport (U.S Department of Energy).

8.4 Plant Location, Layout and Startup

Plant Location

There are several important factors to consider when choosing a location for the plant needed for this project. The first of these is the municipal solid waste would be a nuisance to neighboring communities due to the unpleasant odor. As a result, a location needs to be chosen in an area where neighbors will not be inconvenienced by the smell or where other foul odors are present. As a result, two general locations have been identified as potential plant locations. The first is near the Wastewater Treatment Plant which handles waste products and as such the neighboring landowners are unlikely to be bothered by the odor of the food waste. The second location is near the Sanitation Convenience Center, which also handles large amounts of waste and has a pungent odor.

The second factor to consider is the price of land in these areas. Land near both of these identified locations is priced at $1 per square foot making the two locations equally acceptable for the project (2017 Land Values). It is likely that land at 3140 S 61 Street will be used since it is close to the Sanitation Convenience Center, which is less likely to be affected by the odor of the food waste used in processing. Given that our plant will be approximately 30,000 square feet in size, the capital cost for this land will be $30,000.

Layout

The layout of the plant will likely be as shown below in Figure 23.

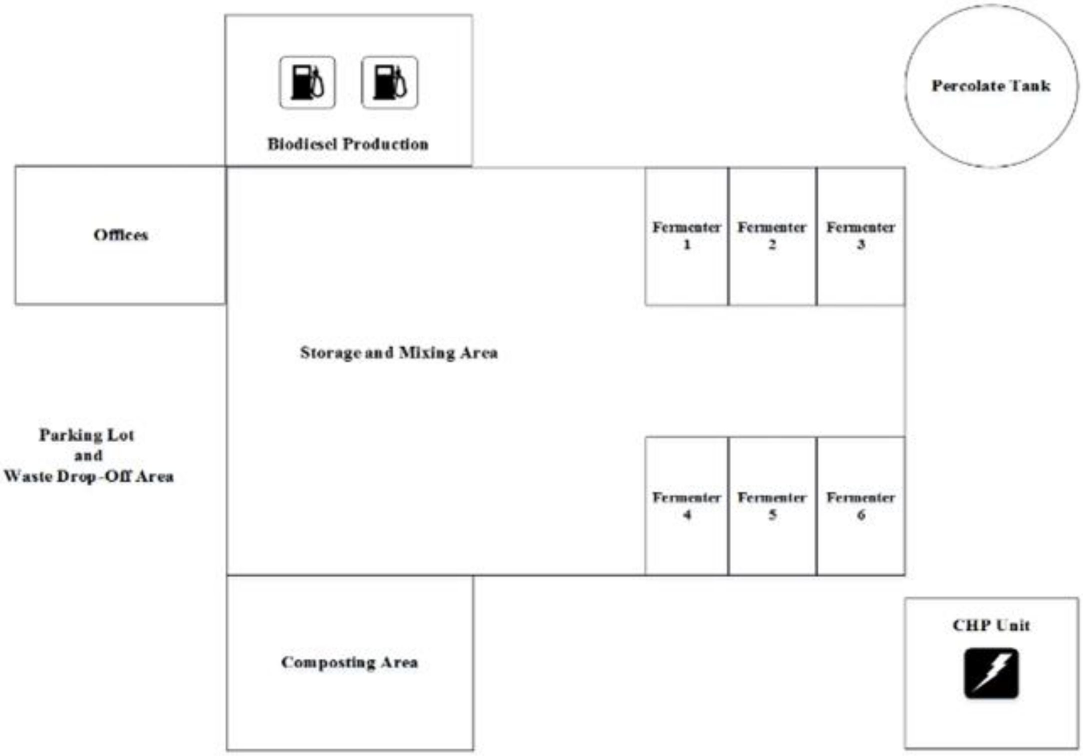


Figure 23. Plant Layout.

Startup

The startup of the anaerobic digester is fairly simple. For the anaerobic digestion system selected, the inoculum for startup should be sludge material from a wastewater treatment plant. This material is unused by the wastewater treatment facility and as such an agreement can be made which would allow this material to be procured for free. The inoculum is generally solid so it can create the percolate as it breaks down in the fermenters. The pH level of the feedstock must be at 7.5 or higher to achieve the best production of biogas. As a result, pH must be monitored and controlled at startup (BIOFerm™ FAQ). One other important aspect of startup is working with the manufacturers to calibrate the software used and fine tune energy production (UWO Biodigester). Working with the software will ensure the maximum amount of energy is produced.

This is important to do at the very beginning of the project so the most amount of product can be made and sold. The 6 fermenters will be run staggered, as shown in the Gantt chart in Figure 24, to allow for a continuous production of biogas to occur.

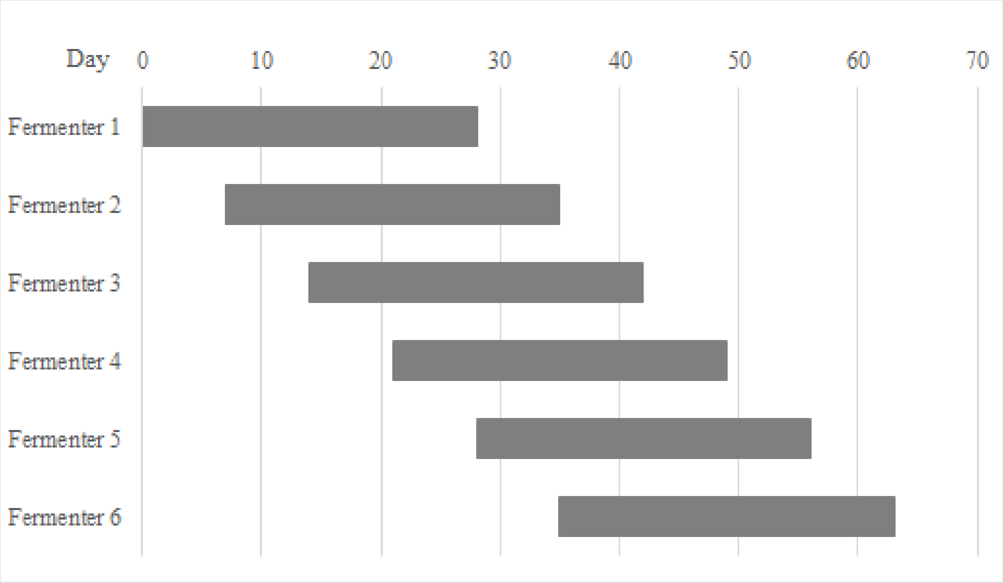


Figure 24. Anaerobic Digestion Gantt Chart. The six fermenters will start operation in a staggered manner to allow for continuous production of biogas.

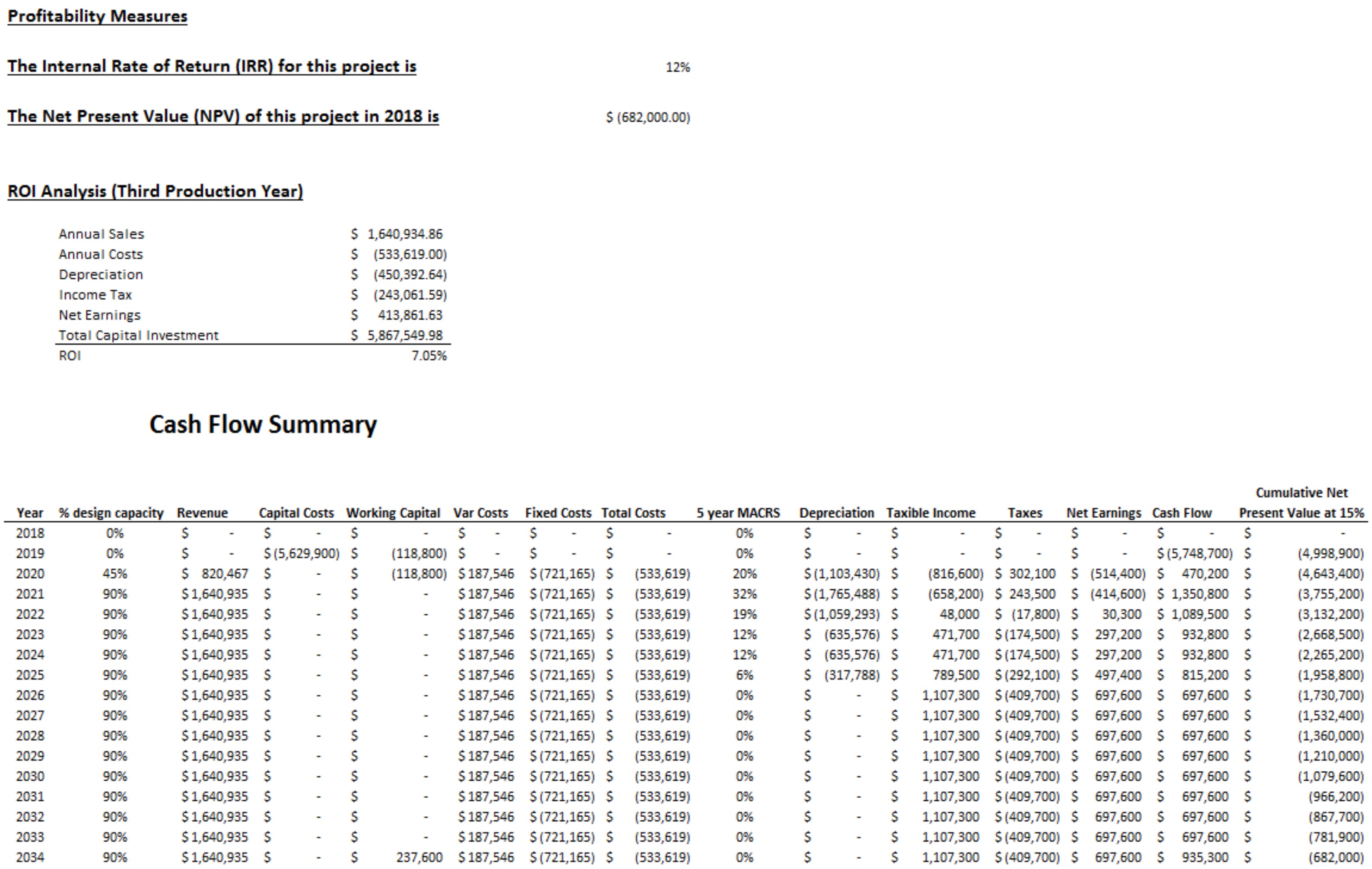
8.5 Potential Funding Sources

One other important aspect of this process to consider is the fact that there are many credits available to help cover the costs of installing and operating a renewable energy plant. One of the largest to consider is the 1603 Program, which is run by the federal government. This program reimburses those who install renewable energy projects to be used in business for a portion of the installation costs after the plant is operational. The maximum amount this program will cover is up to 30% of the project's total costs, which would dramatically increase the profitability of this project (Recovery Act). In addition to this, the RINs and RECs which can be sold for a profit and have been discussed earlier provide an incentive to produce renewable electricity rather than using fossil fuels. One other potential source of funding is obtaining a grant through the Pennsylvania Alternative and Clean Energy Program. For a private project creating a biogas, up to 25% of the cost can be covered by these grants. These sources of funding can help the project to be more profitable and financially attractive in the long term. However, receiving money from the 1603 Program or the Pennsylvania Alternative and Clean Energy Programs are not guaranteed and the exact amount of money that could be granted is unknown. As such, these potential funding sources are not included in the profitability analysis but they are important to consider if the project is to be implemented.

Section 9: Profitability Analysis

The profitability of this facility can be determined by using a rigorous cash flow analysis to determine the net present value (NPV) of the project as well as the return on investment (ROI) and the internal rate of return. The cash flow analysis can be seen below in Figure 25. The project was determined to have a 2018 NPV of approximately (-$682,000) with an IRR of 12% and an ROI of 7.05% after the third year. The cash flow analysis used a 5-year depreciation schedule following the modified accelerated cost recovery system (MACRS) depreciation schedule as specified by the Internal Revenue Service (IRS). We recognize that the cogeneration equipment should follow a 15-year MACRS depreciation schedule but with the cost of this generator being so small compared to the overall price of the project, it was included in the overall project 5-year schedule. Based on these profitability measures, we recommend that further research is put into the process in order to more accurately determine its economic feasibility. We recognize that the negative net present value calculated over a 17-year plant operating life may act as a project deterrent but would like to point out that the project is able to generate consistent positive cash flows. A plant life of over 17 years would generate a positive net present value and later plant expansion by simply adding extra digester chambers or biodiesel processing units could help ramp up revenues. Adding to this, many assumptions and estimations were made when designing the process which must be explored in a more rigorous manner.

Sensitivity analysis was conducted to determine the project's sensitivity to a variety of changes. The IRR values generated during this analysis are shown in Figure 26. This particular project has the luxury of multiple revenue streams and so the sensitivity analysis was focused around the prices of these products and the total permanent investment, as this is where the largest likelihood of pricing deviation exists. It was found that the project was most sensitive to a change in the price of compost. A benefit of the project's diversified revenue streams is that large fluctuations in any one particular product might not necessarily have a significant effect on the overall IRR. This is seen in the sensitivity analysis as there are few scenarios that generate a negative IRR. It is also important to note that this project focused on capturing a just 5% of the total commercial waste market. With minor scaling operations the plant would be able to easily increase its capacity and generate more revenue. There is also the matter of trying to determine the economic benefits of the project from an environmental standpoint. As previously discussed, this project has numerous environmental benefits associated with it which need to be considered. Despite not being lucrative, a self-sustainable project in the field of waste disposal that helps to improve the environment is one worth considering.



Profitability Measures

The Internal Rate of Return (IRR) for this project is 12%

The Net Present Value (NPV) of this project in 2018 is $ (682,000.00)

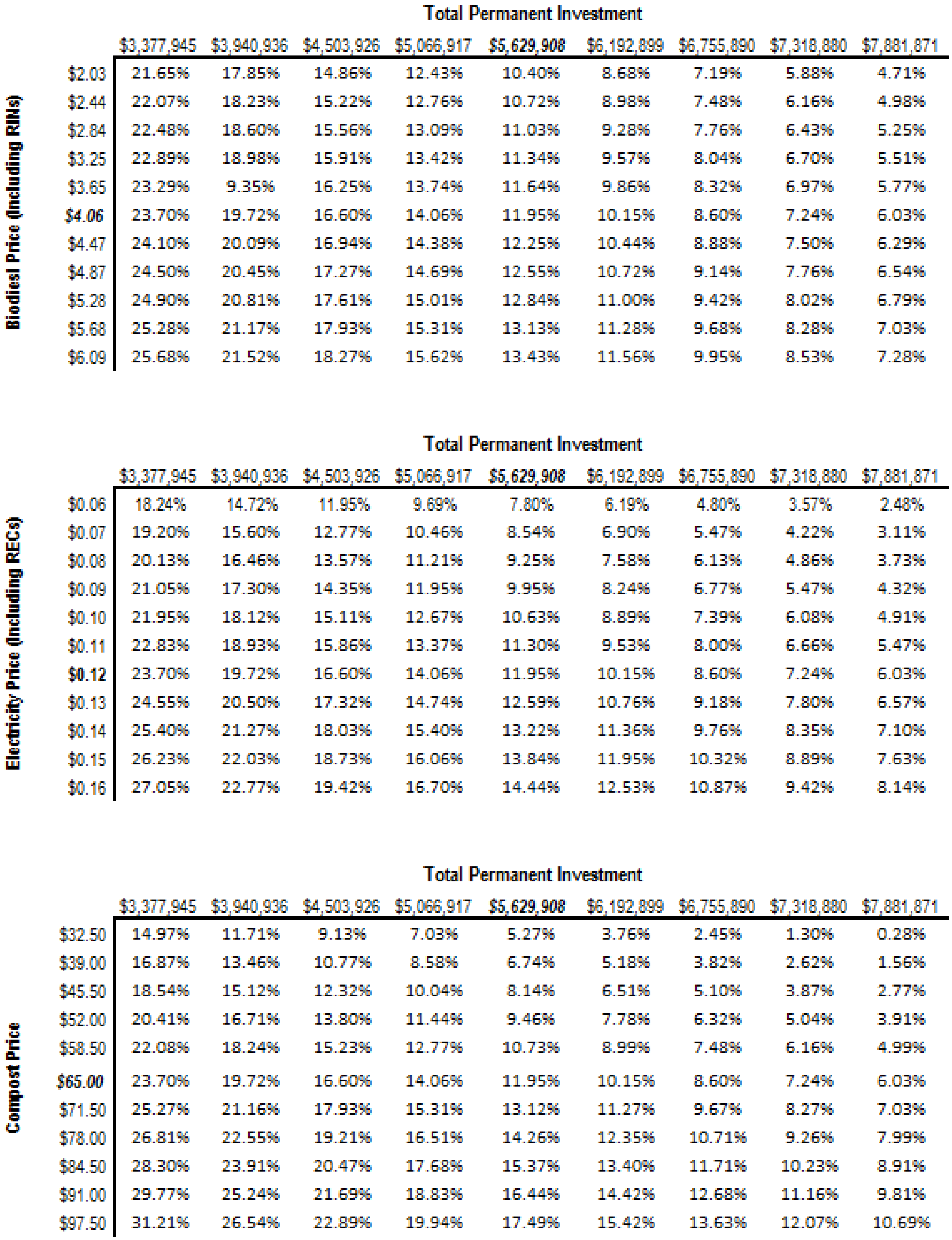
ROI Analysis (Third Production Year)

Annual Sales	$ 1,640,934.86
Annual Costs	$ (533,619.00)
Depreciation	$ (450,392.64)
Income Tax	$ (243,061.59)
Net Earnings	$ 413,861.63
Total Capital Investment	$ 5,867,549.98
ROI	7.05%

Cash Flow Summary

Year	% design capacity	Revenue	Capital Costs	Working Capital	Var Costs	Fixed Costs	Total Costs	5 year MACRS	Depreciation	Taxible Income	Taxes	Net Earnings	Cash Flow	Cumulative Net Present Value at 15%
2018	0%	$ -	$ -	$ -	$ -	$ -	$ -	0%	$ -	$ -	$ -	$ -	$ -	$ -
2019	0%	$ -	$ (5,629,900)	$ (118,800)	$ -	$ -	$ -	0%	$ -	$ -	$ -	$ -	$ (5,748,700)	$ (4,998,900)
2020	45%	$ 820,467	$ -	$ (118,800)	$ 187,546	$ (721,165)	$ (533,619)	20%	$ (1,103,430)	$ (816,600)	$ 302,100	$ (514,400)	$ 470,200	$ (4,643,400)
2021	90%	$ 1,640,935	$ -	$ -	$ 187,546	$ (721,165)	$ (533,619)	32%	$ (1,765,488)	$ (658,200)	$ 243,500	$ (414,600)	$ 1,350,800	$ (3,755,200)
2022	90%	$ 1,640,935	$ -	$ -	$ 187,546	$ (721,165)	$ (533,619)	19%	$ (1,059,293)	$ 48,000	$ (17,800)	$ 30,300	$ 1,089,500	$ (3,132,200)
2023	90%	$ 1,640,935	$ -	$ -	$ 187,546	$ (721,165)	$ (533,619)	12%	$ (635,576)	$ 471,700	$ (174,500)	$ 297,200	$ 932,800	$ (2,668,500)
2024	90%	$ 1,640,935	$ -	$ -	$ 187,546	$ (721,165)	$ (533,619)	12%	$ (635,576)	$ 471,700	$ (174,500)	$ 297,200	$ 932,800	$ (2,265,200)
2025	90%	$ 1,640,935	$ -	$ -	$ 187,546	$ (721,165)	$ (533,619)	6%	$ (317,788)	$ 789,500	$ (292,100)	$ 497,400	$ 815,200	$ (1,958,800)
2026	90%	$ 1,640,935	$ -	$ -	$ 187,546	$ (721,165)	$ (533,619)	0%	$ -	$ 1,107,300	$ (409,700)	$ 697,600	$ 697,600	$ (1,730,700)
2027	90%	$ 1,640,935	$ -	$ -	$ 187,546	$ (721,165)	$ (533,619)	0%	$ -	$ 1,107,300	$ (409,700)	$ 697,600	$ 697,600	$ (1,532,400)
2028	90%	$ 1,640,935	$ -	$ -	$ 187,546	$ (721,165)	$ (533,619)	0%	$ -	$ 1,107,300	$ (409,700)	$ 697,600	$ 697,600	$ (1,360,000)
2029	90%	$ 1,640,935	$ -	$ -	$ 187,546	$ (721,165)	$ (533,619)	0%	$ -	$ 1,107,300	$ (409,700)	$ 697,600	$ 697,600	$ (1,210,000)
2030	90%	$ 1,640,935	$ -	$ -	$ 187,546	$ (721,165)	$ (533,619)	0%	$ -	$ 1,107,300	$ (409,700)	$ 697,600	$ 697,600	$ (1,079,600)
2031	90%	$ 1,640,935	$ -	$ -	$ 187,546	$ (721,165)	$ (533,619)	0%	$ -	$ 1,107,300	$ (409,700)	$ 697,600	$ 697,600	$ (966,200)
2032	90%	$ 1,640,935	$ -	$ -	$ 187,546	$ (721,165)	$ (533,619)	0%	$ -	$ 1,107,300	$ (409,700)	$ 697,600	$ 697,600	$ (867,700)
2033	90%	$ 1,640,935	$ -	$ -	$ 187,546	$ (721,165)	$ (533,619)	0%	$ -	$ 1,107,300	$ (409,700)	$ 697,600	$ 697,600	$ (781,900)
2034	90%	$ 1,640,935	$ -	$ 237,600	$ 187,546	$ (721,165)	$ (533,619)	0%	$ -	$ 1,107,300	$ (409,700)	$ 697,600	$ 935,300	$ (682,000)

Figure 25. Profitability Analysis



Total Permanent Investment

Biodiesel Price (Including RINs)	$3,377,945	$3,940,936	$4,503,926	$5,066,917	***$5,629,908***	$6,192,899	$6,755,890	$7,318,880	$7,881,871
$2.03	21.65%	17.85%	14.86%	12.43%	10.40%	8.68%	7.19%	5.88%	4.71%
$2.44	22.07%	18.23%	15.22%	12.76%	10.72%	8.98%	7.48%	6.16%	4.98%
$2.84	22.48%	18.60%	15.56%	13.09%	11.03%	9.28%	7.76%	6.43%	5.25%
$3.25	22.89%	18.98%	15.91%	13.42%	11.34%	9.57%	8.04%	6.70%	5.51%
$3.65	23.29%	9.35%	16.25%	13.74%	11.64%	9.86%	8.32%	6.97%	5.77%
$4.06	23.70%	19.72%	16.60%	14.06%	11.95%	10.15%	8.60%	7.24%	6.03%
$4.47	24.10%	20.09%	16.94%	14.38%	12.25%	10.44%	8.88%	7.50%	6.29%
$4.87	24.50%	20.45%	17.27%	14.69%	12.55%	10.72%	9.14%	7.76%	6.54%
$5.28	24.90%	20.81%	17.61%	15.01%	12.84%	11.00%	9.42%	8.02%	6.79%
$5.68	25.28%	21.17%	17.93%	15.31%	13.13%	11.28%	9.68%	8.28%	7.03%
$6.09	25.68%	21.52%	18.27%	15.62%	13.43%	11.56%	9.95%	8.53%	7.28%

Total Permanent Investment

Electricity Price (Including RECs)	$3,377,945	$3,940,936	$4,503,926	$5,066,917	***$5,629,908***	$6,192,899	$6,755,890	$7,318,880	$7,881,871
$0.06	18.24%	14.72%	11.95%	9.69%	7.80%	6.19%	4.80%	3.57%	2.48%
$0.07	19.20%	15.60%	12.77%	10.46%	8.54%	6.90%	5.47%	4.22%	3.11%
$0.08	20.13%	16.46%	13.57%	11.21%	9.25%	7.58%	6.13%	4.86%	3.73%
$0.09	21.05%	17.30%	14.35%	11.95%	9.95%	8.24%	6.77%	5.47%	4.32%
$0.10	21.95%	18.12%	15.11%	12.67%	10.63%	8.89%	7.39%	6.08%	4.91%
$0.11	22.83%	18.93%	15.86%	13.37%	11.30%	9.53%	8.00%	6.66%	5.47%
$0.12	23.70%	19.72%	16.60%	14.06%	11.95%	10.15%	8.60%	7.24%	6.03%
$0.13	24.55%	20.50%	17.32%	14.74%	12.59%	10.76%	9.18%	7.80%	6.57%
$0.14	25.40%	21.27%	18.03%	15.40%	13.22%	11.36%	9.76%	8.35%	7.10%
$0.15	26.23%	22.03%	18.73%	16.06%	13.84%	11.95%	10.32%	8.89%	7.63%
$0.16	27.05%	22.77%	19.42%	16.70%	14.44%	12.53%	10.87%	9.42%	8.14%

Total Permanent Investment

Compost Price	$3,377,945	$3,940,936	$4,503,926	$5,066,917	***$5,629,908***	$6,192,899	$6,755,890	$7,318,880	$7,881,871
$32.50	14.97%	11.71%	9.13%	7.03%	5.27%	3.76%	2.45%	1.30%	0.28%
$39.00	16.87%	13.46%	10.77%	8.58%	6.74%	5.18%	3.82%	2.62%	1.56%
$45.50	18.54%	15.12%	12.32%	10.04%	8.14%	6.51%	5.10%	3.87%	2.77%
$52.00	20.41%	16.71%	13.80%	11.44%	9.46%	7.78%	6.32%	5.04%	3.91%
$58.50	22.08%	18.24%	15.23%	12.77%	10.73%	8.99%	7.48%	6.16%	4.99%
$65.00	23.70%	19.72%	16.60%	14.06%	11.95%	10.15%	8.60%	7.24%	6.03%
$71.50	25.27%	21.16%	17.93%	15.31%	13.12%	11.27%	9.67%	8.27%	7.03%
$78.00	26.81%	22.55%	19.21%	16.51%	14.26%	12.35%	10.71%	9.26%	7.99%
$84.50	28.30%	23.91%	20.47%	17.68%	15.37%	13.40%	11.71%	10.23%	8.91%
$91.00	29.77%	25.24%	21.69%	18.83%	16.44%	14.42%	12.68%	11.16%	9.81%
$97.50	31.21%	26.54%	22.89%	19.94%	17.49%	15.42%	13.63%	12.07%	10.69%

Figure 26. Sensitivity Analysis.

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Section 10: Conclusions and Recommendations

Given the proposed project's negative net present value, we have concluded that the process outlined in this report is not profitable. This is largely due to the low capacity and process inefficiency of the electricity generation. The process aimed to focus on 100 large institutions around Philadelphia with a total food waste collection of approximately 9700 tons per year. Processing this waste we were able to generate roughly 5.2MM kWh of energy. At a selling price of $0.12 per kWh, including the sale of RECs generated, the revenue totaled approximately $620,000. Even after including the revenue generated from composting the digestate and converting the spent oil into biodiesel, the total revenues were not enough to offset the relatively high capital costs.

However, an important point to consider is the fact that the process was able to generate positive cash flows following installation, showing the ability for such a process to be self-sustainable. The economics around such a project also fail to take into account the added environmental benefits of the project, such as the greenhouse gas reduction. When weighing in these added benefits, this project may still be an attractive option for governments and municipalities whose sole goal is to produce a self-sustainable means of managing food waste. In addition to this, the project only had a small negative NPV of -($682,000) after being in operation for 17-years. If we were to consider such a project as a long term solution, over 17-years, the project may indeed generate a positive NPV. There is also the possibility to scale up the process. This project focused on just 5% of the total attainable commercial waste. If we were to increase this figure, we would increase the revenue potential of the project and thus be able to reach a positive NPV sooner.

Another unique aspect of this project is the product diversity. As seen in the sensitivity analysis, the process is resilient to price fluctuations in individual products due to its product diversity. The analysis does show the highest sensitivity to the price of compost.

One recommendation would be to increase the plant capacity to be able to process more than the 5% of total commercial food waste. Perhaps expanding collection services to include parts of New Jersey and Delaware would increase the total attainable food waste. We would also recommend partnering with food agencies such as Philabundance where the project would be able to receive significant amounts of food waste from a single source.

Another potential recommendation would be to look at more appropriate scaling factors used for costing estimates. We were fortunate enough to have direct vendor quotes for equipment purchase costs, however, the scaling factors adopted to estimate total investment costs significantly drove up the overall price of the project. Perhaps the operating costs of similar plants can be analyzed to better estimate what these costs would be for this particular type of process.

Section 11: Acknowledgements

We would like to thank our advisor, Dr. Shieh, for his guidance throughout our design project, as well as Dr. Wattenbarger for her initial project proposal. We would like to also express our gratitude to Professor Fabiano, Dr. Vohs, Dr. Gorte, and Dr. Bidstrup Allen for their assistance this semester.

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Throughout the semester, we were also able to draw upon the talents and experiences of several industrial consultants whose prowess in their fields helped us develop and build our ideas. We would to recognize Dave Kolesar, Adam Brostow, Shibal Roy, Gary Sawyer, Mike Grady, and Rick Bockrath, and express our gratitude for the time they gave us.

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The feedback from our advisors, faculty, and consultants has been crucial to the project and in rising to the challenge of becoming chemical engineers. The time that they invested in our group was immensely appreciated and had a noticeable impact on the outcome of the project. We cannot convey the magnitude of our appreciation to each person that made this project possible.

Section 12: Bibliography

Agricultural Marketing Resource Center. (2017). *An Overview of the Biodiesel Market: Production, Imports, Feedstocks and Profitability.*

Alexander, R. (2014, September). 10 Trends in the Compost Marketplace. *Biocycle The Organics Recycling Authority,* p. 32. Retrieved from Biocylce The Organics Recycling Authority.

Aspentech. “Aspen Plus Biodiesel Model.” Aspen Plus Biodiesel Model. 2008. Accessed January 2017.

Beane, A. (2013, November). Solid Waste District Pilots Dry Fermentation Digester. *Biocycle: The Organics Recycling Authority,* pp. 32

Caterpillar Electric Power Division. “Segment Presentatio: Biogas”. PowerPoint Presentation.

Carter, E. (2016, May). *US Biodiesel/Renewable Diesel Market.* Retrieved from US Department of Agriculture.

Elsdon, Richard, and Debnath Pal. "Waste to Energy Plant Process Safety Challenges." *Institution of Chemical Engineers*. Stopford Projects Ltd, 2011. Web. 7 Apr. 2017.

"FAQ." *BIOFerm™ Energy Systems*. BIOFerm, n.d. Web. 07 Apr. 2017.

Garcia, Jose. "Food Waste Recycled as biofuel." (2014).

Grand View Research. (2016, February). *Biofertilizers Market Analysis By Product (Nitrogen Fixing, Phosphate Solubilizing), By Application (Seed Treatment, Soil Treatment) And Segment Forecasts To 2022.* Retrieved from Grand View Research.

Graunke, Ryan. “Food and Fuel: Turning Food Waste to Biogas”. PowerPoint Presentation.

Gunders, D. (2012, August). *Wasted: How America is Losing Up to 40 Percent of It's Food from Farm to Fork to Landfill.* Retrieved from Indiana School Nutrition Association.

Hodge, K. L., Levis, J. W., DeCarolis, J. F., & Barlaz, M. A. (2016, July 7). *Systemic Evaluation of Industrial, Commercial, and Institutional Food Waste Management Strategies in the United States.* Retrieved from American Chemical Society Publications: http://pubs.acs.org/doi/abs/10.1021/acs.est.6b00893?journalCode=esthag

Hogg, D. (2007, November 6). *Options for Dealing with Food Waste.* Retrieved from Institute of Food Research.

"Industry Research Report, 2022." *Biofertilizers Market Size Analysis*. Grand View Research, Feb. 2016. Web. 1 Apr. 2017.

International Energy Agency. (2015). *Renewable Energy Medium-Term Market Report 2015.* Retrieved from International Energy Agency.

National Biodiesel Board. (2009, October). *Benefits of Biodiesel.* Retrieved from Biodiesel: America's Advanced Biofuel.

O'Brien, D. (2010, March). *USDA Projections of Bioenergy-Related Corn and Soyoil Use for 2010-2019*. Retrieved from Agricultural Marketing Resource Center.

"Recovery Act." *1603 Program: Payments for Specified Energy Property in Lieu of Tax Credits*. U.S. Department of the Treasury, 2 Feb. 2017. Web. 07 Apr. 2017.

Seider, Warren D. Product and Process Design Principles: Synthesis, Analysis, and Evaluation. New York: Wiley, 2004. Print.

SprinigBoard Biodiesel. (2014). *Commercial Biodiesel Processors*. Retrieved from SpringBoard Biodiesel.

Townsend, R. E., & Ackerman, F. (2002, December 31). *An Analysis of Competition in Collection and Disposal of Solid Waste in Maine.* Retrieved from Office of the Maine Attorney General.

Union of Concerned Scientists. (1999). *Barriers to Renewable Energy Technologies*. Retrieved from Union of Concerned Scientists.

University of Wisconsin Oshkosh. (2017). *Biogas Systems*. Retrieved from University of Wisconsin Oshkosh.

US Energy Information Administration. (2016, March 29). *Electricty Explained: Electricity in the United States*. Retrieved from US Energy Information Administration.

US Energy Information Administration. (2016, June 3). *US Energy Facts Explained*. Retrieved from Energy Information Administration.

"UWO Biodigester Producing Energy." *BIOFerm™ Energy Systems*. UW Oshkosh Today, 14 Oct. 2011. Web. 07 Apr. 2017.

Waste Management. (2017). *Glossary*. Retrieved from Waste Management.

Weiland, Peter. "Biogas production: current state and perspectives." *Applied microbiology and biotechnology* 85.4 (2010): 849-860.

Wellinger, Arthur, Jerry D. Murphy, and David Baxter, eds. *The biogas handbook: science, production and applications*. Elsevier, 2013.

Zhao, Q., Leonhardt, E., MacConnell, C., Frear, C., & Chen, S. (2010). *Purification Technologies for Biogas Generated by Anaerobic Digestion.* Retrieved from Center for Sustaining Agriculture and Natural Resources.

"2017 Land Values." *Philadelinquency*. N.p., 2017. Web. 11 Apr. 2017. <http://www.philadelinquency.com/map/2017LandValues.html#14/39.9055/-75.1875>.

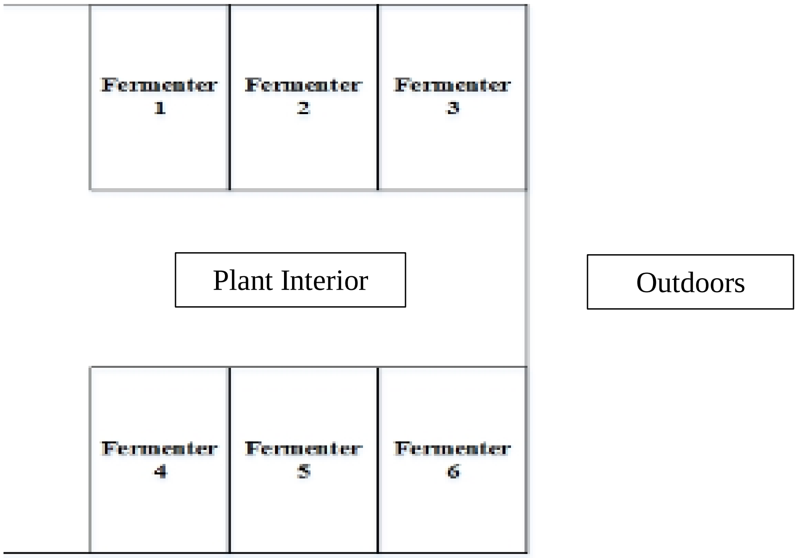
Section 13: Appendix

Appendix A – Calculations

Heat Transfer Calculations for Dry Fermentation System Utilities

The estimated value of annual utilities for this system was calculated with a few assumptions:

1. The interior ambient temperature of the plant is 25 C.
2. The interior of the fermenters are always at 40 C.
3. The cement walls of the fermentation chambers are 6 inches thick.
4. The outdoor temperature is the average Philadelphia winter low at all times, as this would give the maximum amount of utilities needed.
5. For each batch, the energy needed to heat the solid waste is assumed to be a single occurrence. The energy needed to counteract the heat losses to the plant and outdoors is assumed to be on an hourly basis for 28 days.



Values Used for Calculations:

System Temperatures	C	F
Average Winter Low Temperature	-0.69	30.76
Ambient Plant Temperature	25	77
Fermenter Internal Temperature	40	104

Fermenter Dimensions	m	ft
Chamber Width	7.01	23
Chamber Height	5.09	16.7
Chamber Length	24.08	70

Fermenter Wall Areas	m^2	ft^2
Outside Wall (short)	35.6809	384.1
Outside Wall (long)	122.5672	1169
Inside Wall (short)	35.6809	384.1
Inside Wall (long)	122.5672	1169
Shared Wall	122.5672	1169

Assumptions for Model	
Thickness of walls (m)	0.15
Thermal conductivity of concrete $\frac{BTU}{hr*F*ft^2}$	0.7
Max solids in fermenter (tons)	400
Max solids in fermenter (kg)	362874
Average heat capacity of food waste $\frac{KJ}{kg*C}$	3.27
Fermenter batches/year	52
Number times each fermenter is run per year	7

Calculations for Middle Fermenters (2 and 5)

$$\boldsymbol{Energy\ to\ Heat\ Solid\ Waste\ to\ 40\ C} = m_{solids} * C_{p,food} * \left(T_{fermenter} - T_{plant}\right) =$$

$$362874\ kg * 3.27\ \frac{KJ}{kg * C} * (40\ C - 25\ C) = 17798970\ KJ$$

$$17798970\ KJ * \left(0.00028 \frac{kWh}{1\ KJ}\right) = 4985\ KWh$$

$$\boldsymbol{Heat\ Loss\ to\ Inside\ of\ Plant} = \frac{k_{concrete} * A_{short\ inside\ wall} * \left(T_{fermenter} - T_{plant}\right)}{3412\,\frac{\frac{BTU}{hr}}{kWh}}$$

$$= \frac{0.7\ \frac{BTU}{hr * F * ft^2} * 384.1\ ft^2 * (104\ F - 77\ F)}{3412\,\frac{\frac{BTU}{hr}}{kWh}} = 2.13\ kWh$$

$$Total\ Heat\ Loss\ to\ Plant = 2.13\ kWh * 24\ hrs * 28\ days = 1430\ kWh$$

$$\boldsymbol{Heat\ Loss\ to\ Outdoors} = \frac{k_{concrete} * A_{short\ outside\ wall} * \left(T_{fermenter} - T_{outdoors}\right)}{3412\,\frac{\frac{BTU}{hr}}{kWh}}$$

$$= \frac{0.7\ \frac{BTU}{hr * F * ft^2} * 384.1\ ft^2 * (104\ F - 30.76\ F)}{3412\,\frac{\frac{BTU}{hr}}{kWh}} = 5.77\ kWh$$

$$Total\ Heat\ Loss\ to\ Outdoors = 5.77\ kWh * 24\ hrs * 28\ days = 3878\ kWh$$

$$\boldsymbol{Total\ Heating\ Utilities\ Required\ per\ Fermenter\ per\ batch} = 4985\ kWh + 1430\ kWh + 3878\ kWh = 10{,}293\ kWh$$

$$\boldsymbol{Total\ Annual\ Heating\ Utilities\ Required\ for\ Fermenters\ 2, 5} = 14\ batches * 10{,}293\,\frac{kWh}{batch} = 144{,}102\ kWh$$

Heating Utilities for Fermenters 2 and 5	
Energy to heat solid waste to 40 C (KJ)	17798970
Energy to heat solid waste to 40 C (kWh)	4985
Heat loss to inside of building (kWh)	1430
Heat loss to outside of building (kWh)	3878
Total Annual Utilities (kWh)	144102

Calculations for Fermenters 1 and 4

$$\boldsymbol{Energy\ to\ Heat\ Solid\ Waste\ to\ 40\ C} = m_{solids} * C_{p,food} * \left(T_{fermenter} - T_{plant}\right) =$$

$$362874\ kg * 3.27\ \frac{KJ}{kg * C} * (40\ C - 25\ C) = 17798970\ KJ$$

$$17798970\ KJ * \left(0.00028 \frac{kWh}{1\ KJ}\right) = 4985\ KWh$$

$$\boldsymbol{Heat\ Loss\ to\ Inside\ of\ Plant}$$

$$= \frac{k_{concrete} * A_{short\ inside\ wall} * \left(T_{fermenter} - T_{plant}\right) + k_{concrete} * A_{long\ inside\ wall} * (T_{fermenter} - T_{plant})}{3412 \frac{\frac{BTU}{hr}}{kWh}}$$

$$= \frac{0.7\ \frac{BTU}{hr * F * ft^2} * 384.1\ ft^2 * (104\ F - 77\ F) + 0.7\ \frac{BTU}{hr * F * ft^2} * 1169\ ft^2 * (104\ F - 77\ F)}{3412 \frac{\frac{BTU}{hr}}{kWh}}$$

$$= 8.60\ kWh$$

$$Total\ Heat\ Loss\ to\ Plant = 8.60\ kWh * 24\ hrs * 28\ days = 5781\ kWh$$

$$\boldsymbol{Heat\ Loss\ to\ Outdoors} = \frac{k_{concrete} * A_{short\ outside\ wall} * \left(T_{fermenter} - T_{outdoors}\right)}{3412\,\frac{\frac{BTU}{hr}}{kWh}}$$

$$= \frac{0.7\ \frac{BTU}{hr * F * ft^2} * 384.1\ ft^2 * (104\ F - 30.76\ F)}{3412\,\frac{\frac{BTU}{hr}}{kWh}} = 5.77\ kWh$$

$$Total\ Heat\ Loss\ to\ Outdoors = 5.77\ kWh * 24\ hrs * 28\ days = 3878\ kWh$$

$$\boldsymbol{Total\ Heating\ Utilities\ Required\ per\ Fermenter\ per\ batch} = 4985\ kWh + 5781\ kWh + 3878\ kWh = 14{,}644\ kWh$$

$$\boldsymbol{Total\ Annual\ Heating\ Utilities\ Required\ for\ Fermenters\ 2, 5} = 14\ batches * 14{,}644\,\frac{kWh}{batch} = 205{,}016\ kWh$$

Heating Utilities for Fermenters 2 and 5	
Energy to heat solid waste to 40 C (KJ)	17798970
Energy to heat solid waste to 40 C (kWh)	4985
Heat loss to inside of building (kWh)	5781
Heat loss to outside of building (kWh)	3878
Total Annual Utilities (kWh)	205016

Calculations for Fermenters 3 and 6

$$\boldsymbol{Energy\ to\ Heat\ Solid\ Waste\ to\ 40\ C} = m_{solids} * C_{p,food} * \left(T_{fermenter} - T_{plant}\right) =$$

$$362874\ kg * 3.27\ \frac{KJ}{kg * C} * (40\ C - 25\ C) = 17798970\ KJ$$

$$17798970\ KJ * \left(0.00028 \frac{kWh}{1\ KJ}\right) = 4985\ KWh$$

$$\boldsymbol{Heat\ Loss\ to\ Inside\ of\ Plant} = \frac{k_{concrete} * A_{short\ inside\ wall} * \left(T_{fermenter} - T_{plant}\right)}{3412 \frac{\frac{BTU}{hr}}{kWh}}$$

$$= \frac{0.7\ \frac{BTU}{hr * F * ft^2} * 384.1\ ft^2 * (104\ F - 77\ F)}{3412 \frac{\frac{BTU}{hr}}{kWh}} = 2.13\ kWh$$

$$Total\ Heat\ Loss\ to\ Indoors = 2.13\ kWh * 24\ hrs * 28\ days = 1430\ kWh$$

$$\boldsymbol{Heat\ Loss\ to\ Outdoor}$$

$$= \frac{k_{concrete} * A_{short\ outside\ wall} * \left(T_{fermenter} - T_{outdoors}\right) + k_{concrete} * A_{long\ outside\ wall} * \left(T_{fermenter} - T_{outdoors}\right)}{3412 \frac{\frac{BTU}{hr}}{kWh}}$$

$$= \frac{0.7\ \frac{BTU}{hr * F * ft^2} * 384.1\ ft^2 * (104\ F - 30.76\ F) + 0.7\ \frac{BTU}{hr * F * ft^2} * 1169\ ft^2 * (104\ F - 30.76\ F)}{3412 \frac{\frac{BTU}{hr}}{kWh}}$$

$$= 23.34\ kWh$$

$$Total\ Heat\ Loss\ to\ Outdoors = 23.34\ kWh * 24\ hrs * 28\ days = 15{,}682\ kWh$$

$$\boldsymbol{Total\ Heating\ Utilities\ Required\ per\ Fermenter\ per\ batch} = 4985\ kWh + 1430\ kWh + 15{,}682\ \ kWh = 22{,}097\ kWh$$

$$\boldsymbol{Total\ Annual\ Heating\ Utilities\ Required\ for\ Fermenters\ 2,5} = 14\ batches * 22{,}097 \frac{kWh}{batch} = 309{,}358\ kWh$$

Heating Utilities for Fermenters 3 and 6	
Energy to heat solid waste to 40 C (KJ)	17798970
Energy to heat solid waste to 40 C (kWh)	4985
Heat loss to inside of building (kWh)	1430
Heat loss to outside of building (kWh)	15682
Total Annual Utilities (kWh)	309358

Total Annual Utilities for all Fermenters: 658,476 kWh

Total Annual Energy Produced (Electricity + Heat): 10,653,120 kWh

Total Percentage Required by System: 6%

Energy Value of Biogas Calculations

As previously mentioned, the percentage composition of biogas tends to vary with the feedstock. For the purpose of these calculations, the following composition by volume was assumed.

Biogas Component	**Percentage by Volume**
Methane	67.7%
Carbon Dioxide	26%
Nitrogen	6%
Hydrogen Sulfide	<1%

$$Methane\ per\ hour = 228.81\ \frac{m^3\ biogas}{hour} * \ 0.68 = 155.59\frac{m^3\ methane}{hour}$$

$$kWh\ of\ hourly\ biogas\ flow = 155.59\frac{m^3 methane}{hour} * \frac{36\ MJ}{1\ m^3\ methane} * \frac{1\ kWh}{3.6\ MJ} = 1556\ \text{kWh}$$

Biodiesel Processing Green House Gas (GHG) Emission Reduction Calculations

Two important assumptions in this calculation are that:

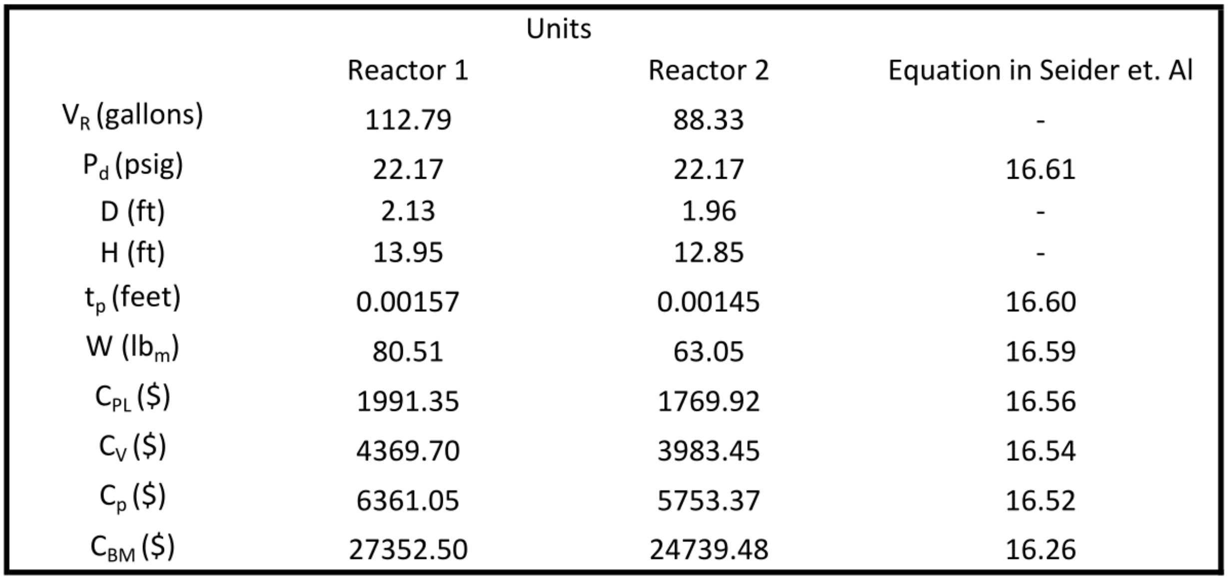
1. The carbon dioxide produced from combustion of 1 gallon of petroleum-based diesel is 22.2 lbs of GHG emissions
2. There is an 86% reduction in GHG emissions when replacing petroleum based diesel with biodiesel

$$Reduction\ in\ Tons = \frac{Waste\ oil\ in\ gallons * 22.2 * 0.86}{2000}$$

$$Total\ Reduction\ in\ GHG\ Emissions\ from\ Project = \frac{72864 * 22.2 * 0.86}{2000} = 696\ tons/yr$$

Large-Scale Biodiesel Process Costing Calculations

The cost for industrial-scale biodiesel reactors was calculated according to costing equations from Seider et. al. The results can be seen in the table below, and the calculations for these figures can be found in the subsequent pages.



	Units		
	Reactor 1	Reactor 2	Equation in Seider et. Al
V_R (gallons)	112.79	88.33	-
P_d (psig)	22.17	22.17	16.61
D (ft)	2.13	1.96	-
H (ft)	13.95	12.85	-
t_p (feet)	0.00157	0.00145	16.60
W (lb_m)	80.51	63.05	16.59
C_{PL} ($)	1991.35	1769.92	16.56
C_V ($)	4369.70	3983.45	16.54
C_p ($)	6361.05	5753.37	16.52
C_{BM} ($)	27352.50	24739.48	16.26

Volume, Height, and Diameter Calculations

The volume of the reactors, V_R, is found via

$$V_R = \dot{V}\tau$$

$$V_{R,reactor\ 1} = 9.40\frac{gal}{hr} * 12\ hr = 112.79\ gal$$

$$V_{R,reactor\ 2} = 7.36\frac{gal}{hr} *\ 12\ hr = 88.32\ gal$$

where $\mathring{V}$ is the inlet flowrate and τ is the residence time of the reactor. To do a good comparison, the values for $\mathring{V}$ and τ were chosen so that they would be the same as the units that were ultimately selected.

When finding the dimensions of the reactor, it is common practice to use an aspect ratio, $\frac{H}{D}$, of 2 in the preliminary analysis. By assuming the reactor vessel is cylindrical, the diameter and height of the vessel can be found as

$$D = \sqrt[3]{\frac{2V_R}{\pi}}$$

$$H = 2D$$

$$D_{reactor\ 1} = \sqrt[3]{\frac{2 * 112.79 \text{ gal}}{\pi}} = 2.13\ ft$$

$$H_{reactor\ 1} = 2 * 2.13\ ft = 4.26\ ft$$

$$D_{reactor\ 2} = \sqrt[3]{\frac{2 * 88.33 \text{ gal}}{\pi}} = 1.96\ ft$$

$$H_{reactor\ 2} = 2 * 1.96\ ft = 3.92\ ft$$

Pressure Calculations (Equation 16.61)

$$P_{d,reactor\ 1} = \exp\{0.060608 + 0.91615[\ln(P_o)] + 0.0015655[\ln(P_o)]^2\} = 22.17\ psig$$

$$P_{d,reactor\ 2} = \exp\{0.060608 + 0.91615[\ln(14.7 \text{ psi})] + 0.0015655[\ln(14.7 \text{ psi}_o)]^2\} = 22.17 \text{ psig}$$

Thickness Calculations (Equation 16.60)

$$t_p = \frac{P_d D_i}{2SE - 1.2P_d}$$

$$t_{p,reactor\ 1} = \frac{22.17 \text{ psi} * 2.13 \text{ ft}}{(2 * 15{,}000 \text{ psi} * 1) - (1.2 * 22.17\ psi)} = 0.00157\ ft$$

$$t_{p,reactor\ 2} = \frac{22.17 \text{ psi} * 1.96 \text{ ft}}{(2 * 15{,}000 \text{ psi} * 1) - (1.2 * 22.17 \text{ psi}) = 0.00145\ ft}$$

Weight Calculations (Equation 16.59)

$$W = \pi(D + t_p)(H + 0.8D)t_p\rho$$

$$W_{reactor\ 1} = \pi(2.13\text{ ft} + .002\text{ ft})(13.95\text{ ft} + 0.8 * 2.13\text{ ft}) * .002\text{ ft} * 490\,\frac{lb}{ft^3} = 80.51\ lbs$$

$$W_{reactor\ 2} = \pi(1.96\text{ ft} + .001\text{ ft})(12.85\text{ ft} + 0.8 * 1.96\text{ ft}) * .001\text{ ft} * 490\,\frac{lb}{ft^3} = 63.05\ lbs$$

Cost of Platform and Ladders Calculations (Equation 16.56)

$$C_{PL} = 410D^{0.73960}H^{0.70684}$$

$$C_{PL,reactor\ 1} = 410 * 2.13\text{ ft}^{0.73960} * 13.95\text{ ft}^{0.70684} = \$1{,}991.35$$

$$C_{PL,reactor\ 2} = 410 * 1.95\text{ ft}^{0.73960}12.85\text{ ft}^{0.70684} = \$1{,}769.92$$

Purchase Cost of Vessel Calculations (Equation 16.54)

$$C_v = \exp\{7.1390 + 0.18255[\ln(W)] + 0.02297[\ln(W)]^2\}$$

$$C_{V,reactor\ 1} = \exp\{7.1390 + 0.18255[ln(80.51\ lbs)] + 0.02297[ln(80.51\ lbs)]^2\} = \$4{,}369.70$$

$$C_{V,reactor\ 2} = \exp\{7.1390 + 0.18255[ln(63.05\ lbs)] + 0.02297[ln(63.05\ lbs)]^2\} = \$3{,}983.45$$

Bare Module Cost Calculations (Equation 16.52)

$$C_p = C_V F_m + C_{PL}$$

$$C_{p,reactor\ 1} = \$4{,}369.70 * 1 + \$1{,}991.35 = \$6{,}361.05$$

$$C_{p,reactor\ 2} = \$3{,}983.45 * 1 + \$1{,}769.92 = \$5{,}753.37$$

$$C_{BM} = C_p F_{BM}$$

$$C_{BM,reactor\ 1} = \$6{,}361.05 * 4.3 = \$27{,}352.50$$

$$C_{BM,reactor\ 2} = \$5{,}753.37 * 4.3 = \$24{,}739.48$$

For the reactor vessels:

P_o = 15 psig
S = 15,000 psig
E = 1
$\rho = 490\,\frac{lb_m}{ft^3}$

$$F_M = 1$$
$$F_{BM} = 4.3$$

The values for S, E, ρ, F_M, and F_{BM}, as well as all the formulas can be found in Seider et. Al, Pages 464-466.

Appendix B – Material Safety Data Sheets and Specification Sheets

SAFETY DATA SHEET

Carbon Dioxide

Section 1. Identification

GHS product identifier : Carbon Dioxide

Chemical name : Carbon dioxide

Other means of identification : Carbonic, Carbon Dioxide, Carbonic Anhydride, R744, Carbon Dioxide USP

Product use : Synthetic/Analytical chemistry.

Synonym : Carbonic, Carbon Dioxide, Carbonic Anhydride, R744, Carbon Dioxide USP

SDS # : 001013

Supplier's details : Airgas USA, LLC and its affiliates
259 North Radnor-Chester Road
Suite 100
Radnor, PA 19087-5283
1-610-687-5253

24-hour telephone : 1-866-734-3438

Section 2. Hazards identification

OSHA/HCS status : This material is considered hazardous by the OSHA Hazard Communication Standard (29 CFR 1910.1200).

Classification of the substance or mixture : GASES UNDER PRESSURE - Liquefied gas
Simple asphyxiant.

GHS label elements

Hazard pictograms :

Signal word : Warning

Hazard statements : Contains gas under pressure; may explode if heated.
May cause frostbite.
May displace oxygen and cause rapid suffocation.
May increase respiration and heart rate.

Precautionary statements

General : Read and follow all Safety Data Sheets (SDS'S) before use. Read label before use. Keep out of reach of children. If medical advice is needed, have product container or label at hand. Close valve after each use and when empty. Use equipment rated for cylinder pressure. Do not open valve until connected to equipment prepared for use. Use a back flow preventative device in the piping. Use only equipment of compatible materials of construction. Always keep container in upright position.

Prevention : Use and store only outdoors or in a well ventilated place.

Response : Not applicable.

Storage : Protect from sunlight when ambient temperature exceeds 52°C/125°F. Store in a well-ventilated place.

Disposal : Not applicable.

Hazards not otherwise classified : In addition to any other important health or physical hazards, this product may displace oxygen and cause rapid suffocation.
May cause frostbite.

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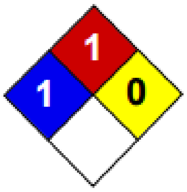

Health	1
Fire	1
Reactivity	0
Personal Protection	G

Material Safety Data Sheet
Glycerin MSDS

Section 1: Chemical Product and Company Identification

Product Name: Glycerin

Catalog Codes: SLG1171, SLG1894, SLG1111, SLG1615

CAS#: 56-81-5

RTECS: MA8050000

TSCA: TSCA 8(b) inventory: Glycerin

CI#: Not available.

Synonym: 1,2,3-Propanetriol; Glycerol

Chemical Name: Glycerin

Chemical Formula: $C_3H_5(OH)_3$

Contact Information:

Sciencelab.com, Inc.
14025 Smith Rd.
Houston, Texas 77396

US Sales: **1-800-901-7247**
International Sales: **1-281-441-4400**

Order Online: ScienceLab.com

CHEMTREC (24HR Emergency Telephone), call:
1-800-424-9300

International CHEMTREC, call: 1-703-527-3887

For non-emergency assistance, call: 1-281-441-4400

Section 2: Composition and Information on Ingredients

Composition:

Name	CAS #	% by Weight
Glycerin	56-81-5	100

Toxicological Data on Ingredients: Glycerin: ORAL (LD50): Acute: 12600 mg/kg [Rat]. 4090 mg/kg [Mouse]. DERMAL (LD50): Acute: 10000 mg/kg [Rabbit]. MIST(LC50): Acute: >570 mg/m 1 hours [Rat].

Section 3: Hazards Identification

Potential Acute Health Effects: Slightly hazardous in case of skin contact (irritant, permeator), of eye contact (irritant), of ingestion, of inhalation.

Potential Chronic Health Effects:
CARCINOGENIC EFFECTS: Not available. MUTAGENIC EFFECTS: Not available. TERATOGENIC EFFECTS: Not available. DEVELOPMENTAL TOXICITY: Not available. The substance may be toxic to kidneys. Repeated or prolonged exposure to the substance can produce target organs damage.

SAFETY DATA SHEET

Hydrogen Sulfide

Airgas
an Air Liquide company

Section 1. Identification

GHS product identifier : Hydrogen Sulfide

Chemical name : hydrogen sulfide

Other means of identification : Hydrogen sulfide; Hydrogen sulfide (H2S); Sulfuretted hydrogen; Sewer gas; Hydrosulfuric acid; dihydrogen sulfide

Product use : Synthetic/Analytical chemistry.

Synonym : Hydrogen sulfide; Hydrogen sulfide (H2S); Sulfuretted hydrogen; Sewer gas; Hydrosulfuric acid; dihydrogen sulfide

SDS # : 001029

Supplier's details : Airgas USA, LLC and its affiliates
259 North Radnor-Chester Road
Suite 100
Radnor, PA 19087-5283
1-610-687-5253

24-hour telephone : 1-866-734-3438

Section 2. Hazards identification

OSHA/HCS status : This material is considered hazardous by the OSHA Hazard Communication Standard (29 CFR 1910.1200).

Classification of the substance or mixture : FLAMMABLE GASES - Category 1
GASES UNDER PRESSURE - Liquefied gas
ACUTE TOXICITY (inhalation) - Category 2
SPECIFIC TARGET ORGAN TOXICITY (SINGLE EXPOSURE) (Respiratory tract irritation) - Category 3
AQUATIC HAZARD (ACUTE) - Category 1

GHS label elements

Hazard pictograms :

Signal word : Danger

Hazard statements : Extremely flammable gas.
Contains gas under pressure; may explode if heated.
May cause frostbite.
May form explosive mixtures in Air.
Fatal if inhaled.
Extended exposure to gas reduces the ability to smell sulfides.
Corrosive to respiratory tract.
Very toxic to aquatic life with long lasting effects.

Precautionary statements

General : Read and follow all Safety Data Sheets (SDS'S) before use. Read label before use. Keep out of reach of children. If medical advice is needed, have product container or label at hand. Close valve after each use and when empty. Use equipment rated for cylinder pressure. Do not open valve until connected to equipment prepared for use. Use a back flow preventative device in the piping. Use only equipment of compatible materials of construction. Always keep container in upright position. Do not depend on odor to detect presence of gas. Approach suspected leak area with caution.

Prevention : Wear respiratory protection. Keep away from heat, hot surfaces, sparks, open flames and other ignition sources. No smoking. Use only outdoors or in a well-ventilated area. Avoid release to the environment. Do not breathe gas.

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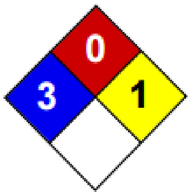


Health	3
Fire	0
Reactivity	2
Personal Protection	J

Material Safety Data Sheet
Potassium hydroxide MSDS

Section 1: Chemical Product and Company Identification

Product Name: Potassium hydroxide

Catalog Codes: SLP4096, SLP3085, SLP4900, SLP2071

CAS#: 1310-58-3

RTECS: TT2100000

TSCA: TSCA 8(b) inventory: Potassium hydroxide

CI#: Not available.

Synonym:

Chemical Name: Potassium Hydroxide

Chemical Formula: KOH

Contact Information:

Sciencelab.com, Inc.
14025 Smith Rd.
Houston, Texas 77396

US Sales: **1-800-901-7247**
International Sales: **1-281-441-4400**

Order Online: ScienceLab.com

CHEMTREC (24HR Emergency Telephone), call:
1-800-424-9300

International CHEMTREC, call: 1-703-527-3887

For non-emergency assistance, call: 1-281-441-4400

Section 2: Composition and Information on Ingredients

Composition:

Name	CAS #	% by Weight
Potassium hydroxide	1310-58-3	100

Toxicological Data on Ingredients: Potassium hydroxide: ORAL (LD50): Acute: 273 mg/kg [Rat].

Section 3: Hazards Identification

Potential Acute Health Effects:
Very hazardous in case of skin contact (corrosive, irritant), of eye contact (irritant, corrosive), of ingestion, of inhalation. The amount of tissue damage depends on length of contact. Eye contact can result in corneal damage or blindness. Skin contact can produce inflammation and blistering. Inhalation of dust will produce irritation to gastro-intestinal or respiratory tract, characterized by burning, sneezing and coughing. Severe over-exposure can produce lung damage, choking, unconsciousness or death. Inflammation of the eye is characterized by redness, watering, and itching. Skin inflammation is characterized by itching, scaling, reddening, or, occasionally, blistering.

Potential Chronic Health Effects:
CARCINOGENIC EFFECTS: Not available. MUTAGENIC EFFECTS: Mutagenic for mammalian somatic cells. TERATOGENIC EFFECTS: Not available. DEVELOPMENTAL TOXICITY: Not available. The substance may be toxic to upper respiratory tract, skin, eyes. Repeated or prolonged exposure to the substance can produce target organs damage. Repeated exposure of the eyes to a low level of dust can produce eye irritation. Repeated skin exposure can produce local skin destruction, or dermatitis. Repeated inhalation of dust can produce varying degree of respiratory irritation or lung damage.

Material Safety Data Sheet

AIR LIQUIDE

Methane

1. Product and company identification

Product name : Methane

Synonym : Methane or natural gas but excluding refrigerated liquid methane or natural gas; methane liquefied; methane in gaseous state

Material uses : Various

CAS number : 74-82-8

Supplier/Manufacturer : Air Liquide Canada Inc.
1250, René-Lévesque West, Suite 1700
Montreal, QC
H3B 5E6
www.airliquide.ca
1-800-817-7697

Prepared by : IHS

In case of emergency : (514) 878-1667

2. Hazards identification

Physical state : Gas. [Compressed gas.]

Color : Colorless.

Odor : Sweet. [Slight]

Emergency overview

Signal word : DANGER!

Hazard statements : FLAMMABLE GAS. MAY CAUSE FLASH FIRE. HIGH PRESSURE GAS. GAS REDUCES OXYGEN AVAILABLE FOR BREATHING. AT VERY HIGH CONCENTRATIONS, CAN DISPLACE THE NORMAL AIR AND CAUSE SUFFOCATION FROM LACK OF OXYGEN. MAY CAUSE TARGET ORGAN DAMAGE, BASED ON ANIMAL DATA.

Precautions : Contains gas under pressure. In a fire or if heated, a pressure increase will occur and the container may burst or explode. At very high concentrations, can displace the normal air and cause suffocation from lack of oxygen. Keep away from heat, sparks and flame. Do not puncture or incinerate container. Do not enter storage areas and confined spaces unless adequately ventilated. Do not breathe gas. Avoid contact with skin and clothing. Use only with adequate ventilation. Keep container tightly closed and sealed until ready for use. Keep container tightly closed.

Routes of entry : Dermal contact. Eye contact. Inhalation.

Potential acute health effects

Inhalation : At very high concentrations, can displace the normal air and cause suffocation from lack of oxygen.

Ingestion : As this product is a gas, refer to the inhalation section.

Skin : Contact with rapidly expanding gas may cause burns or frostbite.

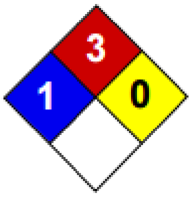
Eyes : Contact with rapidly expanding gas may cause burns or frostbite.

Potential chronic health effects

Chronic effects : May cause target organ damage, based on animal data.

Carcinogenicity : No known significant effects or critical hazards.

Mutagenicity : No known significant effects or critical hazards.



Health	2
Fire	3
Reactivity	0
Personal Protection	H

Material Safety Data Sheet
Methyl alcohol MSDS

Section 1: Chemical Product and Company Identification

Product Name: Methyl alcohol

Catalog Codes: SLM3064, SLM3952

CAS#: 67-56-1

RTECS: PC1400000

TSCA: TSCA 8(b) inventory: Methyl alcohol

CI#: Not applicable.

Synonym: Wood alcohol, Methanol; Methylol; Wood Spirit; Carbinol

Chemical Name: Methanol

Chemical Formula: CH_3OH

Contact Information:

Sciencelab.com, Inc.
14025 Smith Rd.
Houston, Texas 77396

US Sales: **1-800-901-7247**
International Sales: **1-281-441-4400**

Order Online: ScienceLab.com

CHEMTREC (24HR Emergency Telephone), call:
1-800-424-9300

International CHEMTREC, call: 1-703-527-3887

For non-emergency assistance, call: 1-281-441-4400

Section 2: Composition and Information on Ingredients

Composition:

Name	CAS #	% by Weight
Methyl alcohol	67-56-1	100

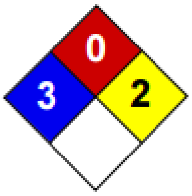
Toxicological Data on Ingredients: Methyl alcohol: ORAL (LD50): Acute: 5628 mg/kg [Rat]. DERMAL (LD50): Acute: 15800 mg/kg [Rabbit]. VAPOR (LC50): Acute: 64000 ppm 4 hours [Rat].

Section 3: Hazards Identification

Potential Acute Health Effects:
Hazardous in case of skin contact (irritant), of eye contact (irritant), of ingestion, of inhalation. Slightly hazardous in case of skin contact (permeator). Severe over-exposure can result in death.

Potential Chronic Health Effects:
Slightly hazardous in case of skin contact (sensitizer). CARCINOGENIC EFFECTS: Not available. MUTAGENIC EFFECTS: Mutagenic for mammalian somatic cells. Mutagenic for bacteria and/or yeast. TERATOGENIC EFFECTS: Classified POSSIBLE for human. DEVELOPMENTAL TOXICITY: Not available. The substance is toxic to eyes. The substance may be toxic to blood, kidneys, liver, brain, peripheral nervous system, upper respiratory tract, skin, central nervous system (CNS), optic nerve. Repeated or prolonged exposure to the substance can produce target organs damage. Repeated exposure to a highly toxic material may produce general deterioration of health by an accumulation in one or many human organs.

ScienceLab.com
Chemicals & Laboratory Equipment



Health	3
Fire	0
Reactivity	2
Personal Protection	

Material Safety Data Sheet
Sulfuric acid MSDS

Section 1: Chemical Product and Company Identification

Product Name: Sulfuric acid

Catalog Codes: SLS2539, SLS1741, SLS3166, SLS2371, SLS3793

CAS#: 7664-93-9

RTECS: WS5600000

TSCA: TSCA 8(b) inventory: Sulfuric acid

CI#: Not applicable.

Synonym: Oil of Vitriol; Sulfuric Acid

Chemical Name: Hydrogen sulfate

Chemical Formula: H2-SO4

Contact Information:

Sciencelab.com, Inc.
14025 Smith Rd.
Houston, Texas 77396

US Sales: **1-800-901-7247**
International Sales: **1-281-441-4400**

Order Online: ScienceLab.com

CHEMTREC (24HR Emergency Telephone), call:
1-800-424-9300

International CHEMTREC, call: 1-703-527-3887

For non-emergency assistance, call: 1-281-441-4400

Section 2: Composition and Information on Ingredients

Composition:

Name	CAS #	% by Weight
Sulfuric acid	7664-93-9	95 - 98

Toxicological Data on Ingredients: Sulfuric acid: ORAL (LD50): Acute: 2140 mg/kg [Rat.]. VAPOR (LC50): Acute: 510 mg/m 2 hours [Rat]. 320 mg/m 2 hours [Mouse].

Section 3: Hazards Identification

Potential Acute Health Effects:
Very hazardous in case of skin contact (corrosive, irritant, permeator), of eye contact (irritant, corrosive), of ingestion, of inhalation. Liquid or spray mist may produce tissue damage particularly on mucous membranes of eyes, mouth and respiratory tract. Skin contact may produce burns. Inhalation of the spray mist may produce severe irritation of respiratory tract, characterized by coughing, choking, or shortness of breath. Severe over-exposure can result in death. Inflammation of the eye is characterized by redness, watering, and itching. Skin inflammation is characterized by itching, scaling, reddening, or, occasionally, blistering.

Potential Chronic Health Effects:
CARCINOGENIC EFFECTS: Classified 1 (Proven for human.) by IARC, + (Proven.) by OSHA. Classified A2 (Suspected for human.) by ACGIH. MUTAGENIC EFFECTS: Not available. TERATOGENIC EFFECTS: Not available. DEVELOPMENTAL TOXICITY: Not available. The substance may be toxic to kidneys, lungs, heart, cardiovascular system, upper respiratory tract, eyes, teeth. Repeated or prolonged exposure to the substance can produce target organs damage. Repeated or prolonged

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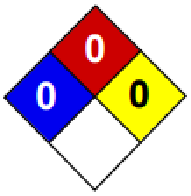
Chemicals & Laboratory Equipment



Health	0
Fire	0
Reactivity	0
Personal Protection	A

Material Safety Data Sheet
Water MSDS

Section 1: Chemical Product and Company Identification

Product Name: Water

Catalog Codes: SLW1063

CAS#: 7732-18-5

RTECS: ZC0110000

TSCA: TSCA 8(b) inventory: Water

CI#: Not available.

Synonym: Dihydrogen oxide

Chemical Name: Water

Chemical Formula: H_2O

Contact Information:

Sciencelab.com, Inc.
14025 Smith Rd.
Houston, Texas 77396

US Sales: **1-800-901-7247**
International Sales: **1-281-441-4400**

Order Online: ScienceLab.com

CHEMTREC (24HR Emergency Telephone), call:
1-800-424-9300

International CHEMTREC, call: 1-703-527-3887

For non-emergency assistance, call: 1-281-441-4400

Section 2: Composition and Information on Ingredients

Composition:

Name	CAS #	% by Weight
Water	7732-18-5	100

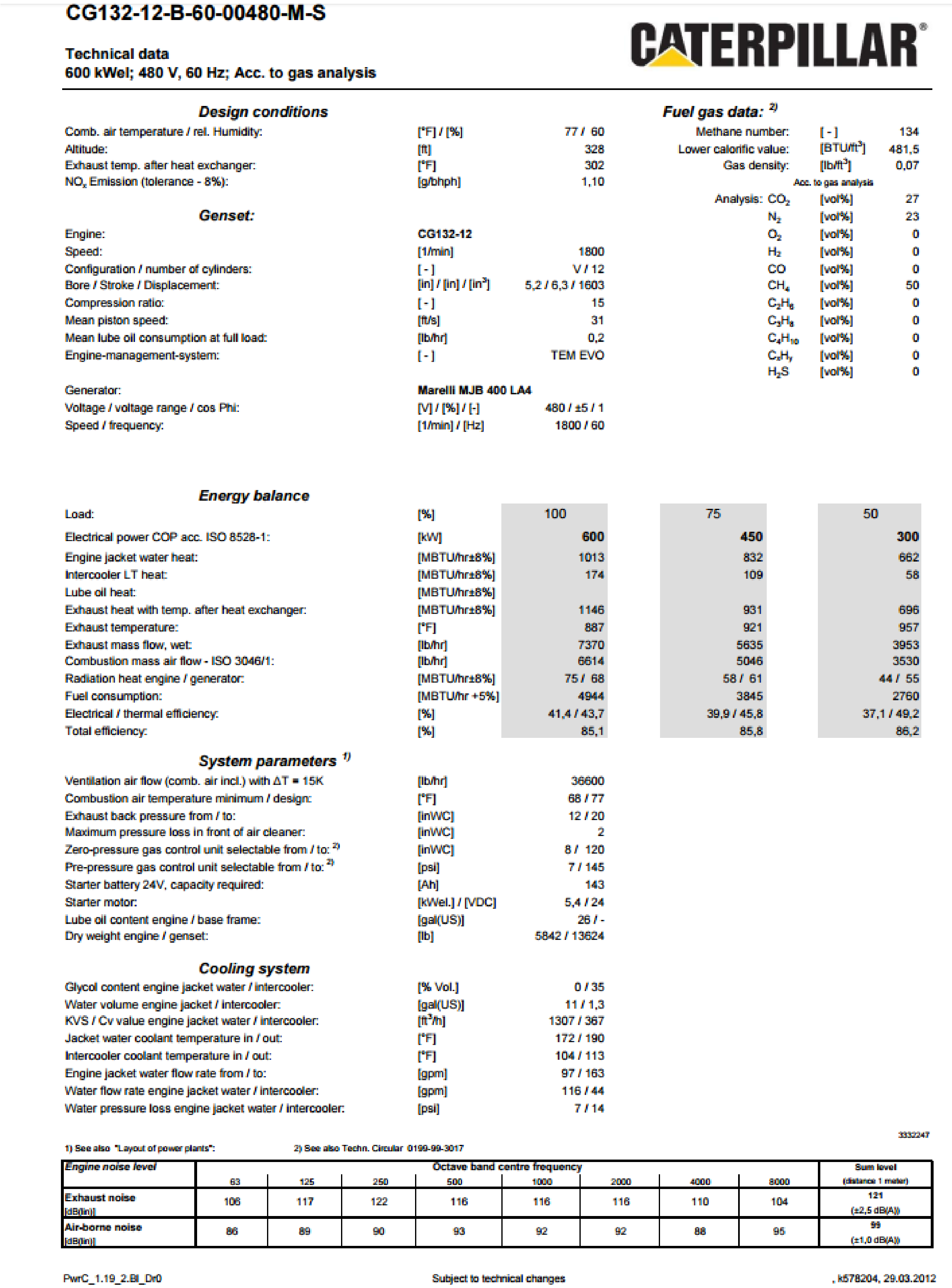
Toxicological Data on Ingredients: Not applicable.

Section 3: Hazards Identification

Potential Acute Health Effects:
Non-corrosive for skin. Non-irritant for skin. Non-sensitizer for skin. Non-permeator by skin. Non-irritating to the eyes. Non-hazardous in case of ingestion. Non-hazardous in case of inhalation. Non-irritant for lungs. Non-sensitizer for lungs. Non-corrosive to the eyes. Non-corrosive for lungs.

Potential Chronic Health Effects:
Non-corrosive for skin. Non-irritant for skin. Non-sensitizer for skin. Non-permeator by skin. Non-irritating to the eyes. Non-hazardous in case of ingestion. Non-hazardous in case of inhalation. Non-irritant for lungs. Non-sensitizer for lungs. CARCINOGENIC EFFECTS: Not available. MUTAGENIC EFFECTS: Not available. TERATOGENIC EFFECTS: Not available. DEVELOPMENTAL TOXICITY: Not available.

Specification Sheets



CG132-12-B-60-00480-M-S

Technical data
600 kWel; 480 V, 60 Hz; Acc. to gas analysis

CATERPILLAR®

Design conditions

Comb. air temperature / rel. Humidity:	[°F] / [%]	77 / 60
Altitude:	[ft]	328
Exhaust temp. after heat exchanger:	[°F]	302
NO_x Emission (tolerance - 8%):	[g/bhph]	1,10

Genset:

Engine:	**CG132-12**	
Speed:	[1/min]	1800
Configuration / number of cylinders:	[-]	V / 12
Bore / Stroke / Displacement:	[in] / [in] / [in³]	5,2 / 6,3 / 1603
Compression ratio:	[-]	15
Mean piston speed:	[ft/s]	31
Mean lube oil consumption at full load:	[lb/hr]	0,2
Engine-management-system:	[-]	TEM EVO
Generator:	**Marelli MJB 400 LA4**	
Voltage / voltage range / cos Phi:	[V] / [%] / [-]	480 / ±5 / 1
Speed / frequency:	[1/min] / [Hz]	1800 / 60

Fuel gas data: 2)

Methane number:		[-]	134
Lower calorific value:		[BTU/ft³]	481,5
Gas density:		[lb/ft³]	0,07
		Acc. to gas analysis	
Analysis:	CO_2	[vol%]	27
	N_2	[vol%]	23
	O_2	[vol%]	0
	H_2	[vol%]	0
	CO	[vol%]	0
	CH_4	[vol%]	50
	C_2H_6	[vol%]	0
	C_3H_8	[vol%]	0
	C_4H_{10}	[vol%]	0
	C_xH_y	[vol%]	0
	H_2S	[vol%]	0

Energy balance

Load:	[%]	100	75	50
Electrical power COP acc. ISO 8528-1:	[kW]	**600**	**450**	**300**
Engine jacket water heat:	[MBTU/hr±8%]	1013	832	662
Intercooler LT heat:	[MBTU/hr±8%]	174	109	58
Lube oil heat:	[MBTU/hr±8%]			
Exhaust heat with temp. after heat exchanger:	[MBTU/hr±8%]	1146	931	696
Exhaust temperature:	[°F]	887	921	957
Exhaust mass flow, wet:	[lb/hr]	7370	5635	3953
Combustion mass air flow - ISO 3046/1:	[lb/hr]	6614	5046	3530
Radiation heat engine / generator:	[MBTU/hr±8%]	75 / 68	58 / 61	44 / 55
Fuel consumption:	[MBTU/hr +5%]	4944	3845	2760
Electrical / thermal efficiency:	[%]	41,4 / 43,7	39,9 / 45,8	37,1 / 49,2
Total efficiency:	[%]	85,1	85,8	86,2

System parameters 1)

Ventilation air flow (comb. air incl.) with ΔT = 15K	[lb/hr]	36600
Combustion air temperature minimum / design:	[°F]	68 / 77
Exhaust back pressure from / to:	[inWC]	12 / 20
Maximum pressure loss in front of air cleaner:	[inWC]	2
Zero-pressure gas control unit selectable from / to: 2)	[inWC]	8 / 120
Pre-pressure gas control unit selectable from / to: 2)	[psi]	7 / 145
Starter battery 24V, capacity required:	[Ah]	143
Starter motor:	[kWel.] / [VDC]	5,4 / 24
Lube oil content engine / base frame:	[gal(US)]	26 / -
Dry weight engine / genset:	[lb]	5842 / 13624

Cooling system

Glycol content engine jacket water / intercooler:	[% Vol.]	0 / 35
Water volume engine jacket / intercooler:	[gal(US)]	11 / 1,3
KVS / Cv value engine jacket water / intercooler:	[ft³/h]	1307 / 367
Jacket water coolant temperature in / out:	[°F]	172 / 190
Intercooler coolant temperature in / out:	[°F]	104 / 113
Engine jacket water flow rate from / to:	[gpm]	97 / 163
Water flow rate engine jacket water / intercooler:	[gpm]	116 / 44
Water pressure loss engine jacket water / intercooler:	[psi]	7 / 14

3332247

1) See also "Layout of power plants":

2) See also Techn. Circular 0199-99-3017

Engine noise level	Octave band centre frequency								Sum level
	63	125	250	500	1000	2000	4000	8000	(distance 1 meter)
Exhaust noise [dB(lin)]	106	117	122	116	116	116	110	104	121 (±2,5 dB(A))
Air-borne noise [dB(lin)]	86	89	90	93	92	92	88	95	99 (±1,0 dB(A))

PwrC_1.19_2.Bl_Dr0

Subject to technical changes

, k578204, 29.03.2012

University of Wisconsin Oshkosh, Biodigester I

The BIOFerm Dry Fermentation anaerobic digester at the University of Wisconsin Oshkosh, dubbed "Biodigester I", is the first industrial-scale dry fermentation anaerobic digestion plant in the Americas. The facility serves as a living, learning laboratory for students and faculty and furthers the University's goals to create a sustainable campus with a net zero impact on the climate and environment.

- Can handle up to 8,000 tons of organics at a time including campus and nearby food waste, yard waste and crop residue
- Produces 2,320,000 kWh on average a year
- Supplies as much as 15% of UWO's electrical needs

Digester Dimensions

Total footprint is 19,000 square feet (storage area 2,000 square feet, mixing area 7,800 square feet). There are four fermentation vessels, each 70' x 23' x 16.7'. Each cycle is 28 days long, with 13 maximum material exchanges per year – around 150 tons of fresh material per exchange.

Emissions Reductions

- The methane produced and used is equivalent to the avoided release of:
- 9,641 metric tons CO_2 equivalent

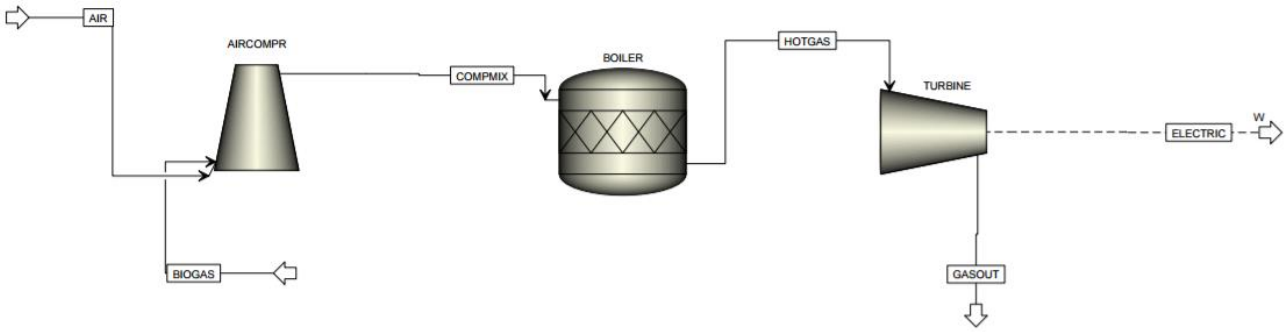
Electricity generation from these renewable sources is equivalent to reducing:

- 2,339 metric tons CO_2 per year from a conventional bituminous coal facility, OR
- 1,372 metric tons CO_2 per year produced from a natural gas facility

UW– Oshkosh plant exterior

Appendix C– Aspen Simulations

Gas Turbine Aspen Simulation



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FLOWSHEET SECTION


 FLOWSHEET CONNECTIVITY BY STREAMS
 ---------------------------------


  STREAM     SOURCE     DEST          STREAM     SOURCE     DEST
  BIOGAS     ----       AIRCOMPR      AIR        ----       AIRCOMPR
  HOTGAS     BOILER     TURBINE       GASOUT     TURBINE    ----
  ELECTRIC   TURBINE    ----          COMPMIX    AIRCOMPR   BOILER


 FLOWSHEET CONNECTIVITY BY BLOCKS
 --------------------------------


  BLOCK       INLETS                  OUTLETS
  BOILER      COMPMIX                 HOTGAS
  TURBINE     HOTGAS                  GASOUT ELECTRIC
  AIRCOMPR    AIR BIOGAS              COMPMIX


 COMPUTATIONAL SEQUENCE
 ----------------------
```

```
SEQUENCE USED WAS:
   AIRCOMPR BOILER TURBINE

OVERALL FLOWSHEET BALANCE
-------------------------

                    ***  MASS AND ENERGY BALANCE  ***
                           IN          OUT       GENERATION   RELATIVE DIFF.
  CONVENTIONAL COMPONENTS
          (KMOL/HR )
     METHANE             3.70158      0.555237      -3.14634     -0.599865E-16
     CO2              5.47527       8.62161       3.14634       0.00000
     WATER             0.00000       6.29268       6.29268       0.00000
     OXYGEN             18.9685       12.6758      -6.29268       0.00000
     NITROGEN            71.2365       71.2365       0.00000       0.00000
  TOTAL BALANCE
  MOLE(KMOL/HR )        99.3818       99.3818       0.00000       0.00000
  MASS(KG/HR   )        2902.90       2902.90                     0.00000
  ENTHALPY(CAL/SEC )    -161043.      -92175.3                   -0.427635

                    ***  CO2 EQUIVALENT SUMMARY ***
   FEED STREAMS CO2E             1725.55      KG/HR
   PRODUCT STREAMS CO2E          602.123      KG/HR
   NET STREAMS CO2E PRODUCTION  -1123.43      KG/HR
   UTILITIES CO2E PRODUCTION     0.00000      KG/HR
   TOTAL CO2E PRODUCTION        -1123.43      KG/HR
```

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ASPEN PLUS   PLAT: WINDOWS   VER: 35.0                 04/10/2017  PAGE 3

                       PHYSICAL PROPERTIES SECTION

COMPONENTS
----------

 ID       TYPE  ALIAS          NAME
  METHANE  C     CH4            METHANE
  CO2      C     CO2           CARBON-DIOXIDE
  WATER    C     H2O            WATER
  OXYGEN   C     O2             OXYGEN
  NITROGEN C     N2             NITROGEN

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                         U-O-S BLOCK SECTION

BLOCK:  AIRCOMPR MODEL: COMPR
-----------------------------
  INLET STREAMS:         AIR         BIOGAS
  OUTLET STREAM:         COMPMIX
  PROPERTY OPTION SET:   NRTL      RENON (NRTL) / IDEAL GAS

                   ***  MASS AND ENERGY BALANCE  ***
                                IN             OUT        RELATIVE DIFF.
   TOTAL BALANCE
      MOLE(KMOL/HR )          99.3818         99.3818         0.00000
      MASS(KG/HR   )          2902.90         2902.90         0.00000
      ENTHALPY(CAL/SEC )      -161043.        -90032.0        -0.440944

                   ***  CO2 EQUIVALENT SUMMARY ***
   FEED STREAMS CO2E           1725.55      KG/HR
```

```
 PRODUCT STREAMS CO2E          1725.55      KG/HR
 NET STREAMS CO2E PRODUCTION   0.00000      KG/HR
 UTILITIES CO2E PRODUCTION     0.00000      KG/HR
 TOTAL CO2E PRODUCTION         0.00000      KG/HR

                      ***  INPUT DATA  ***

POLYTROPIC COMPRESSOR USING ASME METHOD
 OUTLET PRESSURE  BAR                          8.00000
 POLYTROPIC EFFICIENCY                          0.72000
 MECHANICAL EFFICIENCY                          0.98000
```

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ASPEN PLUS   PLAT: WINDOWS   VER: 35.0                  04/10/2017  PAGE 5

                         U-O-S BLOCK SECTION

BLOCK:  AIRCOMPR MODEL: COMPR (CONTINUED)

                       ***  RESULTS  ***

   INDICATED  HORSEPOWER REQUIREMENT  KW                297.308
   BRAKE      HORSEPOWER REQUIREMENT  KW                303.375
   NET WORK REQUIRED                  KW                303.375
   POWER LOSSES                       KW                6.06751
   ISENTROPIC HORSEPOWER REQUIREMENT  KW                190.949
   CALCULATED OUTLET TEMP  C                            371.730
   EFFICIENCY (POLYTR/ISENTR) USED                      0.72000
   OUTLET VAPOR FRACTION                                1.00000
   HEAD DEVELOPED,       M-KGF/KG                       27,070.0
   MECHANICAL EFFICIENCY USED                           0.98000
   INLET HEAT CAPACITY RATIO                            1.38634
   INLET VOLUMETRIC FLOW RATE , L/MIN                   40,675.0
   OUTLET VOLUMETRIC FLOW RATE, L/MIN                   11,101.3
   INLET  COMPRESSIBILITY FACTOR                        1.00000
   OUTLET COMPRESSIBILITY FACTOR                        1.00000
   AV. ISENT. VOL. EXPONENT                             1.37369
   AV. ISENT. TEMP EXPONENT                             1.37369
   AV. ACTUAL VOL. EXPONENT                             1.59140
   AV. ACTUAL TEMP EXPONENT                             1.59140

BLOCK:  BOILER   MODEL: RSTOIC
------------------------------
  INLET STREAM:          COMPMIX
  OUTLET STREAM:         HOTGAS
  PROPERTY OPTION SET:   NRTL      RENON (NRTL) / IDEAL GAS
```

```
                   ***  MASS AND ENERGY BALANCE  ***
                           IN         OUT       GENERATION   RELATIVE DIFF.
  TOTAL BALANCE
  MOLE(KMOL/HR )        99.3818       99.3818       0.00000       0.00000
  MASS(KG/HR   )        2902.90       2902.90                     0.00000
  ENTHALPY(CAL/SEC )    -90032.0      -90032.0                    0.00000

                   ***  CO2 EQUIVALENT SUMMARY ***
   FEED STREAMS CO2E            1725.55      KG/HR
   PRODUCT STREAMS CO2E          602.123      KG/HR
   NET STREAMS CO2E PRODUCTION  -1123.43      KG/HR
   UTILITIES CO2E PRODUCTION     0.00000      KG/HR
   TOTAL CO2E PRODUCTION        -1123.43      KG/HR

                     ***  INPUT DATA  ***
 ASPEN PLUS   PLAT: WINDOWS   VER: 35.0                 04/10/2017  PAGE 6

                           U-O-S BLOCK SECTION

 BLOCK:  BOILER   MODEL: RSTOIC (CONTINUED)
  STOICHIOMETRY MATRIX:

   REACTION #   1:
    SUBSTREAM MIXED   :
    METHANE   -1.00    CO2       1.00    WATER     2.00    OXYGEN    -2.00



  REACTION CONVERSION SPECS: NUMBER=    1
    REACTION #   1:
    SUBSTREAM:MIXED    KEY COMP:METHANE  CONV FRAC: 0.8500
```

```
TWO    PHASE  PQ  FLASH
PRESSURE DROP         BAR                              0.0
SPECIFIED HEAT DUTY   CAL/SEC                          0.0
MAXIMUM NO. ITERATIONS                                 30
CONVERGENCE TOLERANCE                                  0.000100000
SIMULTANEOUS REACTIONS
GENERATE COMBUSTION REACTIONS FOR FEED SPECIES          NO

                    ***  RESULTS  ***
OUTLET TEMPERATURE    C                                1086.0
OUTLET PRESSURE       BAR                              8.0000
VAPOR FRACTION                                         1.0000



REACTION EXTENTS:

  REACTION         REACTION
  NUMBER           EXTENT
                   KMOL/HR
  1                3.1463

V-L PHASE EQUILIBRIUM :

  COMP          F(I)          X(I)          Y(I)          K(I)
  METHANE       0.55869E-02   0.21641E-04   0.55869E-02   816.28
  CO2           0.86752E-01   0.15029E-02   0.86752E-01   1816.3
  WATER         0.63318E-01   0.99710       0.63318E-01   1324.3
  OXYGEN        0.12755       0.24325E-03   0.12755       997.53
  NITROGEN      0.71680       0.11335E-02   0.71680       850.85
```

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ASPEN PLUS   PLAT: WINDOWS   VER: 35.0                 04/10/2017  PAGE 7


                         U-O-S BLOCK SECTION


BLOCK:  TURBINE  MODEL: COMPR
-----------------------------
  INLET STREAM:          HOTGAS
  OUTLET STREAM:         GASOUT
  OUTLET WORK STREAM:    ELECTRIC
  PROPERTY OPTION SET:   NRTL      RENON (NRTL) / IDEAL GAS


                  ***  MASS AND ENERGY BALANCE  ***
                              IN           OUT       RELATIVE DIFF.
   TOTAL BALANCE
      MOLE(KMOL/HR )          99.3818      99.3818      0.00000
      MASS(KG/HR   )          2902.90      2902.90      0.00000
      ENTHALPY(CAL/SEC )      -90032.0     -92175.3     0.232526E-01


                  ***  CO2 EQUIVALENT SUMMARY ***
   FEED STREAMS CO2E            602.123      KG/HR
   PRODUCT STREAMS CO2E         602.123      KG/HR
   NET STREAMS CO2E PRODUCTION   0.00000     KG/HR
   UTILITIES CO2E PRODUCTION     0.00000     KG/HR
   TOTAL CO2E PRODUCTION         0.00000     KG/HR


                      ***  INPUT DATA  ***


  ISENTROPIC TURBINE
   OUTLET PRESSURE  BAR                       1.10000
   ISENTROPIC EFFICIENCY                      0.90000
   MECHANICAL EFFICIENCY                      0.98000
```

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                        U-O-S BLOCK SECTION

BLOCK:  TURBINE  MODEL: COMPR (CONTINUED)

                       ***  RESULTS  ***

   INDICATED  HORSEPOWER REQUIREMENT  KW                -448.681
   BRAKE      HORSEPOWER REQUIREMENT  KW                -439.708
   NET WORK REQUIRED                  KW                -439.708
   POWER LOSSES                       KW                   8.97362
   ISENTROPIC HORSEPOWER REQUIREMENT  KW                -498.535
   CALCULATED OUTLET TEMP  C                             639.726
   ISENTROPIC TEMPERATURE  C                             587.792
   EFFICIENCY (POLYTR/ISENTR) USED                         0.90000
   OUTLET VAPOR FRACTION                                   1.00000
   HEAD DEVELOPED,       M-KGF/KG                    -63,044.2
   MECHANICAL EFFICIENCY USED                              0.98000
   INLET HEAT CAPACITY RATIO                               1.28405
   INLET VOLUMETRIC FLOW RATE , L/MIN                  23,397.8
   OUTLET VOLUMETRIC FLOW RATE, L/MIN                 114,288.
   INLET  COMPRESSIBILITY FACTOR                           1.00000
   OUTLET COMPRESSIBILITY FACTOR                           1.00000
   AV. ISENT. VOL. EXPONENT                                1.29893
   AV. ISENT. TEMP EXPONENT                                1.29893
   AV. ACTUAL VOL. EXPONENT                                1.25096
   AV. ACTUAL TEMP EXPONENT                                1.25096
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                         STREAM SECTION


AIR BIOGAS COMPMIX GASOUT HOTGAS
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STREAM ID              AIR       BIOGAS     COMPMIX    GASOUT     HOTGAS
FROM :                 ----      ----       AIRCOMPR   TURBINE    BOILER
TO   :               AIRCOMPR   AIRCOMPR   BOILER     ----       TURBINE


SUBSTREAM: MIXED
PHASE:                 VAPOR      VAPOR      VAPOR      VAPOR      VAPOR
COMPONENTS: KMOL/HR
  METHANE                0.0        3.7016     3.7016     0.5552     0.5552
  CO2                 1.1993     4.2760     5.4753     8.6216     8.6216
  WATER                 0.0        0.0        0.0        6.2927     6.2927
  OXYGEN               18.9685     0.0       18.9685    12.6758    12.6758
  NITROGEN             70.6535     0.5830    71.2365    71.2365    71.2365
TOTAL FLOW:
  KMOL/HR              90.8213     8.5605    99.3818    99.3818    99.3818
  KG/HR              2639.0004   263.9000  2902.9004  2902.9004  2902.9004
  L/MIN             3.7042+04  3608.5261  1.1101+04  1.1429+05  2.3398+04
STATE VARIABLES:
  TEMP   C             25.0000    35.0000   371.7302   639.7255  1086.0478
  PRES   BAR            1.0130     1.0130     8.0000     1.1000     8.0000
  VFRAC                 1.0000     1.0000     1.0000     1.0000     1.0000
  LFRAC                 0.0        0.0        0.0        0.0        0.0
  SFRAC                 0.0        0.0        0.0        0.0        0.0
ENTHALPY:
  CAL/MOL             -1241.0975 -5.4557+04 -3261.3105 -7143.2712 -3261.3105
  CAL/GM                -42.7124 -1769.7447  -111.6521  -244.5525  -111.6521
  CAL/SEC             -3.1311+04 -1.2973+05 -9.0032+04 -1.9720+05 -9.0032+04
```

```
ENTROPY:
  CAL/MOL-K            1.1605    -5.9220     2.5865     9.4963     9.0099
  CAL/GM-K          3.9940-02    -0.1921  8.8549-02     0.3251     0.3085
DENSITY:
  MOL/CC           4.0865-05  3.9538-05  1.4921-04  1.4493-05  7.0791-05
  GM/CC            1.1874-03  1.2189-03  4.3582-03  4.2333-04  2.0678-03
AVG MW               29.0571    30.8275    29.2096    29.2096    29.2096

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                              STREAM SECTION

ELECTRIC
--------

STREAM ID               ELECTRIC
FROM :                  TURBINE
TO   :                  ----
CLASS:                  WORK

STREAM ATTRIBUTES:
WORK
P        KW           -439.7076

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                           PROBLEM STATUS SECTION

BLOCK STATUS
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***************************************************************************
*                                                                         *
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* Calculations were completed normally                *
*                                                     *
* All Unit Operation blocks were completed normally   *
*                                                     *
* All streams were flashed normally                   *
*                                                     *
***********************************************************************
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