# A FEASIBILITY STUDY OF UTILIZING BIOMASS AT CORNELL'S COMBINED HEAT AND POWER PLANT AS A MEANS OF FURTHER REDUCING CAMPUS GREENHOUSE GAS EMISSIONS

**A Project Report**
**Presented to the Faculty of the Graduate School**
**of Cornell University**
**in Partial Fulfillment of the Requirements for the Degree of**
**Master of Engineering**

**by**
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# 1. EXECUTIVE SUMMARY

Biomass is the largest source of renewable energy in the United States, according to the US Energy Information Administration. Cornell University is fortunate to be located close to some of the most productive farmland in the country, and can possibly take advantage of its Farm Services Operation as a means of producing energy either as electricity or steam for its Ithaca Campus. The potential of using willow grown on Cornell-owned marginal farmland, along with the use of the compost waste stream on campus, to meet Cornell's energy demand will be explored in this report. Cornell has issued a Climate Action Plan to focus on reducing Greenhouse Gas Emissions by 2035 and one alternative is through the use of biomass. Currently, Cornell's Climate Action Plan considers the possibility of utilizing biomass in various ways such as direct combustion, pyrolysis, and generation of a biogas. Direct combustion has the greatest potential at producing the most energy from biomass. Cornell could produce willow wood chips on it's marginal farmlands and use these willow chips in Boiler #8, which is capable of combusting a solid fuel, to produce steam for campus. Another way to utilize biomass on campus is to divert the stream of food waste and other organic matter that is currently being composted, to biogas production. Cornell's compost operations are currently only producing a soil amendment, however it may be more economical and beneficial for the environment to produce energy to meet campus electricity load, especially during peak periods. The compost stream from the Ithaca campus will be analyzed for potential of conversion to biogas fuel that could be used to generate electricity to further meet the campus electricity demand with a renewable source of energy.

The direct combustion of willow grown on Cornell's marginal farmland has been analyzed for potential to meet a reasonable amount of campus heating load. This analysis has determined that the use of biomass to replace natural gas in Boiler #8 at the Combined Heat and Power Plant would not be economical currently, due to the current low cost of natural gas when compared to biomass even though this operation would have the potential at significantly reducing campus greenhouse gas emissions. Cornell's marginal farmland would not be able to sustain a large crop of willow, and could only provide 4,275 MMBTUs/year whereas the demand for Boiler #8 calls for 1,005,967 MMBTUs/year. In the near future, as prices stabilize for natural gas and carbon maybe more strictly regulated, it is possible to mobilize the local community in transforming unused farmland in Tompkins County to growing biomass crops such as willow for Cornell's heating plant. This would have the potential of creating various social benefits such as jobs and economic activity in upstate NY, where unemployment is a concern.

The compost to biogas operations will be more economical in terms of a greater Net Present Value (NPV) as well as a great Internal Rate of Return (IRR) provided that grants from state agencies such as NYSERDA and federal tax credits can help offset the majority of the initial capital costs for the project.

## 2. INTRODUCTION

Cornell University is currently exploring many ways of meeting its meet its goal of carbon neutrality by 2035 as President David Skorton decided to speed up the goal of the university reaching carbon neutrality from the original goal date from 2050 (Friedlander, 2015). One of the most significant actions undertaken by the university was to significantly cut carbon dioxide emissions by switching from using coal to natural gas at its Combined Heat and Power Plant in 2011 (Cornell Energy Resources). Cornell University has undertaken many renewable energy projects since its founding, starting with the hydroelectric plant powering the first electric lights on campus, to the most recent geothermal-powered Lake Source Cooling system and photovoltaic solar array located off-campus. Recently the campus has committed to purchase electricity produced by wind turbines located off-campus. Cornell has detailed a picture of its potential renewable energy infrastructure in its Climate Action Report looking well into the future, shown in Figure 1.

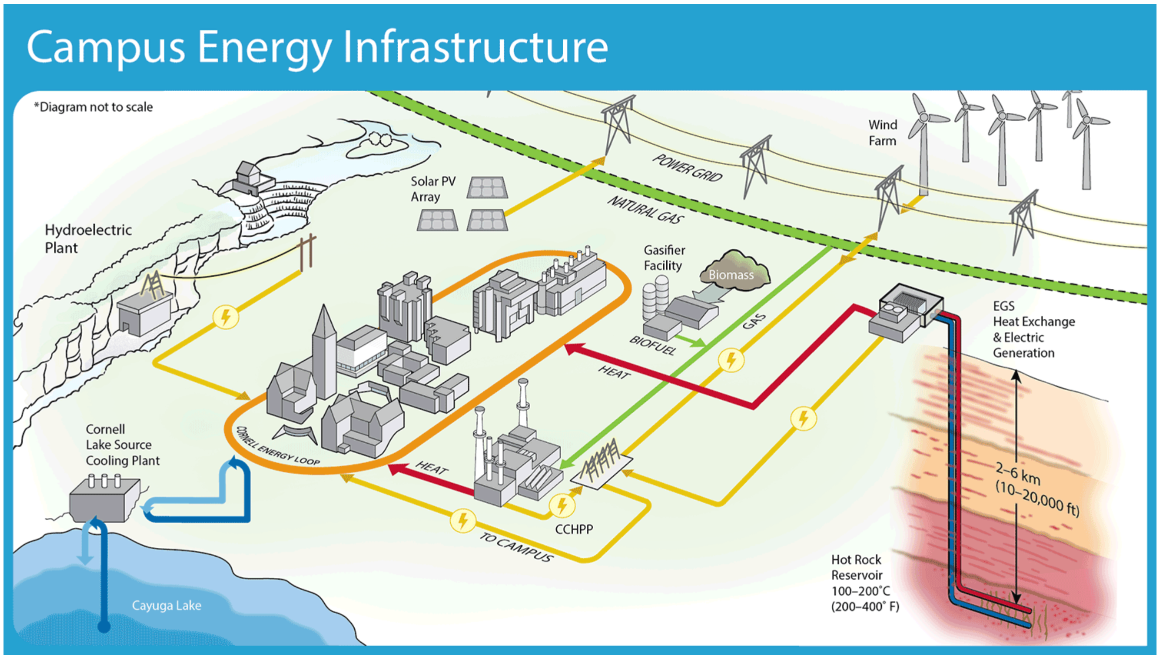
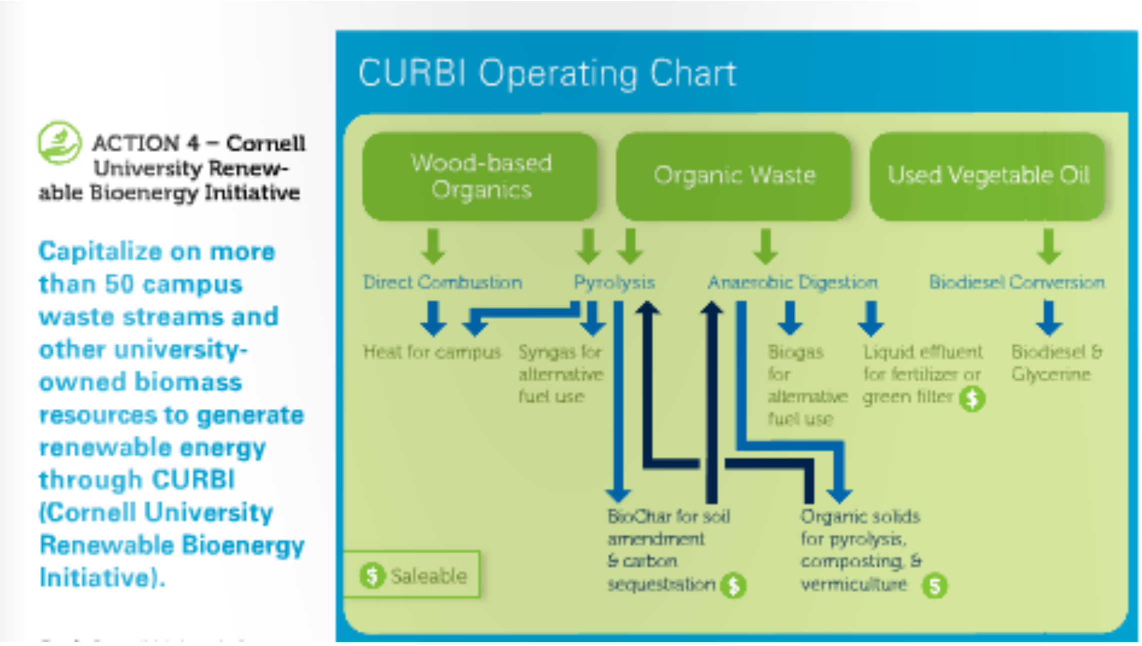


**Figure 1:** Proposed Campus Energy Infrastructure (included is the uncertain state of biomass operations) (2013 Climate Action Plan)

In the future, Cornell University hopes to build an enhanced geothermal system to produce some electricity and steam for the campus electricity and heating loads to help supplement other renewable energy sources, such as wind, hydro, and solar. One area that Cornell's Climate Action Plan highlights is the potential of utilizing biomass in producing electricity and steam for the campus, however very little progress has been made in determining the ways in which biomass could be specifically applied to meet this goal. This report will explore the potential of using locally available biomass in producing electricity and steam in two distinct forms: direct combustion and anaerobic digestion to form a biogas. Such operations are mentioned with very little detail in the Cornell Campus Climate Action Plan, shown in Figure 2.



ACTION 4 – Cornell University Renewable Bioenergy Initiative

Capitalize on more than 50 campus waste streams and other university-owned biomass resources to generate renewable energy through CURBI (Cornell University Renewable Bioenergy Initiative).

**Figure 2:** Explanation of Utilizing Biomass in Cornell's Climate Action Plan (2013 Climate Action Plan)

This report will focus on exploring ways in which biomass could be used as a renewable energy source to decrease greenhouse gas emissions for Cornell. Cornell could use direct combustion, pyrolysis, anaerobic digestion, or biodiesel conversion in an effort to convert biomass to energy. Biodiesel is a very inefficient way to generate energy for campus, as the majority of the feedstock is lost in the energy-intensive conversion process, and its impacts on food prices are debatable. Pyrolysis can be utilized for biomass to energy conversion, however the technology is still costly and being refined, as limitations become evident when the technology is adapted to large-scale power plants.

Direct combustion can provide the greatest amount of energy conversion. Anaerobic digestion is currently developed and refined on both the small and large scales, ranging anywhere from a farm digester to a digester that supplies methane to a power plant. Cornell could utilize both solid fuels and gas at its energy plant. For this reason, both direct combustion and anaerobic digestion will be explored in this project. One way to utilize biomass is determine whether growing willow shrubs on Cornell's marginal farmland is an efficient source of fuel for one of Cornell's boilers at the power plant (Boiler #8), which could still utilize a solid fuel such as coal or biomass. The willow has been converted to a pellet type fuel and combusted directly in the boiler with the sufficient amount of air required for combustion to produce steam. An estimated 10 percent of farmland that is Cornell-owned is marginal, according to Cornell's Real Estate Division (Dean et. al 2014). Such underutilized farmland could sustain the growth of willow, in addition to creating a riparian buffer along the perimeter of the agriculture land. Calculations are considered to determine the potential yields of growing biomass on Cornell's marginal farmlands along with the logistics of such an operation. In addition, the energy content of the willow yields are compared to the needs of Boiler #8 to determine whether the partial or entire needs of the boiler has been met throughout the year. Furthermore, natural gas and willow are compared on the basis of cost and greenhouse gas emissions.

Also included is an analysis of using the existing compost loads generated daily on campus, to produce biogas from the compost in an anaerobic digester. Monthly energy production variations due to changes in compost production are studied along with the economics and feasibility of developing such an operation on land currently available next to the Combined Heat and Power Plant.

## 3. OBJECTIVE

The overall objective of this project is the assessment of the potential use of biomass for energy production at Cornell University. The economic and environmental analysis conducted in this report focuses on two primary applications: the use of organic waste streams on campus to generate a biogas to be transformed to electricity by the use of a fuel cell, and the use of willow chips produced on Cornell-owned marginal farmland to fuel Boiler #8 at the Combined Heat and Power Plant.

## 4. LITERATURE REVIEW

The focus of this literature review is to present the rationale for conducting research on bioenergy systems and exploring the benefits such systems could provide to a concentrated area such as a research university like Cornell. The goal of this project was to apply two bioenergy systems to partially meet the campus energy load. Turning compost into a biogas to produce electricity and the use of willow pellets to generate steam were analyzed in this review for each bioenergy feedstock's role in reducing campus greenhouse gas emissions. The following review of the literature showcases the literature that was most relevant to my research and project, organized into four categories: (4.1) Bioenergy as a Successful Renewable Energy Source, (4.2) Bioenergy (Wood Pellets) on College Campuses, (4.3) Compost as an Energy Source, and (4.4) Greenhouse Gas Reductions of Using Compost and Willow.

## 4.1 Bioenergy as a Successful Renewable Energy Source

Cornell's Climate Action Plan exhibits a major flaw in that several options are specified for utilizing biomass as an energy source, however there is no specified plan for using biomass in the current campus energy distribution system. Several considerations must be taken into account to ensure that bioenergy projects are successful when tied to the grid. *Carlos et al* (2009) elaborate on the crucial steps that must be taken to explore criteria and factors in each specific bioenergy project. Politics and legislation are significant motivators to bioenergy projects such as the NYSERDA grants for various bioenergy projects available here in New York State. Although the planning aspects of the bioenergy projects were important, being able to secure grants will provide greater success for bioenergy projects.

## 4.2 Bioenergy (Wood Pellets) on College Campuses

College campuses across the world are looking for ways to reduce their energy costs as fossil fuel prices are projected to increase into the future. *Meehan et al* (2010) explores sustainable alternatives in biomass feed stocks grown locally for campus energy systems to reduce both costs and greenhouse gas emissions. Specifically, boilers are only included in this study which would utilize pellets in direct combustion at the University College Dublin. This study ignores other means of utilizing biomass such as anaerobic digestion, which has potential at producing biogas from wastes that contain high moisture contents. *Meehan et al* (2010) seem to project their study in the direction that many other college campuses have followed, in terms of utilizing biomass for heat production, through direct combustion. Organic waste streams developed on campus seem to be missing in the study, and will be explored extensively throughout this project, in the production of biogas from compost through anaerobic digestion. Cornell produces significant amounts of organic wastes each day, and as a result these waste streams will be analyzed for potential biogas and electricity production feasibility.

### 4.3 Compost as an Energy Source

Compost could be turned into energy through the production of a biogas by the use of an anaerobic digester. Rajendran *et al* (2012) provide biogas yields for various feed stocks and is the basis on which the FOV Biogas calculator was created with research that occurred at the University of Borås in Sweden. The design and operation of biogas digesters takes place in this paper, and different parameters such as pH, temperature, substrate and loading rates are discussed. Several applications of bioreactors along with governmental policies are also taken into consideration for this paper. Government intervention in bioenergy products seems to be of crucial importance, especially in terms of rebates and grants that help alleviate the initial capital costs, as can been seen in a more broader sense in *Carlos et al* (2009). FOV Biogas, the company that manufactures the system analyzed in this feasibility study, takes into account design parameters specified in this literature source. A design calculator for optimizing an anaerobic digester was discovered through FOV Biogas, and specifies many of the parameters discussed in this paper. The economics model mentioned in the paper incorporated the Net Present Value analysis and was useful in developing the framework for the economics model in this feasibility study. The useful results of this report were providing a framework of using an anaerobic digester to create biogas and how basic parameters, which are incorporated in such a system, could be determined. Rajendran *et al* (2012) does not take into account specific greenhouse gas reductions for utilizing organic wastes to generate a biogas over strictly composting organic wastes.

## 4.4 Greenhouse Gas Reductions of Using Compost and Willow

Brown *et al.* (2008) analyzed the impact that composting has on greenhouse gas emissions, especially those of carbon dioxide and methane. The primary goal of composting is methane avoidance over the use of landfills, since composting theoretically releases only carbon dioxide. Field and lab incubations are utilized to study the methane and carbon dioxide generation potential that result from compost operations, where the methane and carbon dioxide are collected in lab conditions and the results are scaled to the actual size of the system from which samples were taken.

The useful results in this report are the unit rates by which it is possible to calculate total carbon dioxide emissions that result from a certain mass of compost feedstock that is placed in a windrow compost system. A weighted average of unit rates was taken into account to determine the yearly carbon dioxide emissions that occur from the compost system that Cornell currently utilizes. One flaw with the research is that it assumes that the matter will aerobically decompose and only convert into carbon dioxide emissions. Other greenhouse gasses could form since the pile would have to be aerated consistently to ensure that only carbon dioxide is formed. Without the presence of oxygen, other gases such as methane can form and methane is far more potent as a greenhouse gas than carbon dioxide. In addition to the greenhouse gas reductions for composting, it is also possible to determine the reductions for utilizing willow over natural gas in the literature.

*Styles et al* (2008) used a life cycle analysis to determine the greenhouse gas reductions that could occur by utilizing locally grown willow in domestic and industrial heating applications. In Ireland, willow pellets produce about 0.045 kg of carbon dioxide per kWh, compared to natural gas, which produces about 0.248 kg of carbon dioxide per kWh (Styles et. al 2008).

## 4.5 Summary

According to the literature review, bioenergy has many applications, depending on the specific area to which the energy project will be developed. For the purposes of this project, two of the most available bioenergy feed stocks were chosen: organic wastes which are abundant on campus and willow pellets which could potentially be grown on Cornell-owned or nearby underutilized farmland. According to *Carlos et al* (2009), government policies and legislation is of crucial importance when making decisions on bioenergy projects. New York State provides grants and rebates for various bioenergy projects through NYSERDA, which can help make the project more feasible economically. *Meehan et al* (2010) analyze bioenergy projects on college campuses, specifically the University College Dublin utilizing wood pellets for meeting campus heating loads. Organic wastes generated on almost all college campuses are not taken into account to determine feasibility in using these wastes for energy production. As a result, the organic wastes generated at Cornell will be studied in this project. The feasibility of turning organic wastes into biogas and electricity through anaerobic digestion will be studied, and if sensible these methods could be adapted to other college campuses. Furthermore, specific values for calculating biogas yields were determined through

Rajendran *et al* (2012), which provides biogas yields for various feed stocks and an economic NPV model for which the feasibility of anaerobic digesters could be determined. Brown *et al.* (2008) analyzed the impact that composting has on greenhouse gas emissions and *Styles et al* (2008) provided an idea of the greenhouse gas reductions that could occur by utilizing locally grown willow in domestic and industrial heating applications.

# 5. CORNELL CHP PLANT

Cornell's Combined Heat and Power (CHP) Plant has a long history of ensuring that the campus' entire heating load, and a portion of the required electricity, are provided in an economical and reliable manner. In this section, we provide background on the CHP plant. A schematic of the CHP is given in Figure 3. For this purposes of this project, we considered Boiler #8, currently mothballed and not listed in the figure, for the direct combustion of biomass. Details about Boiler #8 are provided in Section 5.1. Boiler #8 will be used for the direct combustion of biomass, as it is currently the only boiler present at the CHP plant that can use a solid fuel for the production of steam. In Section 5.2, the Biogas Production Facility is discussed.

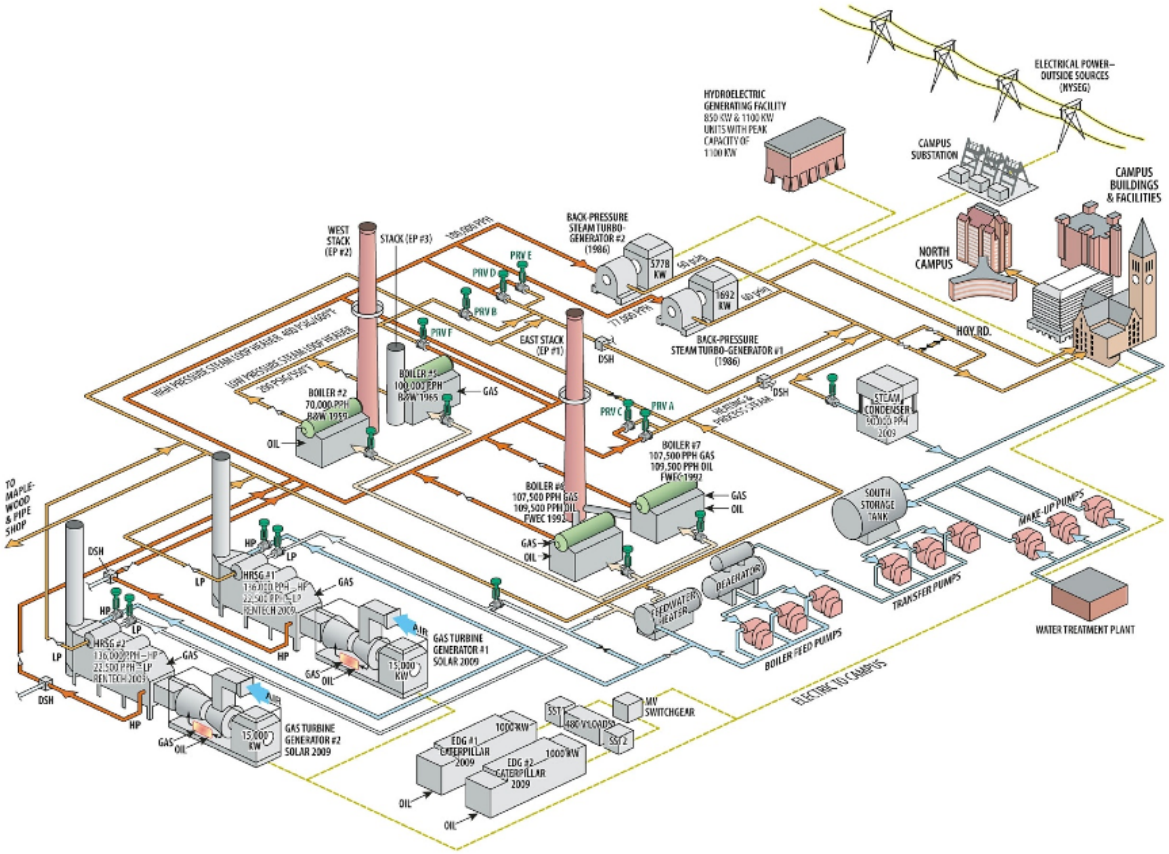


**Figure 3:** The overall layout of the Cornell Combined Heat and Power Plant, including the two natural gas turbines with heat recovery steam generators (that produce both electricity and steam) along with the boilers (that produce only steam). (Cornell Energy Resources Guide)

## 5.1 Boiler #8

In order to explore potential repurposing of Boiler #8 and to determine the feasibility of growing enough willow to supply its demand for fuel, the amount of energy consumed in a year by the boiler is estimated. This number is compared to the amount of energy that could be obtained the willow grown on Cornell's marginal farmland. If a deficit occurs, the amount of willow that is required to be purchased on the open market is determined. These preliminary calculations were done to determine whether it is possible to grow enough biomass on Cornell's marginal farmlands to meet the yearly demand of this specific boiler.

## 5.2 Biogas Production Facility

Another goal of the project was to determine whether or not the compost produced on campus could be converted into a biogas that would power either one or more fuel cells. Currently, the Cornell CHPP sits near a parcel of land that used to house a very large coal pile for use at the heating plant. Currently, the space is underutilized, as can be seen in Figure 4, and there is potential of constructing a biogas production facility from the compost loads on campus. The feasibility of such an operation is explored later in the report.

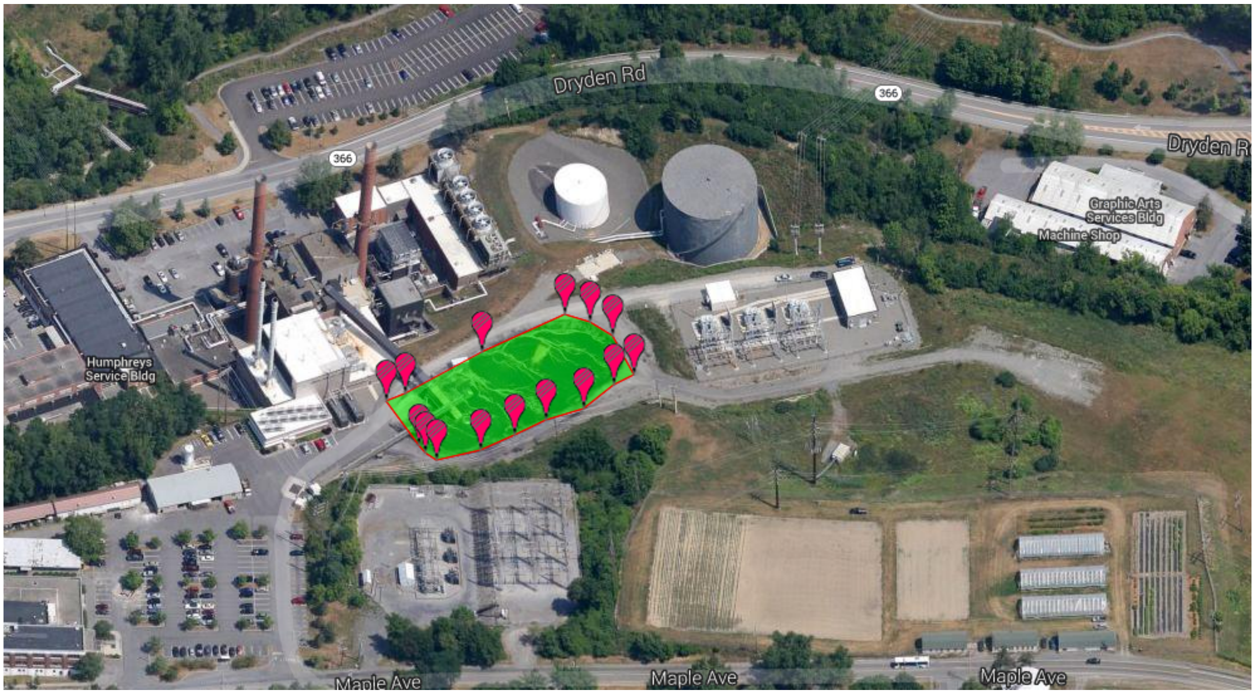


**Figure 4:** The land area, which contained the former coal pile, that is no longer used by the CHPP and could potentially be used to construct a Biogas Production Facility. (Google Maps)

## 6. RESULTS: WILLOW PELLET OPERATIONS IN BOILER #8

The Cornell CHPP has retired all of its coal boilers, aside from Boiler #8, after the construction of the new Cornell Combined Heat and Power Plant was completed. The new CHPP utilizes natural gas in two gas turbines to produce steam and electricity for campus. Boiler #8, seen in Figure 5, has been mothballed due to uncertainties in load growth, prices, and projects in the future. In addition to being able to burn coal, Boiler #8 has the capability to utilize a solid biomass fuel to produce steam to meet campus heating demand.

**Figure 5:** The mothballed Boiler #8, which has a hopper nearby which could be fed a solid fuel such as coal or biomass directly without any major conversions.

Cornell also has a large amount of farmland in its research operations and there are estimates that about ten percent is currently marginal, or unutilized. Willow shrubs are an efficient form of biomass that could be grown quickly on this underutilized space and provide benefits such as a riparian buffer to local streams as well as a means of lessening soil erosion on farm fields. In order to determine the quantity of willow that Cornell could grow on its research farmland, the total number of acres owned by Cornell was determined through Cornell's Real Estate Department. Cornell has approximately 2,200 acres of farmland, of which about 10%, are marginal (Dean et. al 2014). Willow requires about four years growth to first harvest after planting, and then takes three years to grow for future harvests (Willowpedia 2015). Therefore, to ensure a steady supply of willow each year after the first harvest, analysis divided marginal farmland into three equally spaced plots, comprising of 73 acres per plot. Based on a dry energy value, about 78,000,000 BTUs can be generated per acre of willow pellets (Willowpedia 2015). Based on the land area available in each of the plots, Cornell could obtain about 5712 MMBTUs per year from the willow grown in each respective plot. Based on the estimate of about five dry tons being available per acre of willow grown (Heavey et. al), and the energy needed to dry willow will be about 1175 kWh per dry ton (Świgoń et. al 2005) it is estimated that the energy needed to dry willow will be about 1323 MMBTUs per year. In addition, 2% of the energy generated from the combustion of willow will be utilized as energy required for operating the emissions control system that would remove particulates as well as oxides of nitrogen and sulfur that could contribute to acid rain (Policy Implications 1992).

Accounting for the processes of drying and emissions control, it is estimated that the total energy available from willow has been approximately 4,275 MMBTUs per year. The available willow from Cornell's marginal farmlands has been insufficient to meet the energy demands for Boiler #8 at Cornell's heating plant, which has an energy demand that is over one million MMBTUs/year. To cover the shortfall, 58,000 dry tons of willow could be purchased by Cornell's heating plant to meet yearly heating demand. At an average price of about $6.00 per MMBTU (Biomass 2007), the cost has been about $6 million for using willow in Boiler #8 per year.

Recently, the price of natural gas has dropped significantly and Cornell Facilities is purchasing natural gas at a contract price of $4.54 per MMBTU, bringing the cost of using natural gas in the boiler to be about $4.5 million per year. The price difference between potentially using willow over natural gas is about $1.5 million dollars and therefore, from a purely economic perspective the use of willow as an alternative to natural gas is not viable. In this analysis it was assumed that the operating costs, such as emissions control, has been managed through the existing bag house system along with the current sulfur and nitrogen oxide reduction system, and therefore these were not included in the cost analysis.  This cost excludes the ash disposal costs necessary for utilizing biomass, as the ash content is significant, even at about 3% of the original dry mass of willow feedstock (Willowpedia 2015). Based on the number of dry tons of willow required, the ash content has been on the order of 1700 tons. The local cost of solid waste disposal is $85 per ton in the Ithaca, which would equate to an extra operating cost of about $150,000 per year (Permits and Fees).

| Fuel | Cost per year (without inflation) |
|---|---|
| Willow | $6,000,000 |
| Natural Gas | $4,600,000 |
| Price Differential | $1,400,000 |

**Table 1:** The differences in price of using willow and natural gas in Boiler #8 at the heating plant.

## 6.1 Biomass Growing Operations

Currently, Cornell has about 2,200 acres of farmland devoted to research operations, and about 10% of this land has been considered marginal or underutilized (Dean et. al 2014). Therefore, 220 acres will be assumed to be available for planting willow crops (Appendix A-10). Willow has an initial growing period of 4 years, before first harvest, and can subsequently be harvested every 3 years (Willowpedia 2015). In order to provide a steady supply for Cornell's Boiler #8 at the CHPP plant, it was assumed that the 220 acres has been divided up into three equal parcels, so that each year one harvest could occur after the initial growing phase. Each parcel would contain 73 acres of land. Inputs of fertilizer use of about 45.3 kilograms of nitrogen per acre of willow per year (Abrhamson et. al 2010) are assumed for greenhouse gas emissions calculations in addition to the necessary energy inputs for drying, and transportation on both the farm and to the CHP plant. It was assumed that the costs of purchasing such equipment have been negligible as these farms are utilized for research. Cornell also operates an experimental biomass drying facility at the Geneva, NY research facility. Each, year accounting for energy losses in both energy needed to dry willow and from the emissions control system for combustion, the amount of energy that willow could potentially provide has been 4,275 MMBTUs as can be evidenced in Appendix A-10. Therefore, there is a deficit of 100,1692 MMBTUs per year to supply Boiler #8. To provide stable feedstock for the boiler, 13,000 additional acres are required to grow willow, and there is possibility of that amount of underutilized farmland to be available locally within Tompkins County on privately owned farmland (Marx 2013).

## 7. RESULTS: BIOGAS FACILITY OPERATIONS

Another step that Cornell could take toward use of biomass to supply energy needs on the Ithaca campus is through the use of the compost and organic waste streams to produce a biogas as seen in Figure 6. This biogas could be created through the process of anaerobic digestion, instead of composting the waste in windrows to be used as a soil amendment on campus, as is current practice. Cornell currently composts an average of about 536 metric tons of waste per month, or about 18 metric tons per day. These organic waste streams are quite significant and should therefore contribute to energy production while alleviating greenhouse gas emissions on campus through the use as a renewable source of electricity. For the purposes of this report, the biogas produced will be combusted in a Bloom fuel cell to produce electricity.

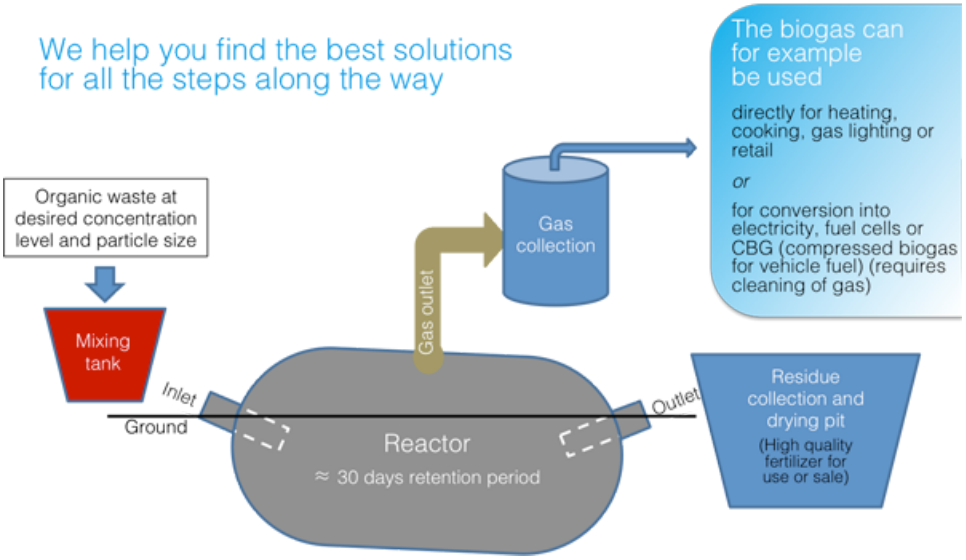
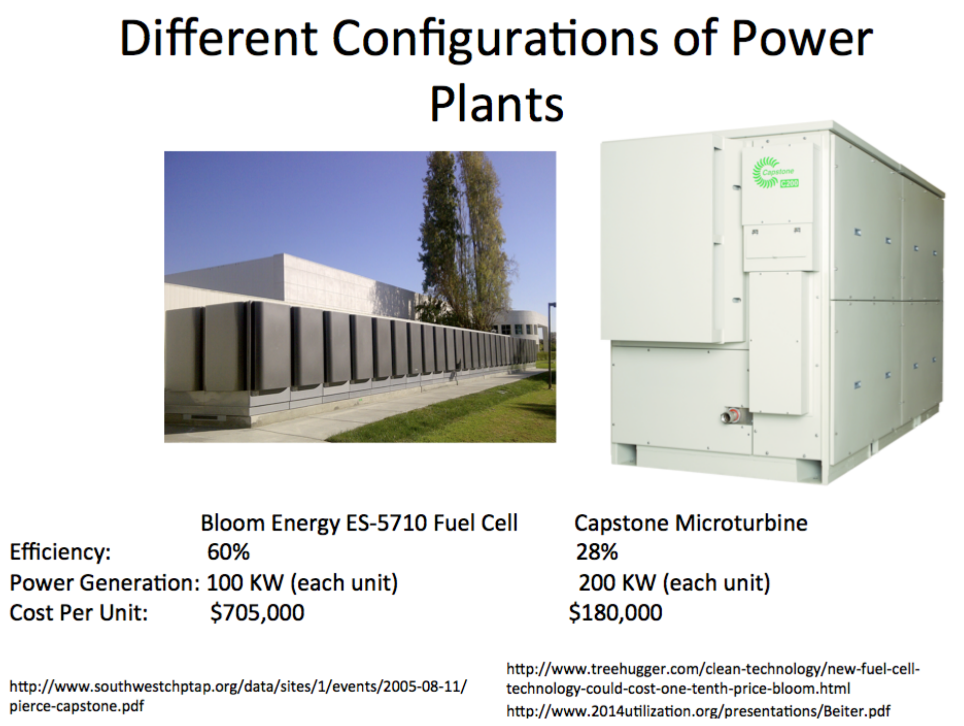


**Figure 6:** A simplistic view of the Biogas Operations, with the reactor (anaerobic digester) in the middle (Source: FOV Biogas)

## 7.1 Fuel Cells & Facility

Initially, the use of a Capstone Microturbine was thought to be an ideal method of converting the biogas into electricity, however it was determined early that such a micro turbine has an efficiency of about 28% (Capstone 2014) and with upfront costs of $180,000 for a 200 kW unit (Pierce 2005). The Bloom Fuel Cells have an efficiency of 60% (LaMonica 2014), when converting the energy stored in biogas to electricity and cost about $705,000 for a 100 kW unit (Treacy 2013). A comparison of both models can be seen in Figure 7, and the rationale for choosing the Bloom Fuel Cells will be explained later in this section.

For this project 4 – 100kW units have been necessary in order to keep up with the biogas production rate during peak months. While the cost of a Bloom fuel cell is significant currently, it is predicted that prices will be decrease to about 1/10th of the current cost within the next several years as companies such as GE or startups such as Redox Power Systems begin to dominate the market (Treacy 2013). In addition, Capstone turbines are known to exhibit issues of corrosion as well as shorter life spans when used in biogas operations, even if the biogas is cleaned before combustion. As a result, the Capstone turbines have an estimated lifespan of 10 years, however with biogas the estimated lifespan drops to approximately two to three years. The Bloom Fuel cells are rated to last ten years even when subjected to the conditions of biogas. There are several sources of funding that could be used to defray the large investment costs of the Bloom Fuel Cells. For example, NYSERDA currently provides major grants for the use of biomass to produce electricity. Under NYSERDA funding, there are several $2 million dollar grants available for projects such as these (PON 2828). In addition, there are several research grants available for large-scale biomass operations through NYSERDA. This project could qualify for these grants, in addition to a 30 % federal tax credit that is typically awarded to either residential homeowners or commercial entities. (Federal Tax Credits) To house the anaerobic digester, the equipment necessary for cleaning the gas, and the micro turbines a facility would have to be built on the former coal pile, co-located on land that is currently of no use to the Cornell Combined Heat and Power Plant.



Different Configurations of Power Plants

| | Bloom Energy ES-5710 Fuel Cell | Capstone Microturbine |
|---|---|---|
| Efficiency: | 60% | 28% |
| Power Generation: | 100 KW (each unit) | 200 KW (each unit) |
| Cost Per Unit: | $705,000 | $180,000 |

http://www.southwestchptap.org/data/sites/1/events/2005-08-11/pierce-capstone.pdf

http://www.treehugger.com/clean-technology/new-fuel-cell-technology-could-cost-one-tenth-price-bloom.html
http://www.2014utilization.org/presentations/Beiter.pdf

**Figure 7:** The different configurations of power plants that were explored in determining the ideal way to combust the biogas to produce electricity.

## 7.2 Compost Stream

Cornell Farm Services is responsible for the collection of organic waste from Cornell's dining halls and other residential facilities, farm operations, veterinary college, and greenhouses. Cornell's Ithaca campus is significantly large enough and is located in a rural region that produces a waste stream that makes it ideal for an anaerobic digestion plant located near the Combined Heat and Power Plant. The data for the compost operations is shown in Appendix A-1 and shows that Cornell currently composts an average of about 6,400 metric tons per year. Currently this compost stream is taken to the Farm Services Composting Facility located about 2.8 miles from central campus, where it is placed in windrows and turned over several times a week to ensure that the pile is able to undergo a complete compost cycle.

## 7.3 Anaerobic Digester

The anaerobic digester that will allow anaerobic bacteria to be sustained along with the organic waste will be bladder-like and be constructed of a proprietary textile and polymer fabric developed by FOV Fabrics and FOV Biogas in Sweden, similar to that of an air bag developed for cars. The digester can be seen in Figures 8 and 9. The material is low cost, durable, lightweight, foldable, flexible, highly resistant to high temperature, and has an estimated life span of about 10 years. (FOV Biogas) The reactor was sized to be approximately 5,000 cubic meters, and therefore the entire cost of such an anaerobic digester and the necessary equipment for feeding the digester and cleaning the biogas, has been approximately $500,000 according to a sample business case obtained on the FOV Biogas website (Business Cases 2015).

The anaerobic digester and associated equipment will require a cover structure on the area of the former coal pile of about 150 meters by 70 meters by 5 meters and the structure is estimated to cost approximately $300,000. The purpose of the structure is to protect the equipment, shown in Figure 8, in addition to the Bloom fuel cells, from climate effects. The land costs for the project are considered negligible as Cornell already owns the land and it is currently underutilized.

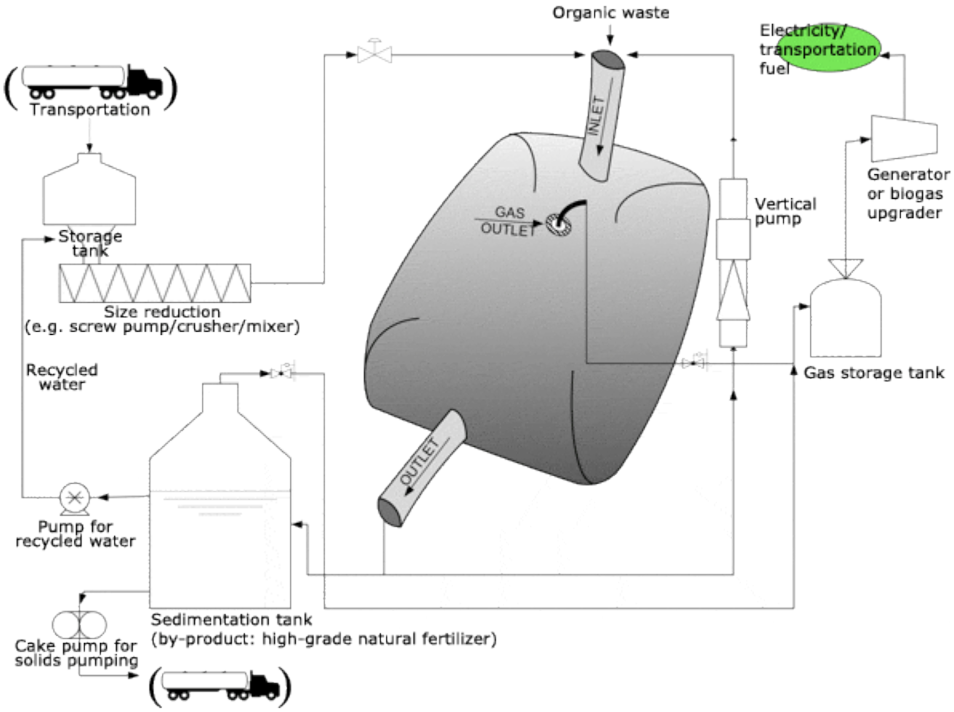


**Figure 8:** The entire system by which an FOV Biogas anaerobic digester operates by, including the feedstock handling and the biogas upgrader along with electricity production (Source: FOV Biogas)

**Figure 9:** Multiple views of the bladder-like material that is used to produce a FOV Biogas anaerobic digester (Source: FOV Biogas)

### 7.4 Compost Collection

Currently, Cornell transports all food and organic waste from campus operations to its compost facility. Compost is collected several times a week throughout various parts of Cornell. This route adds to the greenhouse gas emissions from transportation in addition to those that occur along with the composting process. Trucks from Farm Services must collect organic waste from campus and discharge it onto a windrow system about 3 miles away from central campus. The alternate proposed would bring this organic material to an anaerobic digester at the CHPP plant, reducing the transportation to about 1.5 miles. Because the organic wastes would have to be transported less, fewer gallons of diesel fuel would have to be used, reducing both expenses and greenhouse emissions. According to Cornell Farm Services, Cornell uses about 2,500 gallons of diesel fuel for its compost operations. (Huizinga 2015) The route has been reduced by 50% to transport organic wastes from campus to the power plant instead of the compost facility, shown in Figures 11 and 12, respectively. An estimate of 25% reduction in fuel consumption was assumed for the purposes of this analysis. The campus collection route still uses the majority of transportation fuel and the final trip to the compost facility is estimated to be 25% of the full route. The compost is taken to an outdoor facility where it is allocated to various windrows. These windrows sit outdoors as shown in Figure 10, and are exposed to rain, creating significant amounts of leachate that runs off into a nearby storage pond. This results in water in the pond with a high BOD value because of the organic matter in the runoff, and thus could sustain very little biological activity. The proposed anaerobic digestion facility would provide further benefit by reducing this runoff.

**Figure 10:** The current field where the Cornell Compost Facility is located. Leachate is produced after rain, which collects in a massive pond that contains high levels of Biological Oxygen Demand.

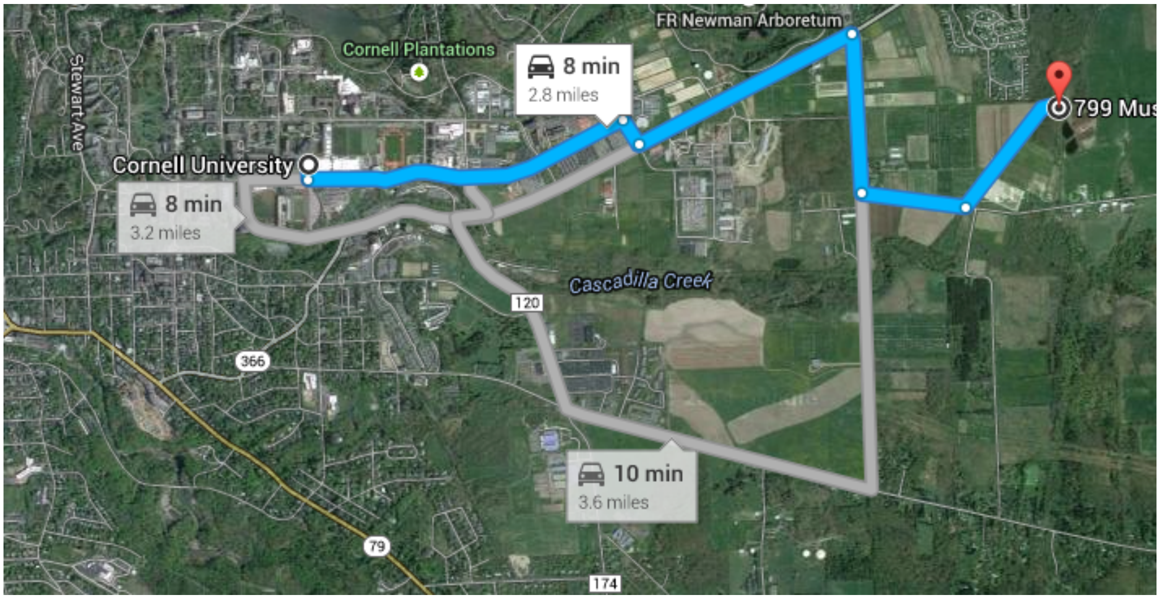


**Figure 11:** The route that is currently being taken from central campus to the Cornell Compost Facility (Google Maps)

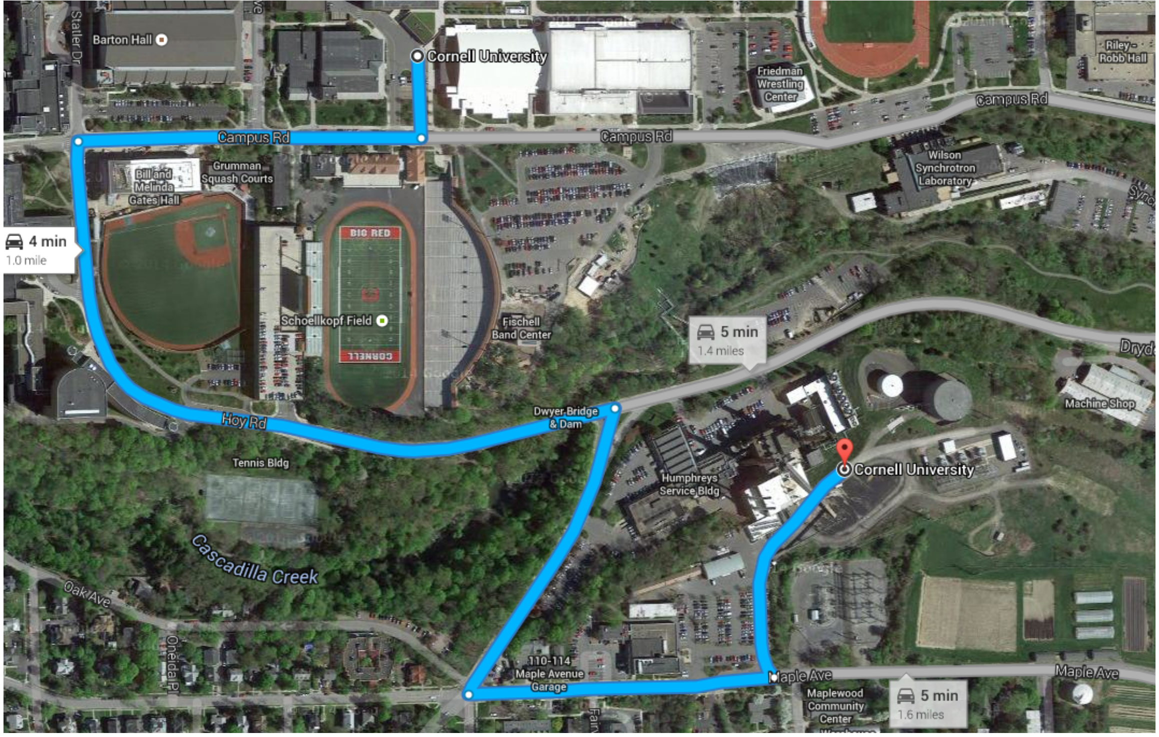


**Figure 12:** The potential of reducing the route by routing all compost operations to the Cornell Combined Heat and Power Plant, where it could be fed into an anaerobic digester. (Google Maps)

### 7.5 Processing of Compost into Biogas

As the compost has been delivered nearby to the CHPP plant, it has been sent to a storage tank inside the facility, where it has been reduced in size through various processing equipment such as a screw pump or crusher that would also agitate and mix wastes together to provide a certain consistency. The slurry of organic wastes would then be directed towards the bladder-style anaerobic digester, where it has been heated and slowly broken down by anaerobic bacteria. A biogas consisting of about 60% methane, 30% carbon dioxide and smaller amounts of other trace gasses such as water and hydrogen sulfide is produced and fed into a biogas storage tank. The gas will then be processed to remove the carbon dioxide, water, and hydrogen sulfide before being combusted in the fuel cell.

Initially, to determine the amount of biogas that could be created using anaerobic digestion, the organic waste streams for various parts of Cornell's Ithaca campus were obtained from Mr. Huizinga of Farm Services, and can be seen in Appendix A-1. The mass of organic wastes generated on campus can be seen in Figure 13, on a monthly basis. In order to determine the biogas generation at each month and a daily average for each month, a biogas production rate was assumed. In Appendix A-5, unit rates (for 1 metric ton of organic waste) are provided which were obtained from FOV Biogas research that was performed at the University of Borås in Sweden. To relate the biogas production rates to the specific campus waste streams, some weighted averages took place and can be seen in Appendix A-5, and Equation 1.

$$Biogas\ Production\ Rate = \sum_{t=1}^{n} Percentage\ of\ Waste\ x\ Standard\ Unit\ Rate$$

(Equation 1)

These weighting factors take into account the unit rates evident in Appendix A-11. After the weighting factors were calculated for biogas generated in cubic meters per day, the organic waste streams in A-1 were used to calculate the biogas generation shown in Appendix A-2, according to Equation 2. The biogas yields can be seen in Figure 14.

$$Biogas\ Generation = mass\ of\ waste\ x\ biogas\ production\ rate$$

(Equation 2)

The values in A-2 are available on a daily, monthly, or yearly basis. It was assumed that the daily values vary mostly by month, as specific daily values for the campus organic waste streams were not available.

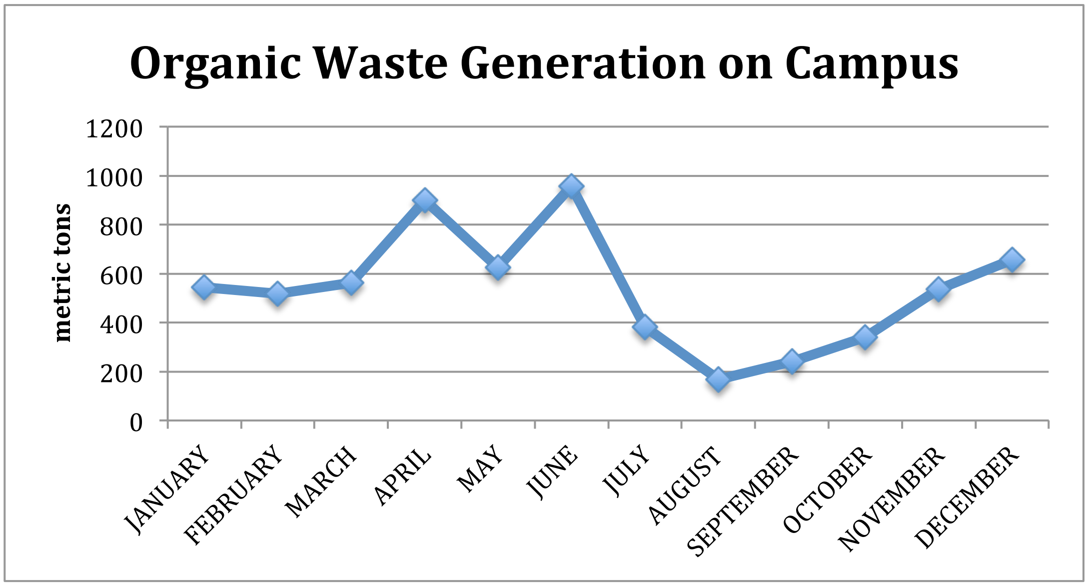


**Figure 13:** Organic wastes generated at Cornell in metric tons per month

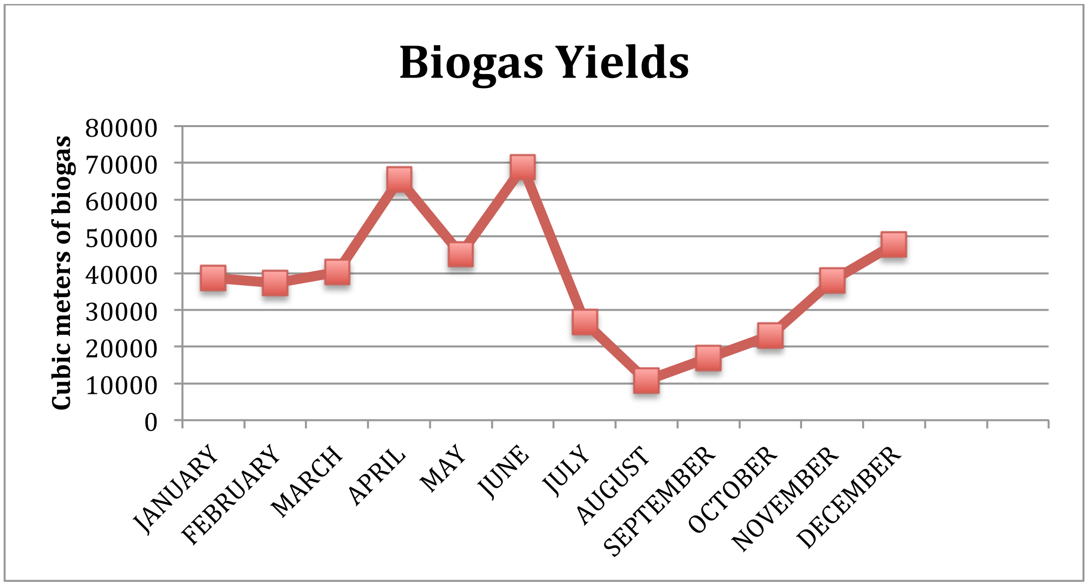


**Figure 14:** The yields of biogas in cubic meters that result from monthly changes in organic wastes

### 7.6 Biogas to Electricity

Assuming that biogas is approximately 60% methane, calculations could be made to determine the approximate electricity production for each month. It was also assumed that a Bloom Fuel Cell could be used with an efficiency of approximately 60%. By using various conversion factors, the biogas streams are converted to cubic feet of natural gas and then to the energy content determined in British Thermal Units of a cubic foot of natural gas. Once a rate of energy per time (BTU/hour) is obtained it is possible to convert this rate into an electricity demand in kW as is seen with the conversion factors listed in A-4, or in Equation 3.

$$\begin{aligned}&Electricity\ Demand\ Supplied\\&= Efficiency\ of\ fuel\ cell\ x\ percentage\ of\ methane\ in\ biogas\ x\ biogas\ supplied\ x\\&energy\ per\ unit\ of\ methane\ in\ biogas\end{aligned}$$

(Equation 3)

Once the electricity demand that can be supplied is determined on a monthly basis, calculations to determine the yearly output are easily determined. The electricity demand supplied on a monthly basis is shown in Figure 15. Utilizing the biogas in the Bloom Fuel Cell it has been possible to generate about $1.76\text{x}10^3$ MWh per year, comparatively Cornell University consumes $2.2\text{x}10^5$ MWh in an average year. Taking into account losses, calculated in A-4, it is possible to see that electricity output has been lost due to the cleaning of biogas and to keep the anaerobic digester heated consistently. Therefore, the yearly electricity production has been $1.48\text{x}10^3$ MWh and the biogas to electricity facility on campus could meet about 0.67% after all losses are taken into consideration. In comparison to other renewable energy projects utilized by the campus this percentage is not insignificant. The hydroelectric plant, when running during a year of normal rainfall could supply 1-2% of campus yearly electricity use. The new solar array in Lansing, NY is estimated to supply about 1% of Cornell's yearly total electricity use.

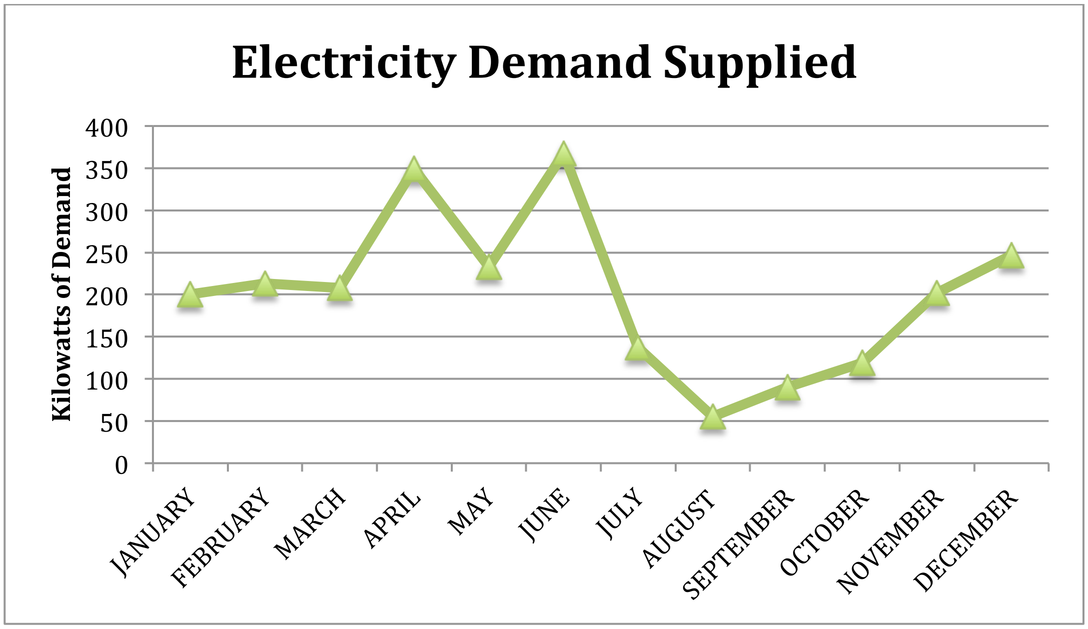


**Figure 15:** Electricity supply that could be generated on a monthly basis as a result of the Compost to Biogas and Electricity Facility

| Biogas to Electricity Generation Facility | |
|---|---|
| Electricity Generation (per year in kWh) | 1,480,000 |
| Total Campus Electricity Consumption (in kWh per year) | 220,000,000 |
| Percentage of Yearly Electricity Consumption Met by Biogas to Electricity Facility | 0.67% |
| Biogas Obtained (per year in cubic meters) | 460,000 |

**Table 2:** The Electricity Generation that occurs yearly at the Biogas to Electricity Generation Facility

## 7.7 Leachate from Anaerobic Digester

The calculations for costs as well as greenhouse gas emissions currently include leachate being disposed of as wastewater, however, it is possible that the leachate could be legally spread on farmland in New York State, as an alternative possibility to reduce costs and provide for a soil amendment to Cornell-owned farmland. It is also possible that the Ithaca Area Wastewater Treatment plant could benefit by extracting some biogas from the organic matter in the leachate by utilizing it in their biogas to energy facility. The implications to groundwater contamination as well as surface runoff should be studied however, before the spreading of leachate on farm fields is considered a viable solution.

# 8 Economic Analysis

Cornell chooses energy projects based on not only the project's ability to reduce greenhouse gas emissions, but also to provide for a sufficient return on investment. The main goal of this section will be to determine not only the feasibility, but also a cash flow and economic explanation on the project, focusing on the Internal Rate of Return and the Net Present Value cash flow analysis, assuming a payback period and lifespan of 10 years for both the boiler and fuel cell.

## 8.1 Willow in Boiler #8 versus using Natural Gas Fuel

The majority of the cost of using willow would result from the need to buy willow on the open market. Since willow is priced at about $6.00 per MMBTU compared to about $4.50 for MMBTU for natural gas, the option of willow is more expensive. Another aspect of utilizing willow is the cost of ash disposal at approximately $148,000 a year. Currently, natural gas is less expensive than willow for the same energy output, but in the future willow could become more favorable as the price of natural gas is currently at the lowest point in the past 10 years. The net present value of using willow or natural gas in Boiler #8, was determined by estimating an yearly cost for each fuel source, adjusting that to inflation, and then discounting the yearly expenditures to the present.

From a simple net present value analysis, it is evident that natural gas would have a higher net present value, however uncertainties in the energy market still exist and a sensitivity analysis has to be taken into account before any conclusions could be drawn.

| Type of Fuel Used in Boiler #8 | Net Present Value |
|---|---|
| Willow | -$60,200,000 |
| Natural Gas | -$44,300,000 |

**Table 3:** Comparison of the costs of using different fuels in Boiler #8 based on the Net Present Value over a 10-year time Period

### 8.2 Biogas to Electricity Operations versus Composting

The composting operation does not generate cash flows, as compost is not sold on the market. Instead, the biogas to electricity operation could generate yearly cash flows after initial investment, assuming a 3% interest rate, of about $29,787 a year after operating costs are taken into account, solely based on the reduction of purchasing extra electricity from the grid. The economics of the biogas to electricity operations assume that the majority of the capital costs will be paid off through federal and state grants. Without state and federal funding it would not be possible for this project to maintain a positive rate of return as the equipment costs outweigh any positive cash flows that could be obtained through utilizing this facility. It is assumed that capital costs has been $3,620,000 and the grants from state agencies such as NYSERDA and federal tax credits would cover $3,586,000 of the project. A federal tax credit exists on projects involving biomass energy, where a 30% tax credit can be obtained through the installation of a bioenergy facility, including capital costs and labor. NYSERDA has several grants currently that focus on large-scale bioenergy projects. For the purposes of the project it was assumed that NYSERDA would award a $2,000,000 grant for the project as renewable electricity projects are encouraged, provided these systems are grid-tied. (PON 2828) The remaining portion has been the result of a federal tax rebate of 30% that could be obtained at the end of the tax year in which the project has been constructed. The net present value of the biogas to electricity project was determined by calculating the net present value of the cash flows that would result from lower energy costs each year, assuming inflation of 3%. When the initial investment of $34,000 was taken into account, the Internal Rate of Return (IRR) was determined to be 90%. A high IRR provides greater certainty that a project will provide economic benefit to Cornell for the initial investment required to construct the facility.

| | |
|---|---|
| Net Present Value | $255,192 |
| Internal Rate of Return | 90% |
| Initial Investment | $34,000 |

**Table 4:** Various Economic Measures Outlined for the Biogas to Electricity Project

# 9 GREENHOUSE GAS REDUCTIONS

Both alternatives to utilize biomass on campus seem to help reduce the overall net addition of greenhouse gasses in carbon dioxide equivalents. Appendix A-4 provides more detail about how the emissions of such operations were calculated on an annual basis, with results in sections 10.1 and 10.2 summarized below.

## 9.1Willow in Boiler #8 versus using Natural Gas Fuel

The greenhouse gas reductions achieved through the use of willow in Boiler #8 in carbon dioxide equivalents were calculated taking into account the farm operations of growing willow, the inputs necessary such as water and fertilizer, and any emissions control required to combust willow. Willow needs to be formed into pellets and dried to about 20% moisture content from the original moisture content of 50-55% at harvest. Cornell is fortunate to have a biomass drying facility at the NYS Agriculture Experiment Station in Geneva, NY, which has the capability of reducing the moisture content of the willow making the willow pellets more appropriate for combustion in Boiler #8. Using rates described in Appendix A-4 and based on the land area and inputs necessary for growing enough willow to supply Boiler #8, it is possible to calculate the greenhouse gas emissions in carbon dioxide equivalents for both utilizing willow and natural gas in the same boiler each year. From the table it is possible to see that utilizing willow pellets to produce steam would have significantly lower net greenhouse gas emissions relative to using natural gas.

| Type of Fuel Used in Boiler #8 | Greenhouse Gas Emissions (carbon dioxide equivalents) (metric tons) |
|---|---|
| Natural Gas | 60,300 |
| Willow Pellets | 7,000 |

**Table 5:** Comparison of the net estimated carbon dioxide emissions of both natural gas and willow pellets

## 9.2Biogas to Electricity Operations versus Composting

The greenhouse gas reductions achieved through the use anaerobic digestion to create a biogas and generate electricity, over regular composting were analyzed. The analysis included the net additions of carbon dioxide into the atmosphere that result from both operations. This analysis included the operations of collection and transport of the compost to a collection area, such as the Cornell compost facility or the CHPP.  After the compost delivery, emissions from the composting process, from conversion of organic waste to biogas, and subsequent combustion, were analyzed. The greatest deal of net emissions seems to result from the composting process. The net addition is much smaller for the steps of biogas collection, as processing and combustion in the fuel cell are a much smaller contribution to the overall emission. In addition, some losses are also incurred where an estimated 2% of total biogas generation is lost due to minor leaks in tanks or the anaerobic digester. These losses were converted to carbon dioxide equivalents, as methane is eighty four times more potent than carbon dioxide. Refer to Appendix A- 4 for the detailed calculations. Table 6, shows that utilizing organic waste streams to produce biogas and electricity would have significantly lower net greenhouse gas emissions than the current method of composting the waste in a field.

| Process | Greenhouse Gas Emissions (carbon dioxide equivalents) (metric tons) |
|---|---|
| Composting | 40,500 |
| Biogas Generation and Combustion | 2,000 |

**Table 6:** Comparison of the net carbon dioxide emissions of composting and electricity generation through biogas combustion.

## 10 SENSITIVITY ANALYSIS

The sensitivity of the various parameters that contributed to the calculations that determined the feasibility of the two methods at utilizing biomass will be analyzed. The expenditure and greenhouse gas emissions will be analyzed in this section as a means of determining how uncertainty could impact the calculations both in terms of the parameters discovered through the literature review in addition to future changes in price that could occur for both willow and natural gas.

## 10.1 Willow in Boiler #8 versus using Natural Gas Fuel Greenhouse Gas Emissions

In order to determine how calculations of carbon dioxide emissions for using willow or natural gas in Boiler #8, would respond to variations of certain parameters, each case was varied from the "optimistic" parameter given in the literature source. The sequestration of carbon dioxide from growing willow was varied and decreased by 15% from the original optimistic case given in the literature. The other parameters obtained on the carbon dioxide emissions of willow were also varied on the same scale, except in this case these would increase by an order of 15% in each case after the optimistic number obtained from the literature, because several references specified parameters that were closely related and these values has been adding carbon dioxide into the atmosphere thereby contributing a greater value to the less optimistic cases.

The combustion of natural gas is a well-known parameter, so it was only varied by 10% increasing for each subsequent case from the optimistic value. The transmission values were varied by 15%, as there are discrepancies in different sources as to the amount of carbon dioxide that is released with the transport and extraction of natural gas from wells. The conclusion that could be drawn from this analysis is evident in Figure 16, where it is evident that natural gas carbon dioxide emissions have a greater sensitivity to the variation in different parameters than do emissions from combusting willow in Boiler #8. The rationale behind these results could be that the exact carbon dioxide emissions from natural gas are still unknown because new processes in extracting natural gas have debatable carbon dioxide emissions or equivalent emissions when including methane loss in the production and transmission. Generally, biomass production systems are smaller than natural gas production and distribution systems, so there is more certainty in making calculations of net carbon dioxide emissions.

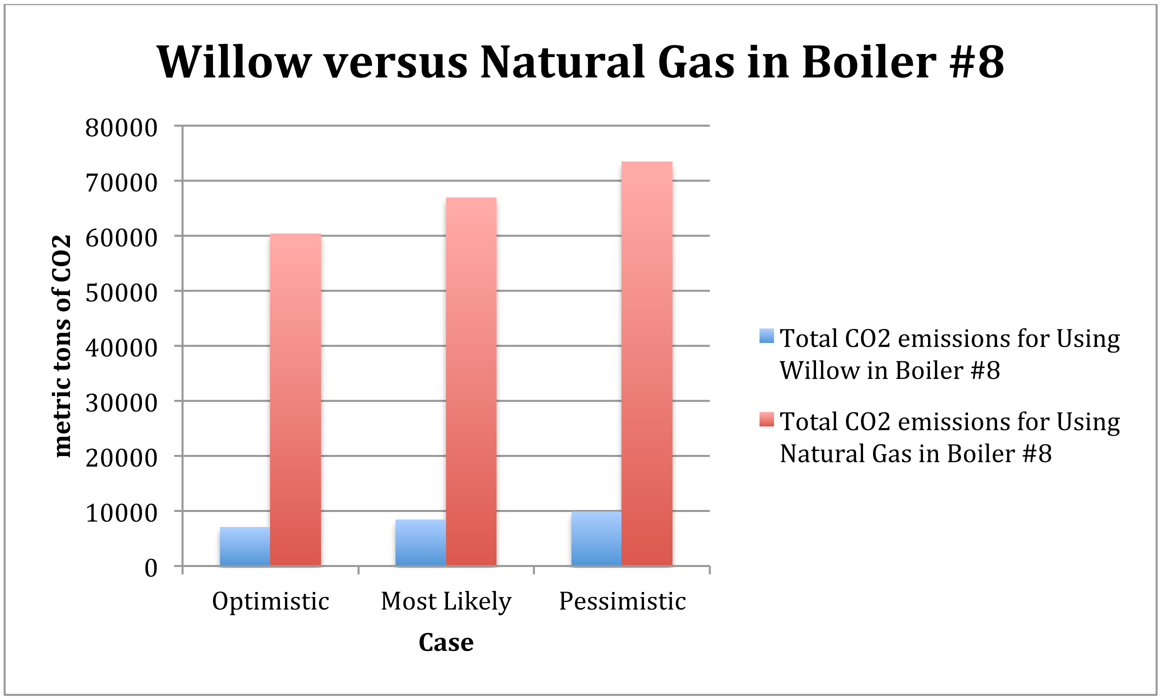


**Figure 16:** Comparison of the net carbon dioxide emissions for using willow versus natural gas as a fuel source in Boiler 8, with three different scenarios

## 10.2 Willow in Boiler #8 versus using Natural Gas Fuel Economic Analysis

The economics of using willow versus natural gas as a fuel source for Boiler #8 also has significant sensitivity. Natural gas is more sensitive to price than are willow chips, mainly because the market for natural gas is constantly changing as supplies increase drastically due to processes such as hydraulic fracturing. The natural gas wells have an expected life of about 40 years in the Marcellus Shale; therefore in the future the price of natural gas will increase as supply diminishes. For the analysis, natural gas was assigned a variation, which increases in price by 60% from each case following the optimistic case. The various parameters of willow were varied by 15% increasing after the optimistic case, as disposal of ash will increase along with the reduction in landfill space. Willow prices have been observed to stay relatively constant, mainly increasing purely due to inflation. From Figure 17, it is evident that the operating costs of willow will be less sensitive to price than will the operating costs of natural gas.

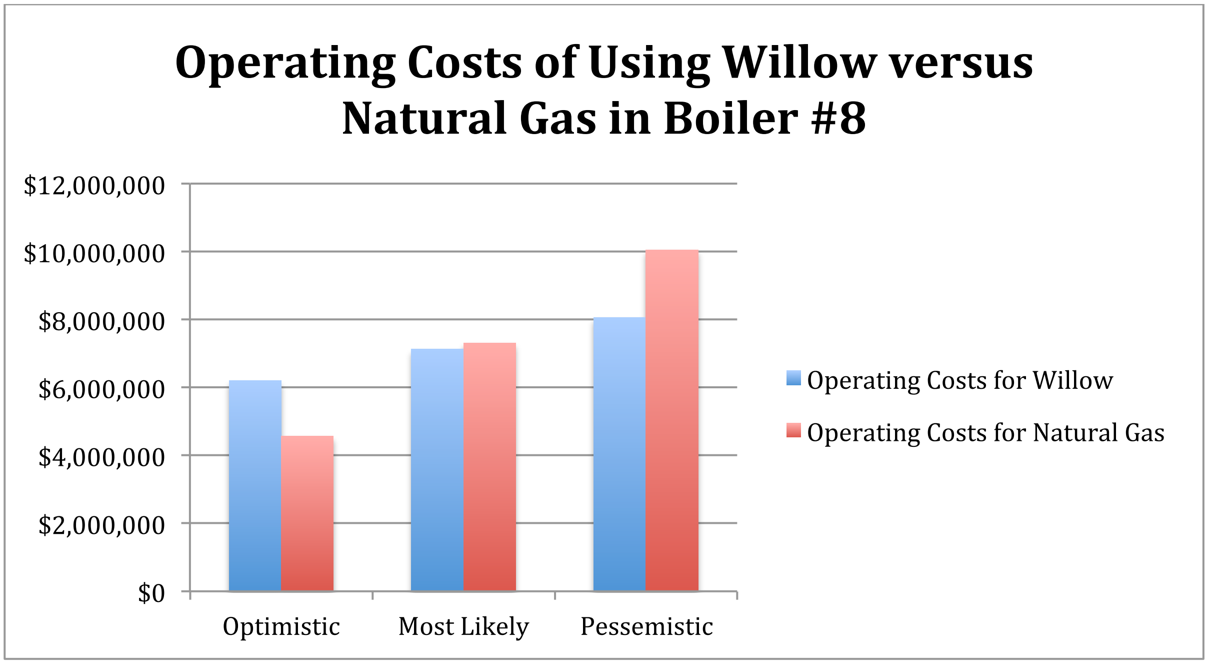


**Figure 17:** Comparison of the operating costs of using willow versus natural gas in Boiler #8, in three distinct scenarios

### 10.3 Biogas to Electricity Operations versus Composting Greenhouse Gas Emissions

A sensitivity analysis of the parameters used to calculate the carbon dioxide emissions for both composting and creating biogas and electricity from organic wastes was performed. The diesel fuel carbon dioxide emissions were varied by about 25%, as there was more uncertainty when exploring the parameters of calculating emissions from diesel fuels when comparing different sources of literature. In addition, the diesel fuel consumption for the operations varies yearly, so the values were varied more than other parameters to compensate for the situation where more diesel fuel has been consumed as part of the compost facility operations. The carbon dioxide emissions from compost were varied by 15% from the optimistic case, through each subsequent case as the value of carbon dioxide emissions from compost, specified in literature provided more analysis into how the number or unit rate was calculated.

For the sensitivity analysis on the compost to biogas and electricity operations, diesel fuel was also varied by 25% to consider uncertainties in the calculation of carbon dioxide emissions, as well as the amount that would actually be consumed on a shortened route to the Cornell power plant. All other parameters were varied by 15% due to the availability of more resources to approximate the validity of specific parameters. From Figure 18, it is evident that composting organic wastes versus creating biogas and electricity from compost would have a greater sensitivity to changes in parameters, as well as significantly higher overall net carbon dioxide emissions for each of the test cases.

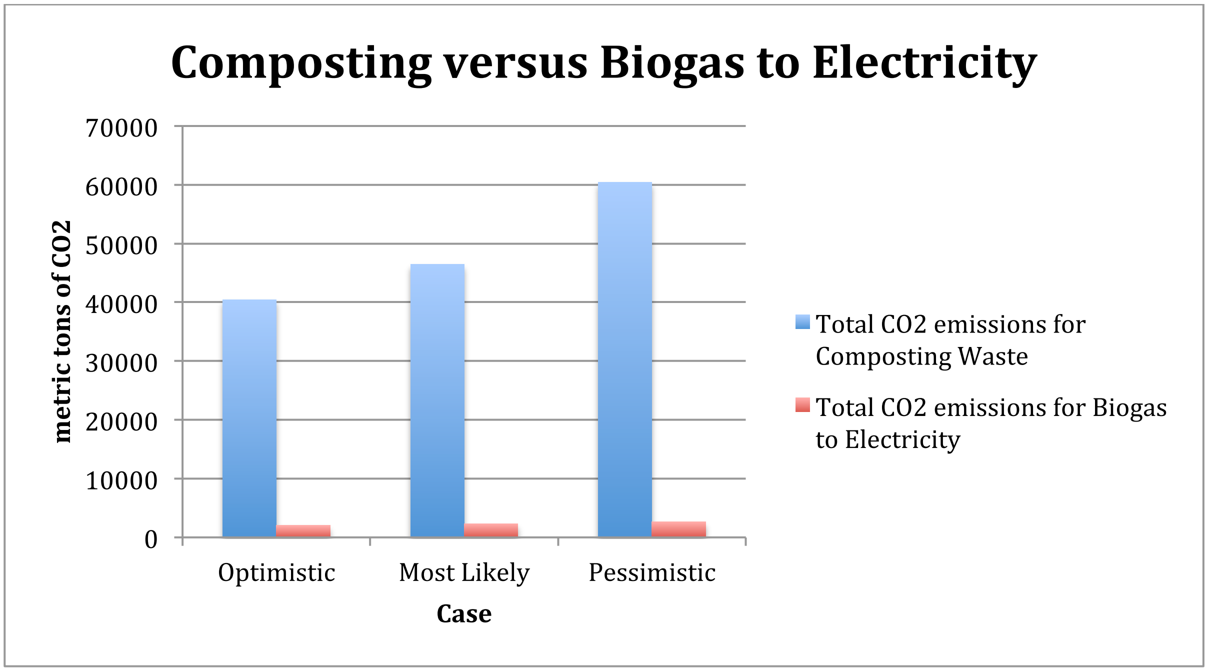


**Figure 18:** Comparison of the net carbon dioxide emissions for composting organic wastes versus using organic wastes to create biogas and electricity, in three different scenarios

### 10.4 Biogas to Electricity Operations versus Composting Economic Analysis

The economics of using biogas generated from compost to generate electricity, as opposed to composting, can be justified through a sensitivity analysis on the economic parameters. The main operating costs from composting arise from the fuel costs required for the operations of the trucks to move compost from the campus to the composting facility. It was assumed that the optimistic fuel price for the trucks has been the current diesel price in Ithaca, NY, which was $3.39 in May 2015. A 15% increase was therefore assumed for subsequent cases for the operating costs of the compost operations. The operating costs for the Biogas to Electricity Facility were assumed to also increase by 15% for each subsequent case, as there was specific evidence for a facility within the parameters listed in FOV Biogas literature. The monetary amount saved from the reduced use of electricity was also scaled down by 15% for each subsequent case, as the calculations relied on parameters that were specified both from industry experience and similarly cited in research literature. From Figure 19, it is evident that the operating costs of the Biogas to Electricity plant has been more price sensitive than the compost operations, as the compost operations rely on one specific parameter: fuel costs, whereas the biogas to electricity plant would rely on generating enough electricity to offset its operating expenses. If the operating expenses exceed the savings achieved through purchasing or generating less electricity using alternative methods, then the facility has been operating at a cash flow negative basis.

The compost to electricity operating costs are also included as part of the sensitivity analysis. Because the equipment for the composting operating is already in place for the compost facility operations, the capital costs were ignored. From Figure 20, it can be seen that the capital costs after rebates, of creating compost from electricity are price sensitive from the optimistic to the pessimistic calculations, as the project is dependent on grants from the federal government and state-level organizations such as NYSERDA. For this reason both the capital costs, and available rebates were varied by 15% as both are known parameters, with information that is readily available. The rebates were decreased by 15% for each subsequent category, whereas the capital costs of the project were increased by 15% for each category after the optimistic.

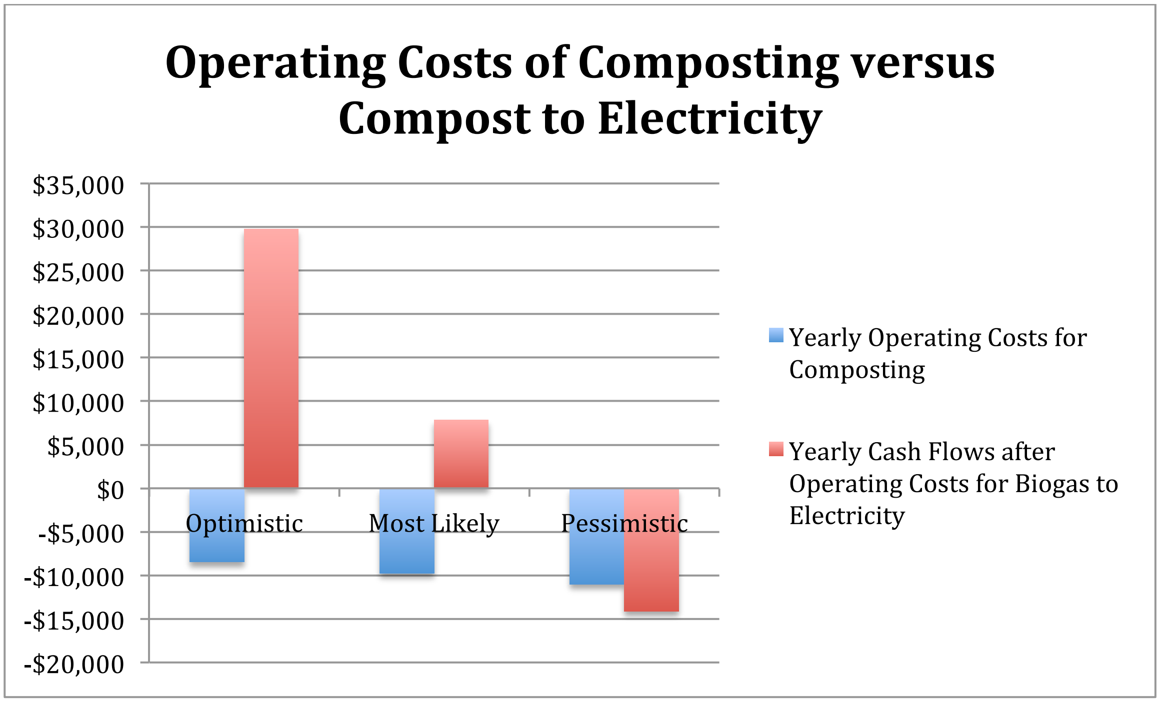


**Figure 19:** Comparison of the operating costs of composting versus creating biogas and electricity from compost, in three distinct scenarios

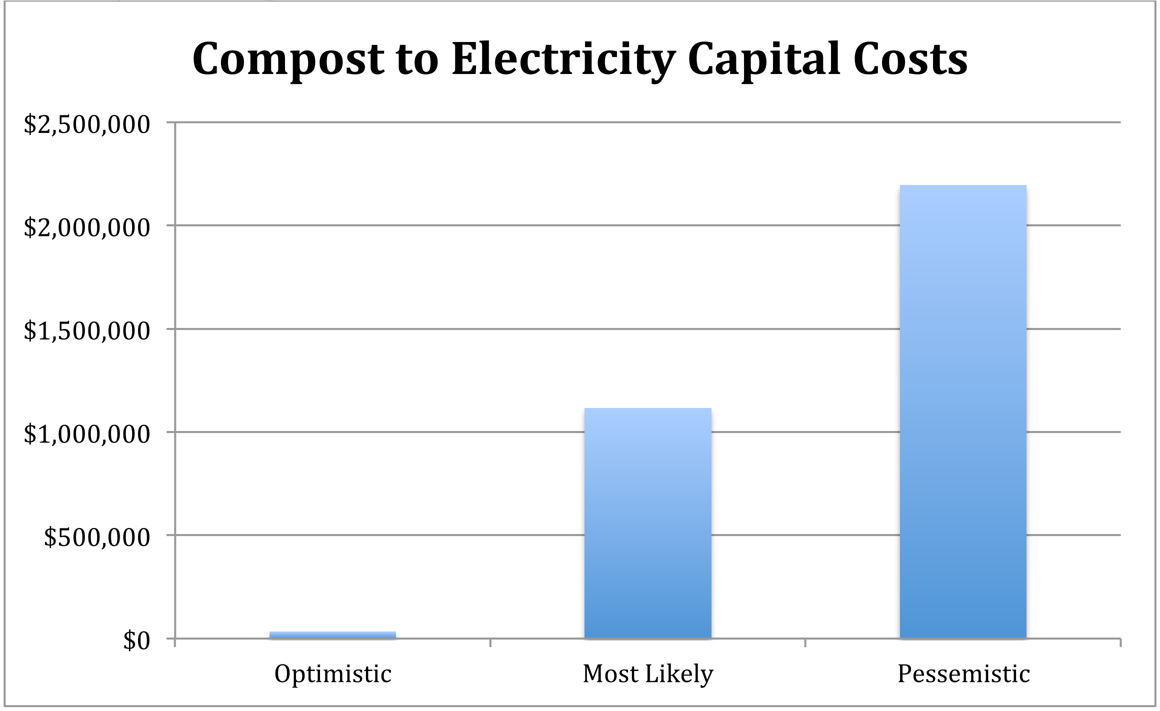


**Figure 20:** Capital costs of creating biogas and electricity from compost in three distinct scenarios

## 11 Conclusions

Biomass has a significant potential at reducing Cornell's climate change footprint through the direct reduction of carbon dioxide emissions. The feasibility study presented in this report focused on two goals: determining whether or not it is possible to utilize biomass at Cornell's last remaining solid fuel boiler, and as determining the feasibility of using the organic waste streams on campus with anaerobic digestion to generate a biogas that could produce a renewable source of electricity via a fuel cell. Both alternatives are feasible and realistic in the sense of engineering calculations. The Biogas to Electricity initiative is feasible depending solely on funding from the federal government and NYSERDA to help offset the initial capital costs of building the proposed system. Once these costs are offset is it possible to achieve a positive Net Present Value and a respectable rate of return, while helping to reduce extra greenhouse gas emissions into the atmosphere. Burning willow in place of fossil fuels in Boiler #8 is much more expensive in the short term, but has a significant impact on reducing greenhouse gas emissions, which contribute to climate change. In the near future, as the cost of natural gas stabilizes it may be more cost-effective to implement combustion of willow chips in Boiler #8, perhaps even to offset the need for the temporary boilers that supply steam during the coldest days of the year. Grants on growing biomass may also help reduce and defray the costs of willow making it more competitive as a fuel.

## 12 Future Work

As means of further work there are many ways in which the results of this report could benefit Cornell in implementing a more sustainable energy system on campus. One major focus area for Cornell's Climate Action Plan is to develop an Enhanced Geothermal System, which can be seen in Figure 21, that could potentially tap into hot rock located underneath the surface and provide a greater amount of campus steam and electricity, while reducing the need for fossil fuels such as oil and natural gas currently being used at Cornell's CHPP. Another step has been to develop a more efficient way of coupling all the renewable energy systems on campus to help overcome issues such as intermittency from wind and solar, and reducing the need to buy electricity from the grid at peak periods. Biomass is shown to have the potential with the use of compost, to meet a small amount of electricity demand on campus by producing a fairly consistent electricity source through the use of the fuel cell. The total output would average about 0.7% of Cornell's total yearly electricity consumption. This yearly output is not insignificant by any means, as Cornell's other renewable energy projects produce yearly outputs within the range of the biogas to electricity plant. The hydroelectric plant in Fall Creek Gorge produces about 1-2% of yearly campus consumption and the new solar farm is estimated to produce 1-2% of yearly consumption.

The electricity provided by the fuel cell has the potential of reducing the amount of electricity Cornell will need to purchase directly from the grid to meet its peak demand. The biogas that is produced could be stored in a much larger tank and has the potential to allow electricity generation during peak periods such as the hottest and coldest days during summer and winter, respectively, thereby further reducing costs by reducing load when electricity costs are the highest. Cornell could also partner with the local community and collect organic wastes from local businesses to expand its biogas operations, and thereby produce more electricity for the campus in the future.

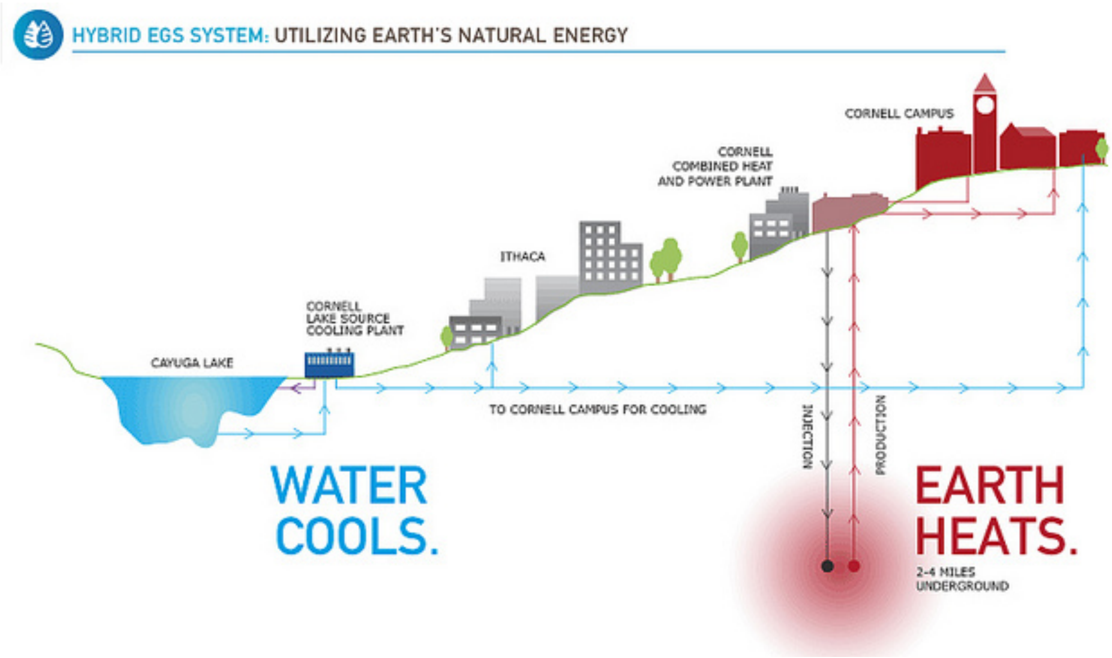


**Figure 21**: The proposed Enhanced Geothermal System that could be tied through the use of a "smart grid" with other renewable energy sources on and off-campus such as the Biogas Generation Facility. (Cornell University Climate Action Plan)

It is also possible to restart Boiler #8 to reduce campus greenhouse gas emissions. While the analysis in the report has determined that it would not be feasible to produce enough willow on Cornell-owned marginal farmland, it is still possible to purchase willow readily on the open market, and willow is very competitively priced with natural gas. Recently, the price of natural gas has declined due to the early success of energy companies involved in hydraulic fracturing and creating an excess supply. The price is unlikely to at this level forever, as natural gas wells become depleted and produce less in the future. Energy prices are very unpredictable so in the future as the price of natural gas resurges to historical norms, Cornell has the potential to quickly adapt at least one boiler to utilize biomass. While the future is always uncertain, there may exist a financial price for emitting carbon dioxide in the future, as was done with nitrogen and sulfur dioxides in the past. Cornell could incorporate these uncertainties in its analysis of utilizing biomass.

As for the purposes of renewable energy and sustainability, biomass is often considered "carbon-neutral," in the sense that the addition of extra carbon into the atmosphere is relatively small compared with that of burning fossil fuels, so biomass would often be exempt from any such carbon tax regulation.

There is a massive deficit in trying to meet the demand of even one boiler (Boiler #8) at Cornell's CHPP plant as can be seen through the calculations in Appendix A-10. Therefore, being located in a rural area could actually benefit Cornell University in that there is a large amount of farmland available for growing the biomass to meet such a deficit. Tompkins County alone has an estimated 7 to 13 thousand acres of unused farmland, which could be utilized to grow biomass for Cornell's power plant. Such a plan would have the potential of creating social benefits. Energy could be purchased locally, providing upstate NY with economic benefits, as Cornell has been able to spend money locally, while at the same time creating jobs in the agriculture sector and benefiting the local economy. New York State could actually benefit in terms of economic and tax activity with the growth of jobs and spending, and provide incentives to farmers to grow biomass crops to help Cornell and other local organizations meet their climate action plans.

Two distinct alternatives have been analyzed for the feasibility of integrating biomass into the energy system at Cornell University. The analysis has focused on efficacy in achieving the environmental goals set forth in the Climate Action Plan, as well as financial viability for the university. In general, both options show potential under specific conditions, for example when natural gas prices make willow combustion competitive in Boiler #8, and with Federal and NYSERDA grants supporting investment in fuel cells for conversion of biogas to electricity. The likelihood of both of these conditions needs further assessment before investment, but the work presented here provides guidelines regarding the most important conditions for ensuring viability of biomass integration into the existing infrastructure at Cornell.

## Appendix
## A-1

**Compost Collections 2014 (in metric tonnes)**

| MONTH | VET | Dairy | HORSE | POULTRY | GREENHOUS | PB & SCAS | ANSCI | OTHER Plantations | Dining | MONTH TOTALS |
|---|---|---|---|---|---|---|---|---|---|---|
| **JANUARY** | 49.3 | 290.3 | 129.8 | 4.0 | 25.7 | 0.0 | 6.2 | 0.7 | 37.5 | 543.4 |
| per day | 1.6 | 9.4 | 4.2 | 0.1 | 0.8 | 0.0 | 0.2 | 0.0 | 1.2 | 17.5 |
| **FEBRUARY** | 52.7 | 226.8 | 140.3 | 3.5 | 11.3 | 0.0 | 0.0 | 8.3 | 75.9 | 519.0 |
| per day | 1.9 | 8.1 | 5.0 | 0.1 | 0.4 | 0.0 | 0.0 | 0.3 | 2.7 | 18.5 |
| **MARCH** | 61.6 | 233.1 | 128.6 | 1.9 | 19.2 | 0.0 | 35.3 | 0.1 | 82.8 | 562.7 |
| per day | 2.0 | 7.5 | 4.1 | 0.1 | 0.6 | 0.0 | 1.1 | 0.0 | 2.7 | 18.2 |
| **APRIL** | 64.8 | 616.9 | 111.5 | 3.8 | 20.7 | 0.0 | 15.1 | 1.1 | 65.0 | 898.8 |
| per day | 2.2 | 20.6 | 3.7 | 0.1 | 0.7 | 0.0 | 0.5 | 0.0 | 2.2 | 30.0 |
| **MAY** | 67.3 | 408.2 | 50.8 | 6.5 | 16.1 | 0.0 | 7.3 | 7.7 | 61.2 | 625.2 |
| per day | 2.2 | 13.2 | 1.6 | 0.2 | 0.5 | 0.0 | 0.2 | 0.2 | 2.0 | 20.2 |
| **JUNE** | 42.0 | 734.8 | 67.6 | 4.2 | 19.9 | 59.0 | 2.7 | 4.1 | 22.1 | 956.4 |
| per day | 1.4 | 24.5 | 2.3 | 0.1 | 0.7 | 2.0 | 0.1 | 0.1 | 0.7 | 31.9 |
| **JULY** | 53.4 | 217.7 | 36.7 | 5.9 | 15.9 | 23.3 | 0.0 | 0.1 | 27.8 | 380.8 |
| per day | 1.7 | 7.0 | 1.2 | 0.2 | 0.5 | 0.8 | 0.0 | 0.0 | 0.9 | 12.3 |
| **AUGUST** | 49.3 | 0.0 | 43.2 | 5.0 | 13.9 | 18.6 | 3.0 | 1.0 | 32.7 | 166.6 |
| per day | 1.6 | 0.0 | 1.4 | 0.2 | 0.4 | 0.6 | 0.1 | 0.0 | 1.1 | 5.4 |
| **SEPTEMBER** | 47.3 | 18.1 | 46.8 | 4.0 | 16.0 | 11.2 | 8.4 | 0.8 | 89.2 | 241.8 |
| per day | 1.6 | 0.6 | 1.6 | 0.1 | 0.5 | 0.4 | 0.3 | 0.0 | 3.0 | 8.1 |
| **OCTOBER** | 66.3 | 0.0 | 93.8 | 3.8 | 23.5 | 7.7 | 26.3 | 25.5 | 93.7 | 340.6 |
| per day | 2.1 | 0.0 | 3.0 | 0.1 | 0.8 | 0.2 | 0.8 | 0.8 | 3.0 | 11.0 |
| **NOVEMBER** | 45.0 | 235.9 | 85.7 | 3.2 | 32.7 | 4.9 | 49.6 | 4.9 | 74.1 | 536.0 |
| per day | 1.5 | 7.9 | 2.9 | 0.1 | 1.1 | 0.2 | 1.7 | 0.2 | 2.5 | 17.9 |
| **DECEMBER** | 39.8 | 444.5 | 79.6 | 3.2 | 19.4 | 0.0 | 9.5 | 0.7 | 58.4 | 655.1 |
| per day | 1.3 | 14.3 | 2.6 | 0.1 | 0.6 | 0.0 | 0.3 | 0.0 | 1.9 | 21.1 |
| | | | | | | | | | | |
| Yearly Totals (metric tons) | | | | | | | | | | |
| BY SOURCE | 638.7 | 3,426.4 | 1,014.5 | 48.9 | 234.2 | 124.6 | 163.5 | 54.9 | 720.4 | 6,426.3 |

TOTAL ALL SOURCES 6426.2699 tonnes

| | TYPE OF MATERIAL | Number of pickups in a week |
|---|---|---|
| VET. | ANIMAL MANURE AND BEDDING | 5 |
| POULTRY | CHICKEN MANURE AND KRAFT PAPER | 1 |
| GREENHOUSE | PLANT MATERIAL AND SOIL | 3 |
| PLANT BR & SCAS | PLANT SAMPLES AND SOIL | 2 |
| AN. SCI | ANIMAL MANURE AND BEDDING | 1 |
| Horse | HOURSE MANURE AND SAWDUST | 1 |
| Plantations | PLANT MATERIAL AND SOIL | 1 |
| Dairy | Liquid Dairy Manure | 3 |
| Dining | Food waste | 5 During School year and 3 during summer |

## A-2

**Generation of Biogas Per Month and Day (cubic meters)**

| MONTH 2014 | VET | Dairy | HORSE | POULTRY | GREENHO | PB & SCAS | ANSCI | OTHER Plantations | Dining | MONTH TOTALS |
|---|---|---|---|---|---|---|---|---|---|---|
| JANUARY | 3011 | 21772 | 9006 | 72 | 1348 | 0 | 393 | 38 | 3091 | 38732 |
| per day | 97 | 702 | 291 | 2 | 43 | 0 | 13 | 1 | 100 | 1249 |
| FEBRUARY | 3222 | 17010 | 9736 | 63 | 595 | 0 | 0 | 438 | 6264 | 37328 |
| per day | 115 | 607 | 348 | 2 | 21 | 0 | 0 | 16 | 224 | 1333 |
| MARCH | 3765 | 17486 | 8924 | 34 | 1010 | 0 | 2250 | 3 | 6833 | 40305 |
| per day | 121 | 564 | 288 | 1 | 33 | 0 | 73 | 0 | 220 | 1300 |
| APRIL | 3959 | 46266 | 7735 | 69 | 1086 | 0 | 966 | 57 | 5359 | 65497 |
| per day | 132 | 1542 | 258 | 2 | 36 | 0 | 32 | 2 | 179 | 2183 |
| MAY | 4115 | 30617 | 3524 | 116 | 848 | 0 | 463 | 405 | 5052 | 45140 |
| per day | 133 | 988 | 114 | 4 | 27 | 0 | 15 | 13 | 163 | 1456 |
| JUNE | 2567 | 55111 | 4689 | 75 | 1043 | 3096 | 173 | 214 | 1826 | 68796 |
| per day | 86 | 1837 | 156 | 3 | 35 | 103 | 6 | 7 | 61 | 2293 |
| JULY | 3266 | 16329 | 2549 | 106 | 833 | 1224 | 0 | 3 | 2290 | 26601 |
| per day | 105 | 527 | 82 | 3 | 27 | 39 | 0 | 0 | 74 | 858 |
| AUGUST | 3011 | 0 | 2996 | 90 | 729 | 976 | 191 | 52 | 2694 | 10739 |
| per day | 97 | 0 | 97 | 3 | 24 | 31 | 6 | 2 | 87 | 346 |
| SEPTEMBER | 2889 | 1361 | 3247 | 72 | 838 | 586 | 538 | 43 | 7357 | 16931 |
| per day | 96 | 45 | 108 | 2 | 28 | 20 | 18 | 1 | 245 | 564 |
| OCTOBER | 4054 | 0 | 6508 | 69 | 1234 | 405 | 1677 | 1338 | 7731 | 23015 |
| per day | 131 | 0 | 210 | 2 | 40 | 13 | 54 | 43 | 249 | 742 |
| NOVEMBER | 2750 | 17690 | 5947 | 57 | 1715 | 257 | 3163 | 257 | 6115 | 37952 |
| per day | 92 | 590 | 198 | 2 | 57 | 9 | 105 | 9 | 204 | 1265 |
| DECEMBER | 2434 | 33339 | 5519 | 57 | 1019 | 0 | 607 | 35 | 4820 | 47832 |
| per day | 79 | 1075 | 178 | 2 | 33 | 0 | 20 | 1 | 155 | 1543 |

| Year Total (m^3/year) | 458868 |
|---|---|

## A-3

Daily Electricity Generation (KW) on a Month to Month Basis

Efficiency of Fuel Cell (Electricity) 60 % Methane in Biogas 60 %

m^3 to cubic feet 35.315 BTUs per ft^3 natural gas 1030

1 BTU/hr 0.000293071 KW 1 day= 24 hours Efficiency of Turbine (Usable Heat) 52

*http://www.afdc.energy.gov/fuels/emerging_biogas.html

| | ELECTRICITY (KW) |
|---|---|
| JANUARY | 200 |
| FEBRUARY | 213 |
| MARCH | 208 |
| APRIL | 349 |
| MAY | 233 |
| JUNE | 367 |
| JULY | 137 |
| AUGUST | 55 |
| SEPTEMBER | 90 |
| OCTOBER | 119 |
| NOVEMBER | 202 |
| DECEMBER | 247 |

| | | |
|---|---|---|
| Total (per year) | 1760999.671 | kWh |
| Total Electricity Consumption on Campus Year | 220000000 | kWh |
| Minus Electricity Expenditures | 284886 | kWh |
| Percentage of Consumption (after losses in operations) | 0.67% | |

## A-4

**Greenhouse Gas Emissions and Reductions (yearly)**

**Compost Operations**

1 gallon diesel = 0.01015140 metric tons of CO2

| **Current Inputs for Compost** | | | | **CO2 Generated** | | |
|---|---|---|---|---|---|---|
| Diesel to power trucks to collect compost | | | 2,500 gallons | | 25 | tonnes CO2 |
| Compost CO2 emissions | | 6.29 Mg CO2/Mg Waste | | | 40421 | tonnes CO2 |
| | 6426.269902 Mg waste collected in a year | | | | | |
| **Total** | | | | | **40447** | **tonnes CO2** |

| **Future Inputs for using Compost to Create Biogas & Electricity Using Fuel Cell** | | | | **CO2 generated** | | | |
|---|---|---|---|---|---|---|---|
| Diesel to power trucks to collect compost | | | 1,875 gallons | | 19 | tonnes CO2 | 25% reduction in diesel use |
| CO2 from combustion of biogas | | | | | 500 | tonnes CO2 | |
| Water Required for Digester | 4803775 gallons | | 0.0015 kWh/gallon | | 23 | tonnes CO2 | |
| Cleaning of Biogas | | 79245 kWh | | 0.0031434 metric tons/kWh | 249 | tonnes CO2 | |
| Methane Release from Reactor (CO2 equivalent) | | 4 metric tons CH4 | converted to CO2 equivalent | | 305 | tonnes CO2 | |
| Heat required for anerobic digester | 6426.269902 tonnes/year | | 32 kWh/tonne | | 646 | tonnes CO2 | |
| Water Treatment of Leachate | 4803775 gallons | | 0.0015 kWh/gallon | | 23 | tonnes CO2 | |
| CO2 released from cleaning | 30% of total biogas is CO2 | | | | 273 | tonnes CO2 | |
| **Total** | | | | | **2037** | **tonnes CO2** | |

| | | | | | |
|---|---|---|---|---|---|
| **To produce same power at CHP Plant:** | **1760999.671 kWh** | **0.00075 metric tonnes/kWh** | **1321** | **tonnes CO2** | http://www.carbonfund.org/how |
| **To buy from local grid** | **1760999.671 kWh** | **0.0031434 metric tonnes/kWh** | **5536** | **tonnes CO2** | |

**Boiler 8 Operations Using Willow**

| **Current burning of Natural Gas** | | | | | | |
|---|---|---|---|---|---|---|
| Natural Gas Combustion CO2 emissions | 10059670 therms | of natural gas | 0.005 metric tons per therm | | 50298 | tonnes CO2 |
| Natural Gas Transmissions CO2 emissions | 10059670 therms | of natural gas | 0.001 metric tons per therm | | 10060 | tonnes CO2 |
| **Total** | | | | | **60358** | **tonnes CO2** |

| **Switching to Willow** | | | | | | |
|---|---|---|---|---|---|---|
| Carbon Sequestration of Willow | 13220 acres needed to grow all | **0.09570799** metric tons/acre | sequestered | 1265 | tonnes CO2 | http://sustainability.tufts.edu/ca |
| Transportation | 13520 gallons diesel | | | 137 | tonnes CO2 | http://www.cipco.net/PM2089W |
| Fertilzer Production Emissions | 45 kg N per acre/year | 3.6 kg CO2-e per kg N | | 2156 | tonnes CO2 | http://www.yara.com/doc/29413_ |
| Drying Emissions & Water Emissions | 387750 kWh | 0.0031434 metric tonnes/kWh | | 1219 | tonnes CO2 | http://www.esf.edu/willow/docum |
| Combustion Emissions | 1005967 MMBTU | 0.00473543 metric tons/MMBTU | | 4764 | tonnes CO2 | http://www.biomassenergycent |
| **Total** | | | | **7010** | **tonnes CO2** | |

## A-5

**Unit rates (per 1 metric ton waste/day)**

| Waste Type: | VET | Dairy | HORSE | POULTRY | GREENHOUSE | PB & SCAS | ANSCI | OTHER Plantations | Dining |
|---|---|---|---|---|---|---|---|---|---|
| Flow rate of Water: (to achieve desired TS) | 3.7 | 2.5 | 3.2 | 1.0 | 5.3 | 5.3 | 2.0 | 5.3 | 1.8 |
| Retention Time: (days) | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 |
| Total Volume of the Digester: (m^3) | 199.9 | 137 | 148 | 40 | 288 | 288 | 107 | 288 | 97 |
| Biogas Generated: (m^3/day) | 61 | 75 | 69 | 18 | 53 | 53 | 64 | 53 | 83 |
| Digestate generated (with water, how much can be used per day in m^3/day) | 3.7 | 2.5 | 3.2 | 1.0 | 5.3 | 5.3 | 2.0 | 5.3 | 1.8 |

*http://www.fovbiogas.com/biogas-calculator/

Assumptions made:
Vet (assuming 70% of animals are horses, 30% bovines) and that 50% of the waste is bedding material, or agricultural waste)
Diary (all cow manure)
Horse (75% horse manure, 25% ag waste as bedding material (sawdust))
Poultry (100% Chicken manure (activated sludge))
Greenhouse(100% ag waste)
PB & SCAS (100% ag waste)
Ansci(assuming 50% of animals are horses, 25% bovines, 25% pigs)
Plantations, Other (assuming 100% Ag waste)
Dining(Assuming 100% Kitchen, Fruit, Restaurant, Vegetable Waste)

## A-6

Flow Rate of Water Needed and Digestate Created (m^3/day, month, and year)

| MONTH | VET | Dairy | HORSE | POULTRY | GREENHOUS | PB & SCAS | ANSCI | OTHER Plantations | Dining | MONTH TOTALS |
|---|---|---|---|---|---|---|---|---|---|---|
| **JANUARY** | 182.2 | 734.5 | 419.3 | 4.0 | 136.8 | 0.0 | 12.2 | 3.9 | 67.4 | 1,560.4 |
| per day | 5.9 | 23.7 | 13.5 | 0.1 | 4.4 | 0.0 | 0.4 | 0.1 | 2.2 | 50.3 |
| **FEBRUARY** | 195.0 | 573.8 | 453.3 | 3.5 | 60.4 | 0.0 | 0.0 | 44.5 | 136.7 | 1,467.2 |
| per day | 7.0 | 20.5 | 16.2 | 0.1 | 2.2 | 0.0 | 0.0 | 1.6 | 4.9 | 52.4 |
| **MARCH** | 227.9 | 589.9 | 415.5 | 1.9 | 102.5 | 0.0 | 70.0 | 0.3 | 149.1 | 1,557.1 |
| per day | 7.4 | 19.0 | 13.4 | 0.1 | 3.3 | 0.0 | 2.3 | 0.0 | 4.8 | 50.2 |
| **APRIL** | 239.6 | 1,560.7 | 360.1 | 3.8 | 110.2 | 0.0 | 30.1 | 5.8 | 116.9 | 2,427.3 |
| per day | 8.0 | 52.0 | 12.0 | 0.1 | 3.7 | 0.0 | 1.0 | 0.2 | 3.9 | 80.9 |
| **MAY** | 249.0 | 1,032.8 | 164.1 | 6.5 | 86.1 | 0.0 | 14.4 | 41.1 | 110.2 | 1,704.2 |
| per day | 8.0 | 33.3 | 5.3 | 0.2 | 2.8 | 0.0 | 0.5 | 1.3 | 3.6 | 55.0 |
| **JUNE** | 155.4 | 1,859.1 | 218.3 | 4.2 | 105.9 | 314.3 | 5.4 | 21.8 | 39.8 | 2,724.1 |
| per day | 5.2 | 62.0 | 7.3 | 0.1 | 3.5 | 10.5 | 0.2 | 0.7 | 1.3 | 90.8 |
| **JULY** | 197.6 | 550.8 | 118.7 | 5.9 | 84.6 | 124.3 | 0.0 | 0.3 | 50.0 | 1,132.3 |
| per day | 6.4 | 17.8 | 3.8 | 0.2 | 2.7 | 4.0 | 0.0 | 0.0 | 1.6 | 36.5 |
| **AUGUST** | 182.2 | 0.0 | 139.5 | 5.0 | 74.0 | 99.1 | 5.9 | 5.3 | 58.8 | 569.8 |
| per day | 5.9 | 0.0 | 4.5 | 0.2 | 2.4 | 3.2 | 0.2 | 0.2 | 1.9 | 18.4 |
| **SEPTEMBER** | 174.8 | 45.9 | 151.2 | 4.0 | 85.1 | 59.5 | 16.7 | 4.4 | 160.5 | 702.1 |
| per day | 5.8 | 1.5 | 5.0 | 0.1 | 2.8 | 2.0 | 0.6 | 0.1 | 5.4 | 23.4 |
| **OCTOBER** | 245.3 | 0.0 | 303.0 | 3.8 | 125.2 | 41.1 | 52.2 | 135.9 | 168.7 | 1,075.2 |
| per day | 7.9 | 0.0 | 9.8 | 0.1 | 4.0 | 1.3 | 1.7 | 4.4 | 5.4 | 34.7 |
| **NOVEMBER** | 166.4 | 596.7 | 276.9 | 3.2 | 174.1 | 26.1 | 98.5 | 26.1 | 133.4 | 1,501.5 |
| per day | 5.5 | 19.9 | 9.2 | 0.1 | 5.8 | 0.9 | 3.3 | 0.9 | 4.4 | 50.0 |
| **DECEMBER** | 147.3 | 1,124.6 | 257.0 | 3.2 | 103.5 | 0.0 | 18.9 | 3.6 | 105.2 | 1,763.2 |
| per day | 4.8 | 36.3 | 8.3 | 0.1 | 3.3 | 0.0 | 0.6 | 0.1 | 3.4 | 56.9 |
| Yearly Totals (m^3) BY SOURCE | 2,362.7 | 8,668.9 | 3,276.9 | 48.9 | 1,248.5 | 664.4 | 324.5 | 292.9 | 1,296.7 | 18,184.3 |
|  |  |  |  |  |  |  |  |  | **Gallons per year** | 4803775 |

## A-7

### Economics of Setting up an Anerobic Digestion Facility

| | | | |
|---|---|---|---|
| | Initial at Time 0 | | |
| **Capital Costs** | | | |
| Land | $0 | | |
| Building | $300,000 | | |
| Anerobic Digester, Gas Cleaning, and Installation Costs | $500,000 | | |
| Bloom Fuel Cell | $2,820,000 | 4 100 KW fuel cells | http://www.fastcompany.com/1561844/how-does-bloom-box-energy-server-work<br>Assuming a fuel cell life of 10 years |
| **Total Capital Costs** | $3,620,000 | | |
| | Starting Year 1 and so on… | | |
| **Operating Costs** | | | |
| Electricity | $14,244 | | |
| Water | $24,018.88 | | |
| Maintenance | $20,000 | | |
| **Total Operating Costs** | **$58,263** | | |
| **Total Electricity Obtained Per Year from Bloom Fuel Cell** | $88,049.98 | Assuming local price of $0.05 per kWh | |
| **Cost of Electricity per kWh Obtained from Bloom Cell** | $0.0524 | per kWh | |

### Economics of Setting up Boiler 8 to Utilize Biomass

| | |
|---|---|
| | Initial at Time 0 |
| **Capital Costs** | |

None, as Boiler Utilized will be the same. In fact, it is the only boiler that can burn biomass with little or no modification, and air pollution controls are already in place

| | |
|---|---|
| **Total Capital Costs** | $0 |
| | Starting Year 1 and so on… |
| **Operating Costs** | |
| Willow | $6,050,218 |
| Disposal Costs of Ash | $148,183.20 |
| ***Assuming Maintenance is the same as Natural Gas** | |
| **Total Operating Costs** | **$6,198,401** |

## A-8

**Sizing of Bioreactor**

| | | |
|---|---|---|
| Max Daily Inputs (tonnes/day) | | 32 |
| Month of Max Production | | JUNE |
| | | |
| Volume Needed w/ Safety Factor | (m^3) | 4851 |
| Assuming a rectangular prism | | |
| Length | m | 45 |
| Width | m | 45 |
| Height | m | 2.5 |
| Maximum Volume Obtained | | 5062.5 |

(LxWxH) would fit in building:
Building housing anerobic digester and equipment would be would be 150 meters by 70 meters by 5 meters

| | |
|---|---|
| **Cost of Bioreactor** | $500,000 |

*http://www.fovbiogas.com

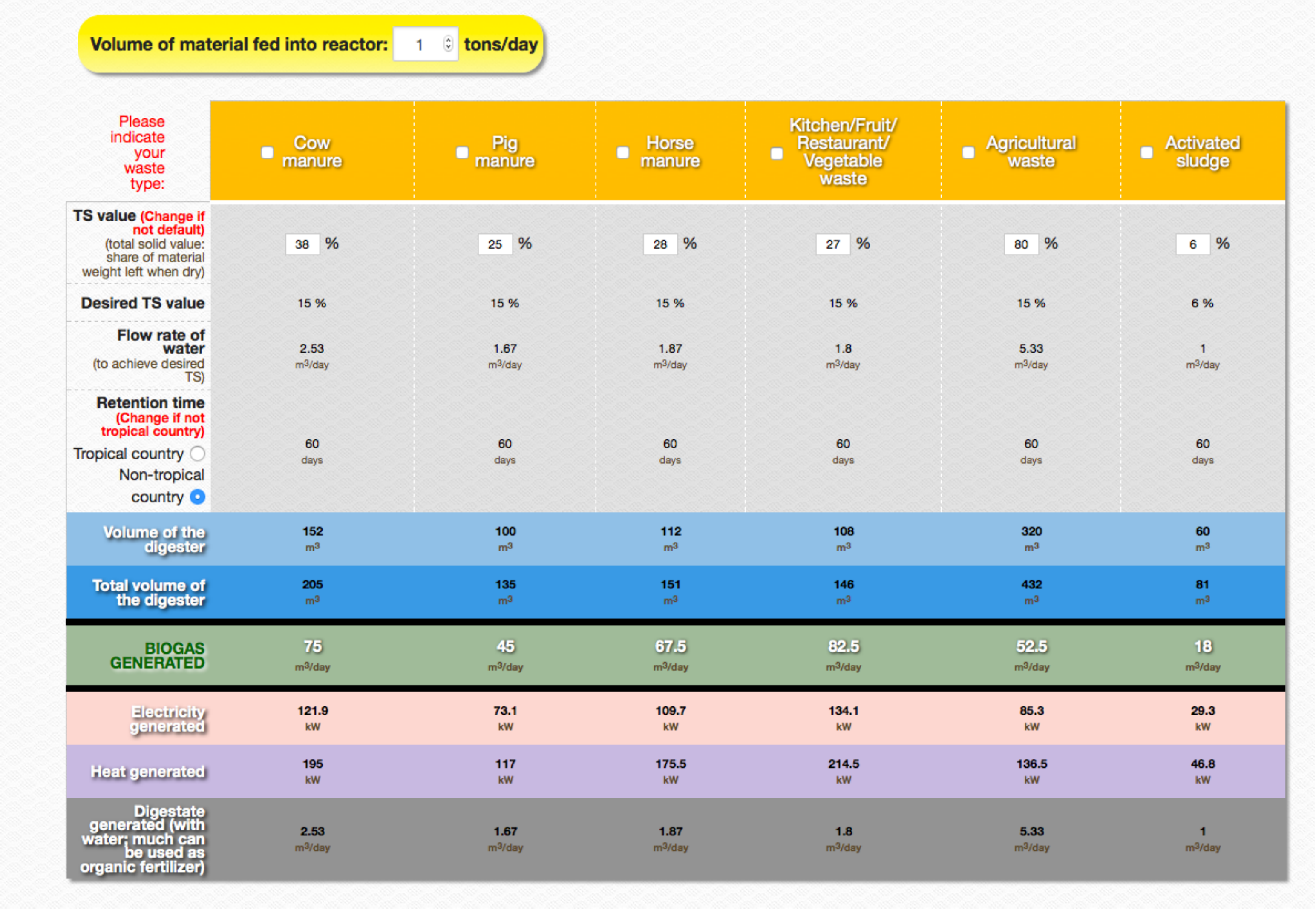
## A-9

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Cost Analysis** | | | | | | | | | | | |
| **Bloom Fuel Cells** | | | | | | | | | | | |
| Year | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Capital Costs | ($3,620,000) | - | - | - | - | - | - | - | - | - | - |
| Grants | $2,500,000 | | | | | | | | | | |
| Tax Credits | $1,086,000 | | | | | | | | | | |
| 30% of total cost, NYSERDA Grants | | | | | | | | | | | |
| Operating Costs | $0.00 | -$58,263.16 | -$60,011.05 | -$61,811.38 | -$63,665.73 | -$65,575.70 | -$67,542.97 | -$69,569.26 | -$71,656.34 | -$73,806.03 | -$76,020.21 |
| | | | | | | | | | | | |
| Cost Savings from Electricity Produced | $0.00 | $88,049.98 | $90,691.48 | $93,412.23 | $96,214.59 | $99,101.03 | $102,074.06 | $105,136.29 | $108,290.37 | $111,539.08 | $114,885.26 |
| | | | | | | | | | | | |
| Total Costs (Yearly) | ($34,000) | $29,787 | $30,680 | $31,601 | $32,549 | $33,525 | $34,531 | $35,567 | $36,634 | $37,733 | $38,865 |
| Discount Rate | 3% | | | | | | | | | | |
| IRR | 90% | | | | | | | | | | |
| **Net NPV** | **$255,192** | | | | | | | | | | |
| | | | | | | | | | | | |
| **Using Biomass for Boiler 8 Instead of Natural Gas** | | | | | | | | | | | |
| Year | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Capital Costs | | - | - | - | - | - | - | - | - | - | - |
| Grants | | | | | | | | | | | |
| Tax Credits | | | | | | | | | | | |
| 30% of total cost, NYSERDA Grants | | | | | | | | | | | |
| Operating Costs | $0.00 | $6,198,400.73 | $6,384,352.76 | $6,575,883.34 | $6,773,159.84 | $6,976,354.63 | $7,185,645.27 | $7,401,214.63 | $7,623,251.07 | $7,851,948.60 | $8,087,507.06 |
| | | | | | | | | | | | |
| Total Costs (Yearly) | $0 | $6,198,401 | $6,384,353 | $6,575,883 | $6,773,160 | $6,976,355 | $7,185,645 | $7,401,215 | $7,623,251 | $7,851,949 | $8,087,507 |
| Discount Rate | 3% | | | | | | | | | | |
| | | | | | | | | | | | |
| **Net NPV** | **$60,178,648** | | | | | | | | | | |
| | | | | | | | | | | | |
| **Using Natural Gas for Boiler 8** | | | | | | | | | | | |
| Year | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Capital Costs | | - | - | - | - | - | - | - | - | - | - |
| Grants | | | | | | | | | | | |
| Tax Credits | | | | | | | | | | | |
| 30% of total cost, NYSERDA Grants | | | | | | | | | | | |
| Operating Costs | $0.00 | $4,567,090.18 | $4,704,102.89 | $4,845,225.97 | $4,990,582.75 | $5,140,300.23 | $5,294,509.24 | $5,453,344.52 | $5,616,944.85 | $5,785,453.20 | $5,959,016.79 |
| | | | | | | | | | | | |
| Total Costs (Yearly) | $0 | $4,567,090 | $4,704,103 | $4,845,226 | $4,990,583 | $5,140,300 | $5,294,509 | $5,453,345 | $5,616,945 | $5,785,453 | $5,959,017 |
| Discount Rate | 3% | | | | | | | | | | |
| | | | | | | | | | | | |
| **Net NPV** | **$44,340,681** | | | | | | | | | | |

## A-10

|  |  |  |  |  |
|---|---|---|---|---|
| **Willow from Cornell Marginal Farmland** |  |  |  |  |
| All Cornell Owned Farmland | 2200 | acres |  |  |
| % of Land that is estimated to be Marginal Farmland | 10% |  |  |  |
| Cornell Marginal Farmland | 220 | acres |  |  |
| Willow takes 4 years to intially grow then, 3 years to harvest so land would be separated into three parcels |  |  |  |  |
| 3 parcels consisting of | 73 | acres each plot |  |  |
| Dry Energy Content | 77,900,000 | BTUs/acre | http://willow.cals.cornell.edu/FAQ.html |  |
| Energy Content Able to be Extracted | 5713 | MMBTUs/yr |  |  |
| Mass of willow per acre, wet | 5 | dry tons/acre-yr | http://www.esf.edu/willow/documents/WillowCropProductionCycle_000.pdf |  |
|  |  |  |  |  |
| Energy Needed to Dry Willow | 1175 | kWh/dry ton |  | Francescato et al., 2008; Swigon & Longauer, 2005; Nellist et al., 1993 |
| Energy Needed to Dry Willow from Parcel, Each Year | 1323 | MMBTU/year |  |  |
|  |  |  |  | Policy Implications of Greenhouse Warming Mitigation, Adaptation, and the Science Base |
| Energy Needed to Run Emissions Control System | 114 | MMBTU/year | 2% of total energy | Panel on Policy Implications of Greenhouse Warming |
| SOx and NOx removal |  |  |  | Committee on Science, Engineering, and Public Policy |
| Total Energy Available from Willow, each year for CHPP | 4275 | MMBTU/year |  | National Academy of Sciences |
|  |  |  |  | National Academy of Engineering |
| *Assuming that labor and materials are of little or no cost since such operations will be performed on research farms |  |  |  | Institute of Medicine |
|  |  |  |  |  |
| *Boiler 7 is the only boiler that can burn biomass directly with little or no conversion necessary, all other boilers cannot |  |  |  |  |
| **Boiler 7 Energy Input (Average, per Year)** | 1005967 | MMBTU/year |  |  |
|  |  |  |  |  |
| Deficit of Willow | 1001692 | MMBTU/year |  |  |
|  |  |  |  |  |
| Therefore, willow would need to be purchased | 57864 | dry tons per year |  |  |
|  |  |  |  |  |
| The current cost of willow is | $6.04 | per MMBTU |  |  |
|  |  |  |  |  |
| The cost of one year of willow would be | $6,050,217.53 |  |  |  |
| The current cost of natural gas | $4.54 | per MMBTU |  |  |
|  |  |  |  |  |
| The cost of one year of natural gas would be | $4,567,090.18 |  |  |  |
|  |  |  |  |  |
| The difference for one year is | $1,483,127.35 |  |  |  |
| Mass of Ash | 1743 | tons of ash | Assuming ash is 3% of dry willow content |  |
| Disposal Cost of Ash | $148,183 | per year | http://www.recycletompkins.org/Garbage/Permits-and-Fees_ |  |
|  |  |  | http://willow.cals.cornell.edu/FAQ.html |  |
|  |  |  | Disposal Costs $85/ton in Tompkins County |  |

## A-11

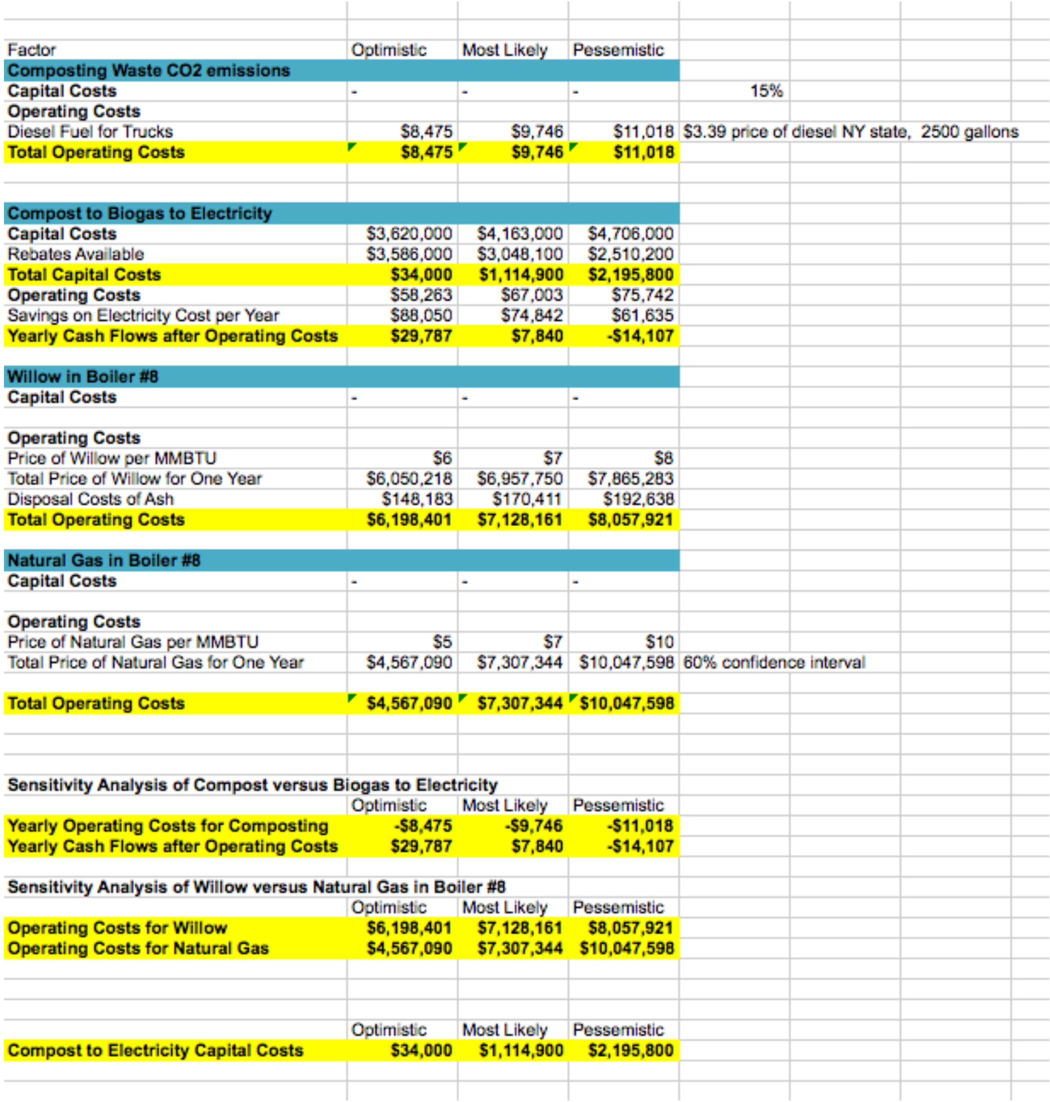


Volume of material fed into reactor: 1 tons/day

| Please indicate your waste type: | ☐ Cow manure | ☐ Pig manure | ☐ Horse manure | ☐ Kitchen/Fruit/ Restaurant/ Vegetable waste | ☐ Agricultural waste | ☐ Activated sludge |
|---|---|---|---|---|---|---|
| TS value (Change if not default) (total solid value: share of material weight left when dry) | 38 % | 25 % | 28 % | 27 % | 80 % | 6 % |
| Desired TS value | 15 % | 15 % | 15 % | 15 % | 15 % | 6 % |
| Flow rate of water (to achieve desired TS) | 2.53 $m^3$/day | 1.67 $m^3$/day | 1.87 $m^3$/day | 1.8 $m^3$/day | 5.33 $m^3$/day | 1 $m^3$/day |
| Retention time (Change if not tropical country)<br>Tropical country ○<br>Non-tropical country ● | 60 days | 60 days | 60 days | 60 days | 60 days | 60 days |
| Volume of the digester | 152 $m^3$ | 100 $m^3$ | 112 $m^3$ | 108 $m^3$ | 320 $m^3$ | 60 $m^3$ |
| Total volume of the digester | 205 $m^3$ | 135 $m^3$ | 151 $m^3$ | 146 $m^3$ | 432 $m^3$ | 81 $m^3$ |
| BIOGAS GENERATED | 75 $m^3$/day | 45 $m^3$/day | 67.5 $m^3$/day | 82.5 $m^3$/day | 52.5 $m^3$/day | 18 $m^3$/day |
| Electricity generated | 121.9 kW | 73.1 kW | 109.7 kW | 134.1 kW | 85.3 kW | 29.3 kW |
| Heat generated | 195 kW | 117 kW | 175.5 kW | 214.5 kW | 136.5 kW | 46.8 kW |
| Digestate generated (with water; much can be used as organic fertilizer) | 2.53 $m^3$/day | 1.67 $m^3$/day | 1.87 $m^3$/day | 1.8 $m^3$/day | 5.33 $m^3$/day | 1 $m^3$/day |

Obtained from FOV Biogas http://www.fovbiogas.com/biogas-calculator/

## A-12



| Factor | Optimistic | Most Likely | Pessemistic | |
|---|---|---|---|---|
| **Composting Waste CO2 emissions** | | | | |
| **Capital Costs** | - | - | - | 15% |
| **Operating Costs** | | | | |
| Diesel Fuel for Trucks | $8,475 | $9,746 | $11,018 | $3.39 price of diesel NY state, 2500 gallons |
| **Total Operating Costs** | **$8,475** | **$9,746** | **$11,018** | |
| | | | | |
| **Compost to Biogas to Electricity** | | | | |
| **Capital Costs** | $3,620,000 | $4,163,000 | $4,706,000 | |
| Rebates Available | $3,586,000 | $3,048,100 | $2,510,200 | |
| **Total Capital Costs** | **$34,000** | **$1,114,900** | **$2,195,800** | |
| **Operating Costs** | $58,263 | $67,003 | $75,742 | |
| Savings on Electricity Cost per Year | $88,050 | $74,842 | $61,635 | |
| **Yearly Cash Flows after Operating Costs** | **$29,787** | **$7,840** | **-$14,107** | |
| | | | | |
| **Willow in Boiler #8** | | | | |
| **Capital Costs** | - | - | - | |
| **Operating Costs** | | | | |
| Price of Willow per MMBTU | $6 | $7 | $8 | |
| Total Price of Willow for One Year | $6,050,218 | $6,957,750 | $7,865,283 | |
| Disposal Costs of Ash | $148,183 | $170,411 | $192,638 | |
| **Total Operating Costs** | **$6,198,401** | **$7,128,161** | **$8,057,921** | |
| | | | | |
| **Natural Gas in Boiler #8** | | | | |
| **Capital Costs** | - | - | - | |
| **Operating Costs** | | | | |
| Price of Natural Gas per MMBTU | $5 | $7 | $10 | |
| Total Price of Natural Gas for One Year | $4,567,090 | $7,307,344 | $10,047,598 | 60% confidence interval |
| **Total Operating Costs** | **$4,567,090** | **$7,307,344** | **$10,047,598** | |
| | | | | |
| **Sensitivity Analysis of Compost versus Biogas to Electricity** | | | | |
| | Optimistic | Most Likely | Pessemistic | |
| **Yearly Operating Costs for Composting** | **-$8,475** | **-$9,746** | **-$11,018** | |
| **Yearly Cash Flows after Operating Costs** | **$29,787** | **$7,840** | **-$14,107** | |
| | | | | |
| **Sensitivity Analysis of Willow versus Natural Gas in Boiler #8** | | | | |
| | Optimistic | Most Likely | Pessemistic | |
| **Operating Costs for Willow** | **$6,198,401** | **$7,128,161** | **$8,057,921** | |
| **Operating Costs for Natural Gas** | **$4,567,090** | **$7,307,344** | **$10,047,598** | |
| | | | | |
| | Optimistic | Most Likely | Pessemistic | |
| **Compost to Electricity Capital Costs** | **$34,000** | **$1,114,900** | **$2,195,800** | |

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