Anaerobic Digestion and Biogas Production Feasibility Study

University of Idaho

UNIVERSITY OF IDAHO
SUSTAINABILITY CENTER

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS AND ACRONYMS

C/N	Carbon to Nitrogen Ratio
CO_2	Carbon Dioxide
CHP	Combined Heat and Power
DSS	Dewatered Sewage Sludge
EPA	Environmental Protection Agency
FM	Full Matter
H_2S	Hydrogen Sulfide
MSU	Michigan State University
PREEC	Palouse Research, Extension and Education Center
RNG	Renewable Natural Gas
TS	Total Solids
UI	University of Idaho
VS	Volatile Solids
WRRF	Water Reclamation and Reuse Facility

Executive Summary

Anaerobic digestion is a biological process that can be utilized to reduce organic waste to a methane-rich biogas and a fertilizer referred to as digestate. Anaerobic digestion facilities, also referred to as biogas facilities, utilize large anaerobic digestion tanks void of oxygen to facilitate this biological process on a large scale. It is in these tanks that organic waste is heated, mixed, and decomposed to produce a carbon-neutral renewable energy in the form of biogas. Biogas is a mixture of primarily methane and carbon dioxide that can be burned and thus, utilized a fuel source. This study analyzed the feasibility of using the University of Idaho (UI) and City of Moscow's organic waste to produce biogas to operate two facility alternatives: combined heat and power (CHP) or renewable natural gas (RNG). The power produced from the CHP system would be used for on-site energy demand and additional energy would be exported to the city grid. Additionally, the heat produced would be used to meet digester heating demands. Alternatively, the renewable natural gas produced would be used to offset the UI Steam Plant and overall UI natural gas usage. The proposed site for the biogas facility is adjacent to the current UI Dairy Center. The annual 10,090 combined tons of organic waste including dewatered sewage sludge (DSS), yard waste, dairy cow manure, food waste, and grass clippings from both the UI and City of Moscow would be converted to a biogas and a resulting digestate fertilizer at this site.

This study utilized a co-digestion economic model from the Environmental Protection Agency (EPA) to assist in estimating costs and biogas output relating to an anaerobic digestion facility. Additionally, it was used to size the potential CHP engine and digestion tank, estimate digester heating demand, and predict capital investment costs. As a note, many assumptions were made in the model as well as this study that should be scientifically confirmed before progressing to facility implementation.

The annual biogas capability of Moscow, Idaho's organic waste was estimated to be 31,191,829 ft^3 using the EPA model. At an assumed 60% methane content in the biogas, this corresponds to 18,715,097 ft^3 of annual methane produced. This gas can provide fuel to generate 222 kW with an internal combustion CHP system. This is enough energy to offset the annual UI consumption by an approximate 3.36% which totals to $114,026 in energy cost savings, assuming $0.069 per kWh. Alternatively, the biogas can be cleaned to almost entirely methane to provide an approximate of 273,012 annual natural gas equivalent therms to the UI. This totals to $163,807 in natural gas savings assuming a purchasing price of $0.60 per therm.

The produced biogas can be used as an energy source which offsets energy costs but the digestate output also introduces cost savings. During anaerobic digestion, some of the solids within the organic materials are consumed by the biological consortium within the tank and converted to biogas. This reduces waste tonnage, thus introducing waste management savings. This study determined that the biogas facility would reduce the organic waste by around an annual 4,122 tons. This corresponds to an annual waste management savings of $201,625. Additionally, the liquid portion of the digestate was assumed to be captured and held in a large tank with an annual fertilizer sale value of approximately $47,033.

The biogas and digestate offer potential savings, income, and renewable energy to Moscow, Idaho but it does not come without a price. With the assistance of the EPA model, the capital investment for a biogas facility was determined to cost $6,228,681 for the RNG alternative and $7,719,081 for the CHP alternative. This cost includes all material costs including the anaerobic digester, digestate storage tank, system automation, pumps, piping, etc. Furthermore, it includes engineering and installation of the facility as well an assumed interest expense.

The operation and maintenance costs were not given by the EPA model, so a case study of Michigan State University's campus anaerobic digester was completed, and operation and maintenance cost data were extrapolated to this study. This cost was estimated to be $65,000 annually with an added labor cost of $50,000. Additional operations costs include the collection and transportation of grass clippings form the UI since this waste stream is not currently collected, as well as on-site energy usage which was assumed to be 15% of the CHP production capability. In total, annual operation and maintenance costs were determined to be approximately $158,792 for the RNG facility and $138,670 for the CHP facility. The RNG facility operation and maintenance costs were slightly higher than the CHP costs because the CHP facility can use energy that it produces while the RNG facility must purchase electricity to meet on-site energy demands.

The payback for the two facility alternatives was then determined using the cost data combined with the estimated avoided costs and income. The operation and maintenance costs as well as the avoided costs were assumed to inflate at a rate similar to their corresponding consumer price index. This resulted in a 16.92-year payback for the RNG alternative and a 26.71-year payback for the CHP alternative. This payback assumes any income made throughout the year is fully applied to the capital cost loan. In summary, the UI and City of Moscow must find outside funding such as government grants and/or donors to help offset the capital investment of a biogas facility if they are to implement this renewable energy technology. If the facility became operational, however, it would save on transportation, energy, and waste management costs as well as provide the UI with a baseload renewable energy source. An anaerobic digestion technology can provide an odor control method, divert waste from landfills, reduce local carbon impacts, and overall make Moscow, Idaho more sustainable.

Scope of Work

The scope of work for this study includes the following:

- Review of anaerobic digestion fundamentals and the requirements that must be met at a biogas facility to optimally produce biogas.
- Overview of CHP and RNG systems.
- Organic waste data collection and analysis of feedstock data from the UI and the City of Moscow.
- Estimation of biogas potential from the available feedstocks using a model from the EPA.
- Case-study review of Michigan State University South Campus anaerobic digester to support biogas facility operations in both a continental temperate climate and campus setting. This case study will also assist to develop a baseline for annual operation and maintenance costs.
- Applicability for biogas upgrading for RNG use in the UI Steam Plant.
- Applicability for electricity production for the City of Moscow grid.
- Economic estimation for the proposed Moscow, Idaho biogas facility using the EPA CoEAT economic analysis model.

Anaerobic Digestion and Requirements

The process of producing biogas and fertilizer through the anaerobic digestion process requires an exceptional understanding of the fundamentals. Anaerobic digestion is a chemical process that takes place at the microbial level. However, when dealing with so much waste, the anaerobic digestion scale can be quite large. Facilities that utilize anaerobic digestion to covert organic waste to energy are often referred to as biogas plants or facilities. Biogas plants contain sequential processes that take a waste product and transform it into an energy source (biogas) as well as an organic fertilizer (digestate). An anaerobic digestion overview, as well as the requirements to optimally produce biogas are detailed below.

Anaerobic Digestion Overview

Anaerobic digestion is a sequence of biological processes that utilize a wide range of microorganisms in the absence of oxygen to convert organic matter to methane-rich biogas (L. Chen & Neibling, 2014). Traditionally, anaerobic digestion has been used in wastewater treatment plants to treat sewage sludge. It is also a popular method for dairy farms to limit manure odors, reduce waste volumes, and simultaneously produce electricity for use on-site or for grid export. Anaerobic digestion, however, is not limited to these applications. In the case of the UI and the City of Moscow, it can be used to convert the wide variety of local organic wastes to biogas and fertilizer. The fuel produced by anaerobic digestion is referred to as biogas which is made up primarily of carbon dioxide and methane. The methane makes this gas combustible, and therefore, a valuable fuel source. The primary use for the methane-rich biogas is electricity and heat generation in a CHP system. Alternatively, the biogas can be cleaned and upgraded to almost entirely methane for natural gas applications, referred to as a RNG, or further compressed to be used as a transportation fuel, referred to as compressed natural gas. The two biogas uses considered for this study are CHP and RNG which will be discussed in more depth in the next section.

Biogas is recognized as a carbon-neutral renewable energy source because it comes from renewable organic sources and is thus biogenic. When organics decompose naturally, they are converted to carbon dioxide. Producing biogas can be viewed as an intermediate step to natural decomposition. The organic matter is first converted to a biogas and upon combustion of the methane, it is converted to almost entirely carbon dioxide. The same carbon dioxide is produced as if the organics were to break down naturally, except a fuel is achieved first. The organic matter that was not converted to biogas during anaerobic digestion, referred to as the digestate, can be used as a fertilizer since it is often rich in nutrients such as nitrogen and phosphorus.

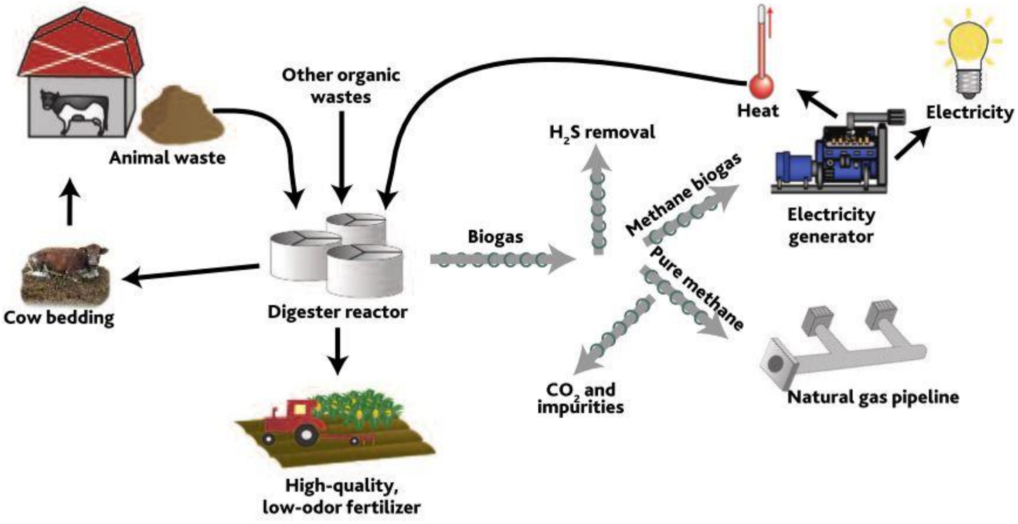
The processes involved in a biogas plant in Moscow, Idaho would include pre-treatment of the organic waste (further referred to as the feedstocks), anaerobic digestion inside a digester tank (see Figure 3), biogas upgrading for utilization, and digestate treatment. These steps are all explained in detail next.

During pre-treatment, feedstocks are conditioned to enhance the anaerobic digestion process and, in turn, increase biogas output. This may involve screening to remove inorganic components, pulverizing the waste, and mixing the various feedstocks in a set ratio. Once the feedstock is prepared, it enters a digester generally through a pumping system. These pumps may have chopper blades in place to further pulverize the feedstocks entering the digester. In the digester, anaerobic digestion takes place. The feedstock mix is heated, continuously stirred by mixers, and kept in the digester for a number of days determined by design. The biogas is produced and collected; digestate is collected at the end of the process.

The last step is to condition the biogas and digestate for its specified use. Generally, this process involves removing the carbon dioxide, water vapor, hydrogen sulfide, and other non-methane components present in the biogas. Gas cleaning will be discussed further in the next section. A large amount of liquid is present in the digestate after anaerobic digestion and solids and liquids must be separated to be used efficiently as a fertilizer. Separating the digestate involves dewatering or drying the material. Depending on the digestate classification desired, the material may have to be heated further to kill remaining harmful pathogens before being applied to cropland.

A typical biogas production configuration is illustrated in Figure 1 below. In the context of the UI and City of Moscow, the other organic wastes shown in the figure would include food waste, DSS, grass clippings, and yard waste.

<u>Figure 1:</u> Typical biogas facility configuration. Taken from (L. Chen & Neibling, 2014).



Biologically, anaerobic digestion is a four-phase microbial process illustrated in Figure 2. The processes include hydrolysis, acidogenesis, acetogenesis, and methanogenesis. There is a great deal of technical literature on this subject but for the sake of this study, the processes are briefly explained as to give some context of the anaerobic digestion process occurring within a digester. In the hydrolysis phase, the input complex organic-rich waste polymers (complex carbohydrates, lipids, proteins, and potentially starch) are broken down to simple monomers (Korres, O'Kiely, Benzie, & West, 2013). The carbohydrates are broken down into sugars, proteins into amino acids, lipids into fatty acids, and starch into glucose (L. Chen & Neibling, 2014). In the acidogenesis phase, soluble monomers are converted to volatile fatty acids as well as acetic acid, hydrogen, and carbon dioxide. The acetogenesis phase converts the volatile fatty acids to acetic acids, hydrogen, and carbon dioxide. The final and most important stage in anaerobic digestion is the methanogenesis phase. This is where the acetic acid, hydrogen, and carbon dioxide is converted into the methane-rich biogas (L. Chen & Neibling, 2014). The typical biogas composition is displayed in Table 1. As a note, the components contained in biogas, along with the methane to carbon dioxide ratio, is largely dependent on the feedstocks utilized. For example, sole digestion of a feedstock such as yard waste will result in a lower percentage of methane while sole digestion of food waste will result in a higher percentage of methane due to differing waste characteristics.

Figure 2: Biological biogas production process. Based on (Korres et al., 2013), (L. Chen & Neibling, 2014), and (Stowe & Coats, 2014)

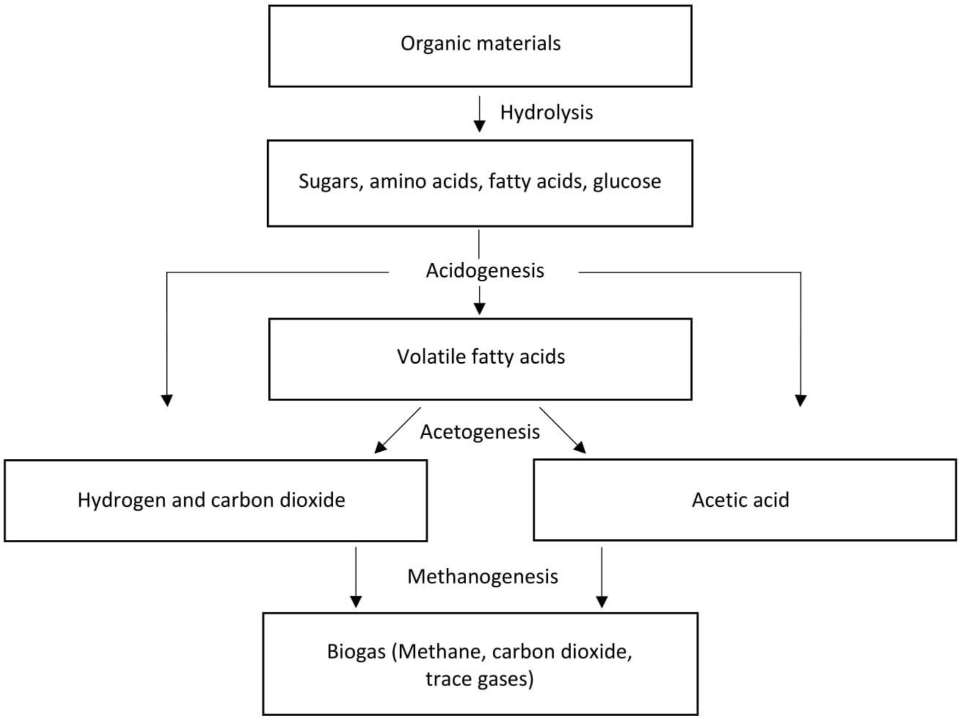


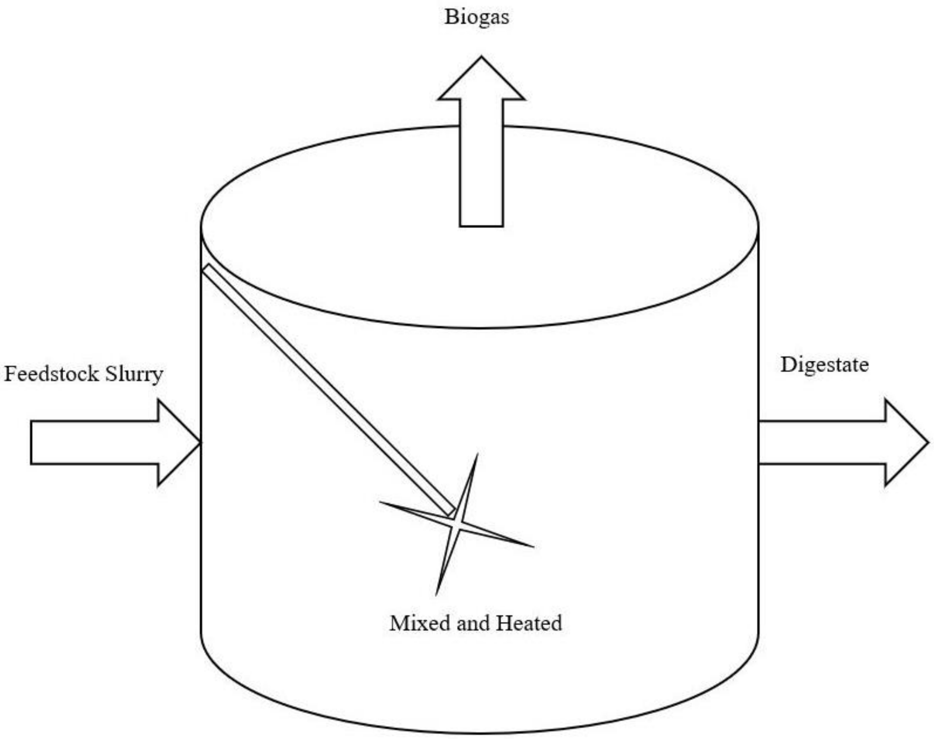
Table 1: General biogas makeup. Based on (Karellas, Boukis, & Kontopoulos, 2010).

Component	Percentage
Methane (CH_4)	55-75%
Carbon dioxide (CO_2)	25-45%
Carbon monoxide (CO)	0-0.3%
Nitrogen (N_2)	1-5%
Hydrogen (H_2)	0-3%
Hydrogen sulfide (H_2S)	0.1-0.5%
Oxygen (O_2)	Trace percentages

The biological populations in the anaerobic digester must be kept in balance to avoid system failure. The microbial populations in the hydrolysis and acidogenesis phases react the fastest to feedstock increases, forming carboxylic acids. The pH range of the digesting material is important for the remaining acetogenesis and methanogenesis processes, so an alkaline substance can be used maintain the proper pH. Methanogenic organisms are the most susceptible to pH and temperature fluctuations, and thus it is imperative to sustain environmental conditions suitable for their growth (L. Chen & Neibling, 2014). As a note, feedstock variations may change which processes require the most attention.

The digester design will be a complete-mix digester utilizing wet anaerobic digestion for the sake of this feasibility study. In a complete-mix digester, the feedstock enters the digester as a slurry, is heated, mixed and retained for an amount of time determined by design; treated waste is discharged from the digester as the digestate. A basic complete-mix digester design is shown in Figure 3. Moreover, the anaerobic digestion process can be wet or dry. As an overview, wet digestion involves feedstocks with a high enough water content to be pumped while dry digestion deals with feedstocks that cannot be pumped. It is assumed by this study that the feedstocks have a high enough water content to utilize wet anaerobic digestion.

Figure 3: Basic complete-mix digester configuration.



Requirements for Optimal Digestion

Requirements for successful, stable anaerobic digestion are detailed below. As an overview, parameters that require control within a biogas facility include heating of the digester, pH, pre-treatment processes, the solids ratio within a digester, loading rate of the digester, and digestate management. Many of these controls are accounted for by the automation equipment in a biogas plant and operation and maintenance of this control equipment is important. Once the facility is designed, the overall process is greatly simplified. These control requirements are explained in detail in this section.

Temperature

Within an anaerobic digester, the material must be heated, and the temperature must be held stable throughout the digestion process. This is done to set an optimal environment for the microbial populations carrying out the digestion process. Anaerobic digestion can be operated in the mesophilic (86-100°F) and thermophilic (122-135°F) temperature ranges (Begum, 2014). Mesophilic digestion is the most common mode of operation around the world because it requires less energy to heat and is more stable than thermophilic digestion. Thermophilic digestion requires more energy to maintain higher temperatures, but kills more pathogens present in the feedstocks, creating a more valuable fertilizer. Thermophilic digesters do not require the material to remain in the digester as long as mesophilic digesters due to a higher reaction rate, and thus have smaller treatment systems (Water Environment Federation, 2017). However, thermophilic digesters are less stable, more susceptible to failure, and harder to control. This study will determine the feasibility of operating the Moscow anaerobic digester in the mesophilic temperature range at 100°F. Digesters are commonly heated by boilers that burn some generated biogas to produce heat. Hot water can then be circulated throughout the walls of the anaerobic digestion to heat the material within. Alternatively, a CHP system can be used to heat the digester as discussed in the next section.

pH

Maintaining near-constant pH within a digester is critical for the methane-forming bacteria. The anaerobic digester pH value must be maintained between 6.5-7.5 to produce the most biogas. Values outside of this range will slow or stop biogas production completely, resulting in system failure (L. Chen & Neibling, 2014). The pH can be controlled by operation staff through the addition of alkaline or acids when needed to prevent digester failure. The design of the digester should limit the number of times operation staff have to intervene. The feedstocks utilized play a large role in the pH processes required at a biogas plant.

Carbon:Nitrogen Ratio

The amount of carbon and nitrogen present in a feedstock is represented by the carbon:nitrogen (C/N) ratio. Anaerobic digestion is optimized when this ratio is between 16:1 and 25:1 (Abbasi, Tauseef, & Abbasi, 2012). A ratio higher than 25:1 indicates the feedstock is too rich in carbon. The methanogens will consume the nitrogen faster than the carbon and the volatile solids will not be consumed completely, thus, limiting the biogas output. Volatile solids represent the organic portion of the feedstock that the microbial populations can convert to biogas. If the C/N ratio is lower than 16:1, there is excess nitrogen in the system which accumulates as ammonia, increasing the pH. Once above 8.5 from ammonia accumulation, it becomes toxic for the methanogens, thus, limiting biogas output and potentially causing system failure (Abbasi et al., 2012). An ideal C/N ratio can be achieved by the appropriate mixing of feedstocks. For example, since yard waste can have a high C/N ratio, mixing it with dairy cow manure, which can have a low C/N ratio, could result in an optimal C/N ratio. The mixing of two or more feedstocks to be followed by anaerobic digestion is referred to as co-digestion. Co-digestion increases the complexity of a biogas production system, but it can also increase the efficiency of converting the feedstocks to biogas. This occurs by optimizing many of the digestion parameters through proper feedstock mixing ratios. Table 2 shows the C/N ratios of the feedstocks considered for this study.

Table 2: C/N ratios of considered feedstocks. Based from (Abbasi et al., 2012), (Erkan, Engin, Ince, & Bayramoglu, 2016), (Steffen, Szolar, & Braun, 1998), and (Idris Tanimu, Idaty Mohd Ghazi, Razif Harun, & Idris, 2015)

Feedstock	**C/N Ratio**
Dairy manure	6-24*
Dewatered sewage sludge	20-25
Grass	12-25
Leaves	30-80
Food Waste	17-30

*Dependent on mixed bedding

Feedstock Surface Area

The microbial populations are only able to break down volatile solids that they are in contact with. Large, bulky materials are less likely to be digested completely because the surface area is small compared to the volume of the material. Optimal digestion occurs when the material is ground and broke down into small pieces before entering the digester. Because of this, a feedstock pre-treatment process should include grinding and the material should be homogenized. Furthermore, the feedstocks must to be transported using pumping systems that generally cannot handle bulky materials, so the portion size of the feedstocks must be reduced.

Retention Time

Retention time is the amount of time the feedstocks must remain within the digester to achieve optimal biogas production. In general, the retention time can be separated into hydraulic retention time and solids retention time. Hydraulic retention time is the total residence time of the feedstocks in the digester tank. A goal of anaerobic digestion is to reduce the hydraulic retention time so more organic material can be digested in a shorter amount of time. A shorter hydraulic retention time is generally associated with a more efficient digester. Solids retention time refers to the amount of time that the solids fraction is retained within the digester. Solid retention time control requires a solids separation stage, wherein the liquid is separated from solids and the solids are returned to the digestion tank. The hydraulic retention and solid retention times are largely determined by the selected digester configuration and the feedstock being digested.

A conventional complete-mix digester operates in fed-batch mode; in most applications, new feedstocks are added to the digester on a regular basis (e.g., every 30-60 minutes), with some digester contents first removed to ensure “fresh” feedstocks are not bypassed without treatment. In this operational configuration, there is no solids-liquid separation stage, and thus the hydraulic retention time is equal to the solids retention time (Abbasi et al., 2012). Complete-mix digesters can operate in continuous mode, but the digestate will contain a greater amount of volatile solids since ultimately some “fresh” feedstock bypasses treatment. The hydraulic retention time assumed in this study is 25 days.

Digester Feeding

The anaerobic digester organic loading rate is one of the most important design parameters. The organic loading rate is the rate at which new feedstocks are added to a digester per unit volume. An excessive organic loading rate can lead to accumulation of carboxylic acids, thus, lowering the pH to a toxic level for the methanogens and causing system failure (Abbasi et al., 2012); such a failure is referred to as going “sour.” The system can be stabilized by reducing the organic loading rate until the pH re-stabilizes, or by adding sufficient alkalinity. A low organic loading rate indicates the system is not optimized, and the biogas output will not be as high as the design potential.

Mixing

The material within a digester must be kept homogenous while undergoing anaerobic digestion. Mixing is thus required to maintain stability and optimize biogas production. Mixing the material limits the formation of foam and helps maintain a uniform temperature throughout the digester (Abbasi et al., 2012). Mixing also keeps the solids in suspension and inoculates new material with the anaerobic digester microbial consortium (Lindmark, Thorin, Fdhila, & Dahlquist, 2014). However, excess mixing may be a waste of energy, leading to a less efficient digestion process, and can also cause foaming. Continuous digester mixing is not required, instead, periodic mixing can sufficiently maintain the feedstock and microbial consortium in necessary contact. There are many different mixing technologies including mechanical agitation, circulation pumps, gas injection, and stirring by gas formation (Deublein & Steinhauser, 2010a). The type of mixing is dependent on the feedstock and is an important design consideration. The most common type of mixing for a complete mix digester is a mechanical agitation system. This involves spinning mechanical turbines within the digester to mix the material. This study will assume the mixing method is mechanical agitation.

Toxicity

Many elements, compounds, ions, and materials have been studied in relation to their inhibitory effect on anaerobic digestion. Heavy metals such as zinc, chromium, nickel, and cadmium have been shown to have a negative effect on methane producers (Alta, 2009). Care should be taken to keep excess metallic substances out of digesters. Accumulation of ammonia, sulfide, detergents, and a number of organics have been shown to be toxic to digesters as well (Y. Chen, Cheng, & Creamer, 2007). Light metal ions such as sodium, potassium, and calcium are required for microbial growth but higher concentrations can become inhibitory and even toxic (Y. Chen et al., 2007). Inhibitory materials should be removed from feedstocks before digestion. The composition of the anaerobic digestion feedstock should be known to enhance biogas output. Additionally, digesters should be cleaned regularly to limit the accumulation of toxins. Feedstock screening for inorganic materials should be a pre-treatment process.

Digestate Characteristics

As described, anaerobic digestion produces both biogas and digestate. Thus far, the focus has been on maximizing the biogas output. In general, biogas is the more valuable of the two outputs, so the main emphasis is on this production. However, the digestate has value as well. The feedstocks digested as well as the anaerobic process largely determine the quality of the digestate. The DSS from the Moscow Water Reclamation and Reuse Facility (WRRF) as well as dairy manure has the potential of containing bacterial pathogens and viruses that pose a threat to human health. These pathogens can include *Salmonella, Escherichia coli, Listeria*, *etc.* Pathogen destruction is dependent on the temperature of anaerobic digestion and the retention time. The Environmental Protection Agency categorizes digestate as Class A or B; classification is dependent pathogen populations, metal concentration, and vector attraction reduction characteristics. In the context of biosolids, vectors are flies, mosquitos, birds, rodents, etc. that can transmit pathogens to other hosts (United States Environmental Protection Agency, 1994). The concern is that said vectors could transmit potential pathogens into the environment, should they come in contact with the digestate. Vector reduction is associated with digestion of organic matter, such that vectors are less likely to be attracted to the product. Class A digestate or biosolids are more valuable, in that the product has been treated to a higher level, and thus can be used in more applications. Class A digestate pose little risk to human safety and can be used as a normal fertilizer (United States Environmental Protection Agency, 1994). Class B solids are ranked below Class A and can be used in fewer applications because of the digestate characteristics. Class B digestate must be managed by the producer, should the product be used as a fertilizer. Digestion in the mesophilic temperature range is generally not high enough to kill off all the pathogens present in the feedstocks so only Class B is obtained. The process design usually has to be modified or extra steps must be added to achieve Class A. Pasteurization of the digestate at 70°C for 60 minutes is often one added step for mesophilic digesters to achieve greater pathogen destruction (Abbasi et al., 2012). This study will conservatively assume Class B, thus the solid digestate must be additionally composted to be utilized as fertilizer.

After digestion, the digestate is dewatered and separated into solids and liquids which both can be used as a fertilizer. The solids will be composted and then used as a fertilizer while the liquids are held in a storage tank until they can be land applied. A storage tank is necessary because the fertilizer can only be used seasonally. Some systems collect biogas from the liquid digestate tanks as well as the digester but this study will assume biogas collection is only on the anaerobic digestion tank.

Biogas Utilization

This study is to determine the feasibility of using the biogas for electricity production or in natural gas boilers in the UI Steam Plant. Each method requires slightly different processes and equipment. An overview of CHP as well as RNG systems are listed below.

Combined Heat and Power

A CHP system at the biogas facility involves the production of heat and power through the combustion of biogas produced during the anaerobic digestion process. CHP is also referred to as cogeneration. Producing electricity and heat is the most common use of biogas in anaerobic digestion facilities. As an overview, the CHP process involves gas cleaning, combustion, driving a generator, and heat exchange. Each step is described below.

Gas Cleaning

Employing CHP using biogas requires that the gas is cleaned to eliminate harmful compounds that cannot be burned or are corrosive. The main compounds removed from the biogas before burning are water vapor and hydrogen sulfide (H_2S). Water vapor must be removed to increase the heating value of the gas and to prevent corrosion in the gas lines. Water vapor can be removed by decreasing the temperature of the gas line; the water will condense and can be collected for removal. Another method to remove water vapor involves refrigeration and pressurization of the biogas to induce condensation. Lastly, the biogas can be passed through an absorption medium such as silica gel to collect the water vapor (Begum, 2014).

Removing H_2S present in the biogas is important because it is a corrosive gas that can be damaging to CHP equipment. Specifically, when the H_2S is burned in the CHP engine, it can combine with water to form sulfuric acid which is also corrosive (Clarke Energy, 2014). H_2S can be removed from the biogas using water scrubbing, activated carbon or other media, biofiltration, or injecting a small amount of oxygen into the headspace of the digester. Water scrubbing technologies utilize injected water to capture the H_2S. Activated carbon can be used to absorb the H_2S. The biogas can also be passed through iron hydroxide or oxide media mixed with wood chips to absorb the H_2S. Biofiltration uses microbial populations to metabolize the H_2S. The biogas is passed through a media such as moss or wood chips that contain a high population of microbes. Lastly, a small amount of oxygen can be injected into the top of the digester where the biogas is held. This chemically eliminates some of the H_2S before it even leaves the digester. This last method can be dangerous because once oxygen is introduced to the biogas, it becomes combustible. So, the injected oxygen must be carefully controlled.

Once the water vapor and H_2S have been removed from the biogas, it can be passed to the CHP engines to be burned. Biogas CHP engines are generally designed to be able to handle mixed CO_2 with the CH_4, so CO_2 removal is not necessary.

Combustion

Once biogas has been sufficiently pretreated to remove contaminants, the next step is to burn the biogas. There are many CHP engine designs to achieve this including internal combustion engines, microturbines, and steam turbines (Bastian et al., 2011). The basis of the combustion stage is to use the biogas to generate heat and drive an engine generator to produce electricity. An internal combustion engine achieves this by driving a piston much like an automobile engine, and heat is captured using a hot water circuit associated with jacketing the engine generator and potentially the exhaust piping. Microturbines use the combusted gas to spin a turbine. Steam turbines use the heat produced by combustion to heat water and produce pressurized steam to drive a turbine. An internal combustion CHP engine with an electrical efficiency of 35% and a heat capture efficiency of 43% will be assumed for this study.

Electricity Generation

The biogas is burned and used to spin a shaft; this spinning motion is central to electricity generation. The shaft is used to spin inside the generator rotates metal coils between magnets inside the generator. This creates current and is used to produce power. A CHP system encompasses a generator and a variety of electrical equipment to regulate power production and export it to the city grid.

Heat Exchange

CHP systems are unique in that they utilize the heat produced by power generation. This heat is generally captured using water. Heat can be captured from both the engine and the outlet flue gases. Water is circulated throughout the CHP engine using piping. As the biogas combusts, the water is heated. Additionally, the flue gases contain heat and by running heat exchange piping around exhaust pipes, supplementary heat can be obtained. This heat can then be transferred back to the anaerobic digester. The water is pumped through pipes in the digester walls to transfer heat to the digesting material.

Renewable Natural Gas

RNG systems remove almost all the non-methane components from the biogas so it can meet natural gas standards and be used in conventional natural gas applications. In the context of this study, the biogas would be upgraded to a natural gas quality for usage in the UI Steam Plant. The Steam Plant runs primarily (90%) on biomass energy but uses natural gas as a reserve. The RNG biogas facility would involve advanced gas cleaning and injection into the city grid.

Gas Cleaning

The biogas is cleaned in the same way as a CHP system in that the H_2S and water vapor is removed. Additionally, the CO_2 present in the biogas must be removed to isolate the methane. Natural gas is nearly 100% methane, so the biogas must be meet this quality as well. The CO_2 can be eliminated using many different upgrading systems including water scrubbing, membrane systems, pressure swing absorption, and chemical CO_2 absorption to name a few.

Gas Compression

The gas is then compressed to the pressure of the natural gas grid once the biogas is upgraded to natural gas quality. This involves a compressor and a metering system to track the gas sent to the grid. Alternatively, the RNG could be compressed and sent through a piping system directly to the Steam Plant rather than exported to the city grid.

Environmental Protection Agency CoEAT Model

An anaerobic co-digestion economic analysis model was utilized from the EPA to assist in determining feasibility. This model is called CoEAT and is available for download from https://www.epa.gov/anaerobic-digestion/anaerobic-digestion-tools-and-resources. It was developed by Steve Rock and Jonathan Ricketts and initially designed for wastewater treatments plants to utilize in determining the feasibility of adding food waste to their current anaerobic digesters. However, the model is flexible, and case-specific information can be included to determine feasibility for any organization considering anaerobic digestion. A combination of waste and cost data from the UI and the City of Moscow, as well as feedstock research and energy data obtained through peer-reviewed publications was combined with data provided by the model to determine feasibility for Moscow, Idaho.

The model provides fixed and recurring costs, solid waste diversion savings, capital costs, and biogas production and associated energy value. It is meant for an initial feasibility assessment and employs various assumptions. As a note, the EPA intended for this model to be the first step for an organization considering anaerobic digestion and they recommend further analysis before implementation. The model was made specific to Moscow, Idaho by using the feedstock data obtained, location climate data for annual heating requirements, and waste disposal and energy costs specific to the University of Idaho and the City of Moscow.

Assumptions Made in Study

Many assumptions were made in both the EPA model as well as the data obtained for the study. These assumptions were based on data backed by the sources included in this paper as well as the Michigan State University case study. Further steps out of the scope of this project are necessary to validate these assumptions. These assumptions include:

- The biogas produced is made up of 60% methane.
- Biogas production is 15 ft^3 per pound of volatile solid destroyed.
- The digester achieves a 50% volatile solids destruction.
- The hydraulic retention time for the digester is 25 days.
- The biogas facility can handle the high solids content of the feedstocks and use a wet anaerobic digestion process.
- 50% of the non-grass clippings yard waste from the University of Idaho as well as the City of Moscow is indigestible and would go straight to composting.

- The feedstock solids data obtained from publications can be averaged to estimate the average solids content of the feedstocks.
- The lactating dairy cows produce 85 pounds of manure daily.
- The anaerobic digester is 20% larger than required to allow for future growth.
- The boiler efficiency is 75%.
- The discount rate for the capital investment loan is 4%.
- Loan repayment occurs in 15 years.
- Engineering and installation costs total 15% of the material capital costs.
- The waste management savings total $48.91 per ton of feedstock converted to biogas or liquid digestate.
- The combined heat and power engine electric efficiency is 35% and heat efficiency is 43%.
- The gas purification efficiency of the renewable natural gas system is 98%.
- Solids can be dewatered to 25% solids.
- The digester is operational year-round.
- No government subsidy or grant assistance for project funding.

These assumptions will be explained in detail as they arise in the study.

Biogas Production Capability

A co-digestion biogas plant can produce a valuable renewable fuel source to offset energy usage by combining the different organic waste streams available in Moscow, Idaho. The amount of this biogas produced is of utmost importance to determine both economic and technical feasibility. This section will analyze the organic feedstocks available for digestion, the site considered, and will illustrate the biogas production capability in Moscow, Idaho.

Available Feedstocks

There are five locally attainable organic feedstocks available for collection and use in an anaerobic digester to produce biogas and digestate in Moscow, Idaho. Each is detailed below.

Dairy Cow Manure

The dairy cow manure available for digestion comes from the Dairy Center in the Palouse Research, Extension and Education Center sector of the UI. The Dairy Center houses 96 dairy cows and around 100 yearlings. While the yearlings are allowed access to pasture, the lactating cows are often confined to concrete. This makes manure collection easy and necessary. Currently, the manure from the dairy cows is collected and composted. The amount of waste available for digestion was calculated by estimating the daily collectible manure output of each dairy cow to be 85 pounds of manure slurry.

Yard Waste

The UI as well as the Palouse Research, Extension and Education Center (PREEC) engages in landscaping such as shrub and tree clipping, weeding, and leaf collection. This waste is currently composted at the UI composting site adjacent to the Dairy Center. Additionally, the City of Moscow operates many yard waste collection sites including Potlatch, Idaho, Genesee, Idaho, the Moscow Recycling Center, and self-haul drop-off at the Solid Waste Processing Facility operated by Latah Sanitation Inc. The majority of the yard waste collected by the City of Moscow comes from the Moscow Recycling Center. This yard waste is composed of grass, leaves, clippings, sticks, Christmas trees, and other everyday yard waste. Currently, all the City of Moscow yard waste is transported to the Solid Waste Processing Facility where it is composted.

Bulky, cellulosic organic materials such as wood, sticks, and shrubbery contain lignin which decomposes slowly (Deublein & Steinhauser, 2010b). These materials can be ground up and placed in a digester, but volatile solids destruction is likely to be minimal in a complete-mix digester. Longer retention times are required to break down this feedstock which results in higher capital costs due to a larger digester. Because of this, the yard waste inventory numbers for the UI, PREEC, and City of Moscow has been conservatively reduced by 50% to account for the removal of yard waste that is unable to be digested. This undigestible yard waste would be managed as it is currently through composting.

Dewatered Sewage Sludge

The City of Moscow WRRF currently transports its DSS to the Solid Waste Processing Facility composting site operated by Latah Sanitation Inc. where it is composted with the yard waste from the Moscow Recycling Center. The DSS is transported to this composting site after having gone through a belt press at the WRRF to remove excess liquid. The biogas facility would receive the DSS instead of the Solid Waste Processing Facility.

Food Waste

The UI currently engages in food waste collection from the Commons and the HUB dining facilities on campus. The collected materials include food and paper wastes that are currently composted with the dairy cow manure at the UI compost site located by the Dairy Center. The food waste category contains a wide variety of organics including fruits, vegetables, bread, and meats. Napkins and other paper wastes are collected at the dining facilities and composted as well.

Grass Clippings

Grass clippings are the one organic waste stream that is not currently collected. The UI engages in lawn mowing but does not collect and dispose of the grass clippings. Instead, the grass is left to decompose on the lawns. The quantity of grass available has been estimated by a study by UI facilities personnel. Collecting these clippings will introduce an operating expense that will be considered in the economics section.

Site Consideration

The site considered for the biogas facility is adjacent to the Dairy Center in Moscow, Idaho. This location is considered because it is close to the cow manure feedstock, on University of Idaho property, and conveniently located just out of the urban setting. A facility in this location would eliminate the odors that currently come from the Dairy Center while remaining close enough to feedstock sources to eliminate the need for long feedstock hauling. The site considered is shown below.

Figure 4: Proposed site location and feedstock sources. Taken from Google Maps.

This figure shows the location of the University of Idaho, UI Steam Plant, Moscow WRRF, Moscow Recycling Center, and the UI Dairy Center. These locations are important because they contain all the feedstock supply locations, the considered biogas facility location, and where the RNG alternative is intended to be used. The biogas plant would be located at the Dairy Center in the upper left corner.

Biogas Production Characteristics

The CoEAT EPA model was utilized to estimate the biogas output of a anaerobic digestion facility in Moscow, Idaho. Important terms used in this section include total solids, volatile solids, and specific gravity. The total solids percentage represents the number of solids (non-water content) present in any given amount of feedstock. Volatile solids are the percentage of the total solids that the microbial populations can convert to biogas. The volatile solids are represented as a percentage of the total solids because there are solids the microbial populations cannot consume. The specific gravity is the ratio of the density of the feedstock with respect to water. This parameter was used to size the anaerobic digester. Additionally, biogas output is displayed as a measure of volume per weight of volatile solids.

An important limitation of this study is the lack of site-specific feedstock digestion data. Volatile solid percentages can vary drastically in any given feedstock. For example, different varieties of leaves in the yard waste category can contain different volatile solid percentages dependent on how long they have been on the ground and if they have been rained on. Additionally, food waste is a broad category that can contain many different materials with different biogas production characteristics. Table 3 shows the feedstock characteristic information that was utilized for this study obtained from peer-reviewed publications. Some of the data is conveyed as a range while others are a set amount. The dairy manure total solids and volatile solids were obtained from a research paper that utilized dairy manure from the UI Dairy Center but the other data is obtained from sources other than Moscow, Idaho. The biogas output prediction was taken from the EPA model. It was estimated that the biogas output would be within 12-18 ft^3 per pound of volatile solids destroyed. This range was averaged to be 15 ft^3 per pound of volatile solids destroyed for estimating purposes. Additionally, co-digestion would likely increase biogas output, but a quantitative amount cannot be determined without experimental tests that were not completed for this study. So, the biogas will be estimated as if the feedstocks were solely digested without combining the feedstocks together in a homogeneous blend.

Table 3: Feedstock characteristics data. Taken from (Deublein & Steinhauser, 2010b), (W. Zhang et al., 2014), (Smith et al., 2015), (Pandit & Das, 1996), (Environmental Protection Agency and Office of Resource Conservation, 2016), and (Lorimor, Power, & Sutton, 2004).

Feedstock	**TS (% Full matter)**	**VS (% TS)**	**Specific Gravity**	**Biogas ($ft^3 lb_{VS,destryoyed}^{-1}$)**
Dairy cow manure	12.8 - 16.3	82.7 – 85.7	0.99	15.0
Leaves	Not given	82	0.148-0.380	15.0
Grass cuttings	37	93	0.148-0.380	15.0
DSS	17.7	67.0	1.071	15.0
Food waste	14-18	81-97	0.455	15.0

All data was converted to the imperial system
TS = total solids, VS = volatile solids

Table 4 conveys the specific numbers that were used for the sake of feasibility. For lack of scientific total solids, volatile solids, and biogas output information specific to this study, the information from Table 3 was averaged. The UI, PREEC, and City of Moscow yard waste data were assumed to be the average of the leaves and grass clippings characteristics.

Table 4: Feedstock biogas production data. Taken from (Brown, Shi, & Li, 2012), (R. Zhang et al., 2007), (Li, Liu, & Sun, 2015), (W. Zhang et al., 2014), (Lorimor et al., 2004), (Environmental Protection Agency and Office of Resource Conservation, 2016), and (Pandit & Das, 1996).

Feedstock	**TS (% Full Matter)**	**VS (% TS)**	**Specific Gravity**	**Biogas ($ft^3/lb_{VS,destroyed}$)**
Dairy cow manure	14.6	84.2	0.99	15.0
Yard waste*	37	88	0.264	15.0
DSS	17.7	67.0	1.071	15.0
Food waste	16	89	0.455	15.0
UI grass clippings	37	93	0.264	15.0

All data was converted to the imperial system
*PREEC and City of Moscow yard waste, TS = total solids, VS = volatile solids

Feedstock Inventory

Inventory amounts were determined by information provided by Eugene Gussenhoven and Tim Davis. Mr. Gussenhoven is the Director of Utilities and Engineering Services at the UI. He provided the UI and PREEC yard waste, food waste, and grass clippings data relevant to this study. Mr. Davis is the Sanitation Operations Manager for the City of Moscow. He provided the DSS and City of Moscow yard waste data for this study. The dairy manure waste was calculated from the method discussed in the dairy cow manure section. Table 5 and Figure 5 represent the annual organic feedstock availability for a city-wide biogas production facility including materials from both the City of Moscow and the UI. Waste numbers have increased over the years but not by a significant amount. For example, the annual variance for DSS since 2012 ranged from -1.47% to 4.55%. This study will determine feasibility from 2016 tonnages since the annual variance is relatively small. The digester will be 20% oversized in the digester sizing section to account for increasing waste streams as Moscow's population increases.

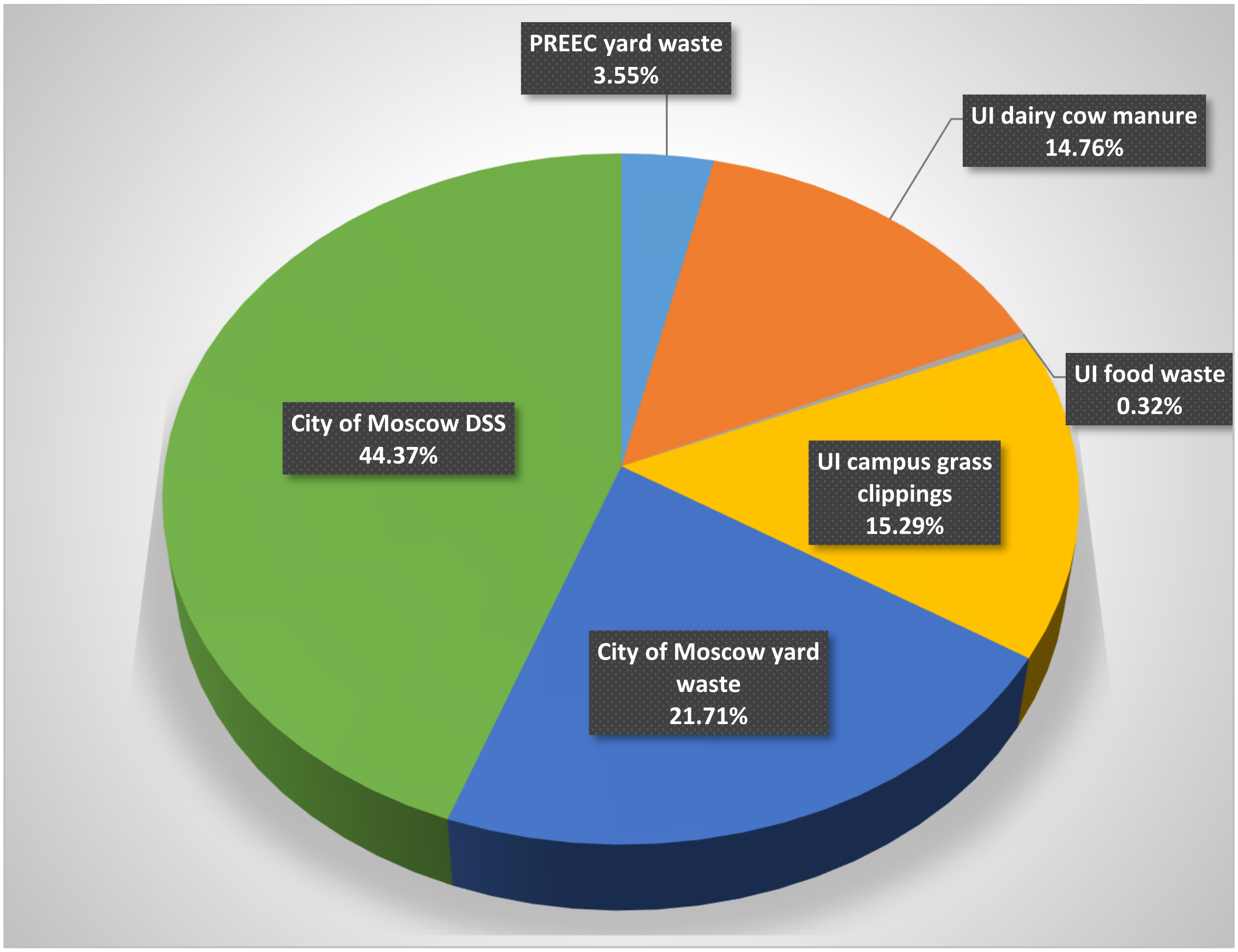
Table 5: UI and City of Moscow feedstocks from 2016 data

Feedstock	Tons
PREEC yard waste	358.5
UI dairy cow manure	1,489.2
UI food waste	32.0
UI campus grass clippings	1,543.0
City of Moscow yard waste	2,190.5
City of Moscow DSS	4,477.0
Total Tonnage	10,090.2

Note: The PREEC and City of Moscow yard waste data were reduced by 50% to account for the removal of wood materials.
DSS = dewatered sewage sludge

This data is further illustrated in the pie chart below.

Figure 5: Feedstock percentages for 2016



Digester Sizing and Heating

With the assistance of the EPA model, the digester size and heating requirement was calculated. The digester size is a function of the retention time, feedstock density, and annual quantity to be digested. Table 6 illustrates the size required as calculated in the model. The digester was sized 20% larger than required to allow for expansion.

Table 6: Anaerobic digester sizing

Anaerobic digester size required (gal)	227,074
Size after 20% oversizing (gal)	**272,488**
Size (ft^3)	36,427
Height (ft)	45.0
Diameter (ft)	32.1

Once the digester size was calculated, the heating requirement could be determined. It is assumed that the digester would be heated by the biogas produced at the facility. The EPA model calculates the biogas required to satisfy a mesophilic temperature of 100°F within the digester. Additionally, the feedstocks must be brought up to the digester temperature, so the initial temperature of the feedstocks was assumed to be 47.8°F. This is likely to vary throughout the year, but it is the average annual temperature of Moscow, Idaho so it can be assumed the average temperature of the feedstocks would be similar (United States Climate Data, 2018). The specific heat of the homogenized feedstocks was conservatively assumed to be 1.2 Btu/lb°F which is slightly higher than water. The lower heating value (LHV) of the methane is used in this study with the assumption that the water present in the gas is a vapor after combustion or has been removed. The following table illustrates the heating requirement for the anaerobic digester if a boiler was used as the heat exchange equipment. This is the case for an RNG system, but the biogas required in a CHP system will differ dependent on the CHP heating efficiency. This is addressed in the electricity offset section.

<u>Table 7:</u> Annual digester heating requirements

Assumed temperature of received feedstocks (°F)	47.8
Temperature within digester (°F)	100
Annual initial feedstock heating (MBtu/year)	1262
Annual energy loss from digester (MBtu/year)	420
Annual heating demand (MBtu/year)	**1682**
Methane content of biogas	60%
LHV of methane (Btu/ft^3)	1011
Heating efficiency of the boiler	75%
Biogas required to meet heating demand (ft^3)	**3,697,110**

Biogas Estimation

The tonnages and waste characteristics allow for biogas production to be estimated. Table 8 combines the tonnage information and waste characteristics to estimate the biogas and methane capabilities of a city-wide biogas facility. It was conservatively assumed that the methane content of the biogas is 60%. The biogas methane content average from Table 1 is 65% but since there is a large amount of yard waste in this study, the methane content estimation was lowered by 5%. The volatile solids destruction in a typical mesophilic digester is 45% to 55% (Water Environment Federation, 2017). It was estimated that the system would achieve 50% volatile solids destruction and convert these solids to biogas.

Table 8: Annual biogas production estimation

Feedstock	**Tons**	**TS (% FM)**	**VS (% TS)**	**VS Destruction (%)**	**Biogas conversion ($ft^3/lb_{VS,destoyed}$)**	**Biogas (ft^3)**	**Methane (ft^3)**
PREEC yard waste	358.5	37.0	88.0	50.0	15.0	1,750,914.0	1,050,548.4
UI dairy cow manure	1,489.2	14.6	84.2	50.0	15.0	2,746,055.0	1,647,633.0
UI food waste	32.0	16.0	89.0	50.0	15.0	68,352.0	41,011.2
UI grass clippings	1,543.0	37.0	93.0	50.0	15.0	7,964,194.5	4,778,516.7
City of Moscow yard waste	2,190.5	37.0	88.0	50.0	15.0	10,698,402.0	6,419,041.2
City of Moscow DSS	4,477.0	17.7	67.0	50.0	15.0	7,963,911.5	4,778,346.9

All data was converted to the imperial system.
FM = full matter, VS = volatile solids, TS = total solids, DSS = dewatered sewage sludge

Natural Gas Offset

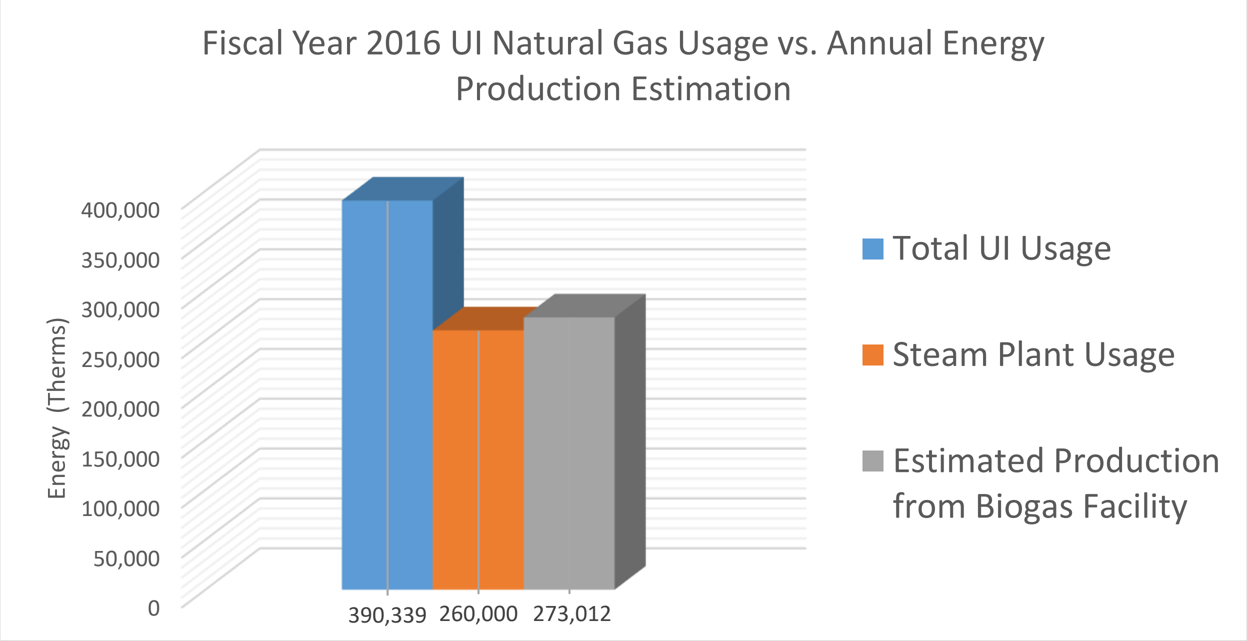
Biogas contains carbon dioxide and other gases mixed with the methane which lowers the heating value of the gas. Natural gas, on the other hand, is nearly 100% methane and thus, has a higher heating value. After the non-methane gases have been removed from the biogas, it can then be measured like natural gas. Natural gas is measured in therms which is roughly equivalent to 10,000 Btu. Table 9 shows the renewable natural gas estimations with data provided by the EPA model.

Table 9: Annual renewable natural gas production estimation

Annual biogas estimation (ft^3)	31,245,770
Biogas needed for heating (ft^3)	3,697,110
Net biogas (ft^3)	27,548,660
Methane percentage in biogas	60%
Annual usable methane (ft^3)	16,529,196
LHV of methane (Btu per ft^3)	1,011
Total usable Btu	27,851,695,706
Btu per therm	99,976
Therms sent through gas cleaning	278,584
Gas cleaning efficiency	98%
Therms of renewable natural gas produced	273,012

This data is compared against the UI natural gas consumption data from the 2016 fiscal year to illustrate the natural gas offset potential of a city-wide biogas facility. The figure below shows this comparison.

Figure 6: UI 2016 natural gas usage vs. RNG production estimation



The biogas facility has the potential to offset the annual UI consumption by an estimated 70% and offset the Steam Plant natural gas usage by an estimated 105%. This would cause the Steam Plant to generate steam from 100% renewable energy sources.

Electricity Offset

The second alternative considered is a CHP system. Additional biogas would not be used for heating since the heat simultaneously produced by the internal combustion engines would be utilized to heat the digester. The EPA model gives that the engines would capture 8,150 MBtu per year with an assumed heat efficiency of 43%. This exceeds the annual requirement of 1,682 MBtu for the digester. The excess heat produced would be vented to the atmosphere.

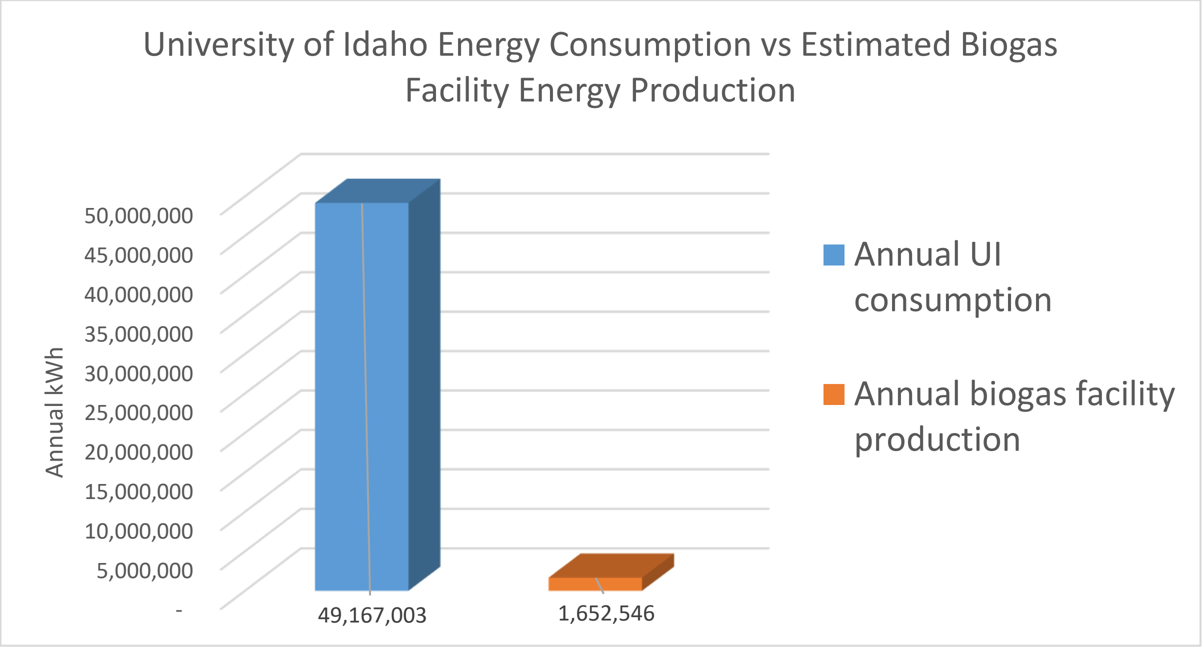
The EPA model was additionally utilized to size the CHP system as well as estimate the energy output. The system and energy calculations with the conversions used as shown below in table 10. As a note, the on-site energy usage of the biogas facility is estimated to be 15% of the annual energy produced. This percentage was chosen based upon the case study provided in a later section. The economics of this energy usage as well as energy required for the RNG alternative will be considered in the economics section.

Table 10: Annual CHP energy production estimation

Annual biogas estimation (ft^3)	31,245,770
Methane percentage in biogas	60%
LHV of methane (Btu per ft^3)	1,011
Methane energy conversion (Btu per kWh)	3,412
Engine electricity efficiency	35%
Engine size (kW)	222
kWh produced annually	1,944,172
On-site energy usage assumed to be 15% of production estimation (kWh)	291,626
Energy exported to grid (kWh)	1,652,546

This estimation is compared against the UI energy consumption data in the 2016 fiscal year in the figure below.

Figure 7: UI electricity usage vs electricity production estimation



The biogas facility has the potential to offset UI energy consumption by an estimated 3.36%.

Digestate Estimation

The digestate from the digester has an economic value as well. Most design considerations at a biogas facility are focused on increasing gas production but the digestate amounts are also important. The digestate can serve as a land-applied fertilizer and in Moscow, Idaho, agriculture applications are plentiful. The digestate is made up of the undigested solids that are left after the 25-day hydraulic retention time as well as the liquids to be removed during dewatering. The volatile solids were estimated to have been 50% destroyed during the digestion process. So, the remaining matter is made up of the non-volatile solids, 50% of the volatile solids that were present before digestion, and the non-solids content (primarily water). The digestate must be dewatered to separate the solid and liquid fertilizers. The solid portion can be composted or directly land applied. The liquid portion is full of nutrients and can be used as a fertilizer as well.

In Moscow, Idaho, the digestate cannot be land applied during the winter months so there must exist a storage tank to hold the liquid digestate until usage. A tank must be sized large enough to hold this liquid digestate which is illustrated in the table below. It was assumed the liquid digestate has a density comparable to water. Additionally, it is assumed that the tank must be large enough to hold a full year's worth of liquid digestate and the dewatering equipment used can condense the solid digestate to 25% total solids.

Table 11: Annual digestate estimation

Annual feedstocks inserted to digester (tons)	10,090.20
TS before digestion (% FM)	25.1%
VS (% TS)	82.2%
VS before digestion (tons)	2,083.1
TS before digestion (tons)	2,533.5
Liquid present in feedstocks before digestion (tons)	7,556.7
TS after digestion (% FM)	14.8%
TS after digestion (tons)	1,492.0
Digestate before dewatering (tons)	9,048.7
Solid digestate after dewatering (tons)	5,967.8
Waste reduced by facility (tons)	**4,122.4**
Liquid digestate obtained from dewatering (tons)	3,080.8
Liquid digestate obtained from dewatering (gal)	828,785.6
Required liquid digestate storage tank with 20% oversizing (gal)	**994,542.7**

TS = total solids, FM = full matter, VS = volatile solids

This table illustrates the annual solid and liquid digestate estimations. It also shows the biogas facility can reduce around 4,122 tons of waste annually. This reduction saves money on waste management costs that will be considered in the economic analysis section.

Carbon Offset Potential

Managing organic waste through anaerobic digestion is recognized as a carbon neutral practice. The organic feedstocks absorb carbon dioxide throughout their life cycles, converted to methane during anaerobic digestion, and then converted back to carbon dioxide when burned. In this way, no additional carbon is introduced to the environment. Composting takes a similar approach in that the waste is converted to carbon dioxide through decomposition in the presence of oxygen (aerobic). This process is not perfect, however, and some anaerobic conditions develop within a compost pile. This releases methane to the atmosphere which, according to the EPA, is 25 times more potent as a greenhouse gas than carbon dioxide (United States Environmental Protection Agency, 2017). This methane release is equivalent to 340.2 carbon dioxide equivalents per ton of waste composted (Hao, Chang, Larney, & Travis, 2001). Managing waste through anaerobic digestion avoids some of this methane release from composting.

Additional carbon savings come from decreased fuel consumption from waste transport vehicles. Switching the waste management site from the Solid Waste Processing Facility operated by Latah Sanitation to the UI Dairy Center offers decreased transportation distances, thus, fuel savings and decreased carbon emissions. The mileage between the current waste sites is illustrated below.

Table 12: Transportation distances between waste sites. Taken from Google Maps

	Miles	**Miles saved per trip**	**Miles added per trip**
Potlatch to the Dairy Center	17.9	6.1	
Potlatch to Latah Sanitation	24		
Genesee to the Dairy Center	17.7	2.8	
Genesee to Latah Sanitation	20.5		
Moscow WRRF to the Dairy Center	2.6	4.4	
Moscow WRRF to Latah Sanitation	7		
Moscow Recycling to the Dairy Center	1.3	4.8	
Moscow Recycling to Latah Sanitation	6.1		
UI to the Dairy Center	1.8		1.8
Latah Sanitation to the Dairy Center	7.1		7.1

This information was then utilized to calculate the annual mileage saved by switching the organic waste management site to the UI Dairy Center and the corresponding carbon offset.

Table 13: Annual carbon savings from reduced waste transportation

Average tons per trip*	29.08
Moscow WRRF DSS (tons)	4,477.00
Potlatch yard waste (tons)	42.68
Moscow Recycling yard waste (tons)	1,914.31
Genesee yard waste (tons)	218.93
Latah Sanitation yard waste (tons)	2,205.14
UI grass clippings (tons)	1,543.00
Trips from WRRF	154
Trips from Moscow Recycling	66
Trips from Genesee	8
Trips from Latah Sanitation	76
Trips from UI	53
Miles saved	1,014
Miles added	634
Net miles saved	**381**
Pounds of CO_2 per ton-mile**	0.35671
Carbon saving from decreased transportation (lbs)	**3,948**

*Taken from a spreadsheet provided by Tim Davis

**Taken from (Mathers, 2015)

The annual mileage saving is not significant, but this table was displayed to show that introducing a new waste stream in the grass clippings and transporting waste from the Latah Sanitation site would not introduce additional transportation miles, but, in fact, save them.

Additionally, carbon savings come from using the digestate as fertilizer versus mineral fertilizers. For every ton of mineral fertilizer used, 9.7 tons of carbon dioxide equivalents are released (European Biogas Association, 2015). It is estimated that digestate can provide around 72% of the total nutrients required by crops and the remaining 28% would have to be supplemented by mineral fertilizers (Environment Agency, 2008). With this information, the total annual carbon savings by the biogas plant can be calculated.

Table 14: Annual carbon savings

Composting avoided (tons)	4,122
Carbon dioxide equivalents from emitted methane during composting (lbs per ton)	340
Liquid digestate (tons)	3,081
Carbon dioxide equivalents from using mineral fertilizers (lbs per ton)	9,700
Mineral fertilizer avoidance (%)	72%
Transportation carbon equivalent emissions avoided (lbs)	3,948
Carbon equivalent offset potential (lbs)	22,922,970
Carbon equivalent offset potential (tons)	11,461

To give some context, this is the carbon equivalent of burning around 1,302,441 gallons of E10 gasoline a year (United States Energy Information Administration, 2017). This carbon saving is not considering any additional carbon output from the facility itself. The RNG facility will have to use electricity from the grid to meet on-site power demands. This has carbon impacts that were not considered in this study.

Case Study Analysis and Applicability

Michigan State University Anaerobic Digestion Facility

I have selected the Michigan State University (MSU) anaerobic digestion facility as a case study to support this paper due to the similar facility operations as the considered facility in Moscow, Idaho. Michigan State University is located in central Michigan in the City of East Lansing. MSU has a student enrollment of 47,955 as of Spring 2018 which is a little more than four times the size of the UI (Michigan State University, 2018). The MSU anaerobic digestion facility is unique because it is located on-campus and not associated with wastewater treatment like the majority of anaerobic digestion sites in the United States.

The MSU biogas facility is located adjacent to the Dairy Teaching and Research Center on the south side of campus. It is here that approximately 20,000-22,000 annual tons of feedstocks are converted to digestate and biogas. Many of these feedstocks are central to campus operations including food waste from several campus dining halls, kitchen food waste, cow manure, and fats, oils, and grease. Additionally, MSU obtains external feedstock sources, including fats, oils, and grease and milk processing waste from the greater Lansing area as well as food waste from the Lansing food bank. The facility acts as an alternative waste management option for third-party waste producers much like landfills and wastewater treatment sites that take organics. The site is instrumental in campus waste management by facilitating waste reduction, handling, and disposal internal to university versus paying an outside party to facilitate the waste management process.

The facility became operational in 2013 after construction by Anaergia, a biogas company based out of California. The process from concept to operation took around three years.

In short, the operations faculty and professors at MSU inventoried organics from campus and outside sources that were available to be digested. From there, a complete mix digester design was decided upon, the project was funded, and it was sent out for bid.

The overall system design is a 450,000-gallon complete mix, mesophilic anaerobic digester with an adjacent 2.4 million-gallon liquid digestate storage tank. The anaerobic digestion tank is mixed by a hydraulic dual propeller system. The biogas is collected from the anaerobic digester and utilized in a CHP system to produce 2.8 million kWh of energy annually. This is enough to power the facility itself as well as several buildings on campus. The total facility consumption is 10-20% of the produced electricity. The digester is heated from the CHP system using an external heat exchanger. The heat produced is also used in on-site buildings and for a food waste reception tank.

The feedstocks are received at the facility in two reception tanks; the first is designed for manure while the other receives the remaining feedstocks. The materials are pumped to a central mixing tank and inserted into the anaerobic digester. New material is added 2-3 times each day. The system's designed hydraulic retention time is 25 days and achieves an average of 50% volatile solids destruction. Material within the anaerobic digester is sent to a screw press once every morning where the solids and liquids are separated. The solids are composted while the liquids are sent to the digestate storage tank. The digestate tank is not heated or mixed but is necessary to hold the digestate until it can be applied to croplands in warm months.

Biogas is collected from both the anaerobic digestion and digestate tanks. The roofs of the digesters contain flexible membranes that allow for gas storage and pressurization. The methane content of the biogas produced is an estimated 67%. The biogas must be partially cleaned before undergoing combustion in the CHP system. A small amount of oxygen is injected into the headspace of the digester to chemically remove some H_2S in the tank itself. From the tank headspace, the gas is piped below ground where water vapor condenses and is collected. Additionally, the gas is cooled to 37 degrees Fahrenheit to further remove condensation. It is then pushed through activated charcoal to remove any remaining H_2S. The gas is then burned in a 16-cylinder MAN CHP engine without removing CO_2. This engine can handle a wide range of methane fluctuations in the biogas. An integrated flare is also in place to burn excess gas produced in case of maintenance on the engine or a system failure.

The facility cost $5.1 million to construct and has an estimated payback of 15 years. A breakdown of the costs is given below in Table 15.

Table 15: MSU facility construction costs

System	Cost
Anaerobic digester	$2.2 million
Digestate tank	$1.7 million
CHP system	$800,000
Site improvements	$400,000
Total	**$5.1 million**

The digester has an estimated lifetime of 20 years before major overhaul such as roof replacement will be necessary. The pumps have a shorter lifespan of around 5-7 years. The equipment must be properly maintained to achieve these lifespans. MSU has a maintenance contract for the CHP generator and changes the oil in the CHP engine twice a year. Carbon filters are changed, equipment is greased, and general maintenance is undergone. A full-time operator works at the facility Monday – Friday and a student employee assists on the weekends. Overall, the operation and maintenance of the facility are estimated at $50,000-$80,000 yearly excluding labor.

The image below illustrates the majority of the facility. The green shipping container on the far-left hand side of the picture contains the CHP system. The cleaned biogas is burned in the CHP internal combustion engine within the container to produce power and heat. Power control and safety equipment are also contained within. The black tube on top of the container is the integrated flare where biogas can also be burned if needed. The CHP system contains exhaust ventilation to allow excess heat that is not needed for the digester to escape to the atmosphere. The white tank in the middle is the anaerobic digester where the feedstocks are broken down and biogas is produced. The green tank on the right-hand side of the picture is the digestate tank. Here, the liquid digestate is held until it can be used in the warm months. Both the anaerobic digester and the digestate tank contain a flexible roof that allows for biogas pressurization and storage.

Figure 8: MSU biogas facility

This facility offers many advantages to MSU. These include on campus waste management, renewable power production, landfill waste diversion, fertilizer production, and odor reduction to only name a few. Baseload, renewable energy is supplied to campus while a fertilizer is produced simultaneously. Waste, which would otherwise be placed in a landfill, is made into usable products.

The MSU facility operations provide an excellent example of a biogas facility in a climate like Moscow, Idaho. The facility is located at MSU's dairy which is directly applicable to the proposed operation at the UI. This case study stands as an example of how a university operated facility can manage waste from both the city and the university to produce a usable renewable energy.

Economic Analysis

The economics behind a biogas facility can be broken down into capital costs, operation and management costs, avoided costs from the produced biogas, income from the digestate, and avoided waste disposal costs. The economics are subject to variance and largely dependent on the anaerobic digestion process, utility costs, and other location-specific data. This section will outline the economics with the support of the EPA CoEATs model, local utility costs, current waste disposal costs for the City of Moscow and UI, as well information from the MSU case study.

Capital Costs

Capital costs related to a biogas production facility involve all one-time costs associated with bringing the facility into operation, made up mostly of construction/equipment expenses. Biogas facility capital costs are determined by the processes, design, and size of the facility as well as the company contracted to build the plant. There are many biogas facility contractors around the world that design and construct facilities dependent on the design desired and the feedstocks available. The facility construction would be sent out for bid by contractors once feedstock agreements are obtained and a specific digester design is considered. Since this project is not ready to be sent out for bid, baseline capital costs will be estimated by totaling major costs associated with each process required at a biogas facility. These costs are shown in the following table as taken from the EPA CoEAT model. All costs should be considered within a ±15% range.

Table 16: Capital costs. Derived from the EPA CoEAT model.

Major costs for digestion	Cost per unit ($/unit)	Units Needed	Total cost ($)
50' truck weighing scales	$32,700	1	$32,700
Foundation for scales	$20,000	1	$20,000
Print kiosk (for weight records)	$4,000	1	$4,000
Software capable of running reports	$10,000	1	$10,000
PC computer	$2,000	1	$2,000
Odor control system	$85,000	1	$85,000
Feedstock pre-processing equipment	$450,000	1	$450,000
Pumps	$90,000	2	$180,000
Trommel screen	$110,000	1	$110,000
Feedstock buffer tank ($/ft3)	$9	300	$2,700
Digester mixers	$40,000	2	$80,000
Liquid digestate tank ($/ft3)	$9	132,960	$1,196,642
Gas collection equipment	$75,000	1	$75,000
Hydrogen sulfide scrubber tank	$5,000	1	$5,000
Monitoring equipment (SCADA)	$100,000	1	$100,000
Permitting	$100,000	1	$100,000
Environmental impact statement	$250,000	1	$250,000
New full solid waste permit	$6,300	1	$6,300
Land preparation	$30,000	1	$30,000
New water service	$110	1	$110
Anaerobic digester tank ($/ft3)	$27	36,429	$983,581
Feedstock receiving station	$139,000	1	$139,000
		Total	$3,862,033
		Engineering and installation (15%)	$579,305
		Total cost	$4,441,338

These cost estimates do not include extra investment into a renewable natural gas or combined heat and power system other than a hydrogen sulfide scrubber tank. Moreover, the capital costs displayed above do not consider interest expenses for the capital cost loan. These additional investments costs are given in the following two tables.

Table 17: Capital investment for a RNG facility

Cost of facility before engineering and installation	$3,862,033
Gas upgrading system	$150,000
Total material cost	$4,012,033
Engineering and installation (15% of material cost)	$601,805
Cost before interest	$4,613,838
Interest (4% discount rate, 15-year period)	$1,614,843
Total capital cost	**$6,228,681**

Table 18: Capital investment for a CHP facility

Cost of facility before engineering and installation	$3,862,033
Combined heat and power system ($ per kW)	$5,000
System possible (kW)	222
Cost of combined heat and power system	$1,110,000
Total material cost	$4,972,033
Engineering and installation (15% of material cost)	$745,805
Cost before interest	$5,717,838
Interest (4% discount rate, 15-year period)	$2,001,243
Total capital cost	**$7,719,081**

Each process involved in a biogas facility requires capital investment and makes up the costs in the table above. As discussed in the anaerobic digestion overview, these processes are feedstock receiving and pre-treatment, digestion, biogas storage, upgrading, and utilization, and digestate separation and storage.

The feedstock receiving area is a place where the wastes are dropped off by delivery vehicles and potential inorganic materials are removed. A typical receiving bay involves manual observation and removal of objects like plastics and metals. The prepared feedstocks are then put through a grinder to reduce the size of the material to increase biogas production. The feedstocks are combined in a predetermined ratio, pulverized, and injected into the anaerobic digester in the pre-treatment section of the biogas facility. The equipment necessary for the pre-processing step is included in the capital costs in table 16. Feedstocks in Moscow, Idaho are subject to seasonal variability due to a large portion of the population being college students that leave during the summer months. All the organic waste sources are dependent on the population of Moscow, so a feedstock storage area was sized to hold 10,000 gallons to allow for buffering. Additional feedstock storage may be necessary but was out of the scope of this project.

After pre-treatment, a pump fills the digester with the feedstock slurry where they sit for the designed retention time. The budgeted digester contains two mechanical mixers, a heating system, pumps for inlet feedstock and outlet digestate, piping, and the physical digester tank itself. The tank cost was estimated using the size required as calculated in the biogas production capability section.

The biogas system contains a variety of safety and gas upgrading equipment. The biogas will require cleaning and upgrading whether it is used at the Steam Plant or for electricity generation. These processes were discussed in the biogas utilization section. The hydrogen sulfide scrubber tank is included in the overall facility costs while the renewable natural gas alternative includes additional gas cleaning equipment.

The last process associated with a biogas plant is digestate treatment and storage. The digestate will be dewatered to separate it into solids and liquids. A belt press or some other dewatering equipment is necessary as well as an outlet pump and piping. The liquid digestate would be stored in the digestate tank sized in the previous section until it could be sold and/or land applied. The solid digestate would be composted and could be used as a soil amendment. The value of this soil amendment is dependent on the classification of the digestate which was out of the scope of this study.

Additional one-time costs involve site improvements, plant engineering, labor, permitting, interest, and facility automation. The engineering and installation of the facility are estimated to be 15% of the material costs and the discount rate is assumed to be 4% on a 15-year loan. Permitting, an environmental impact statement, and a SCADA control system program are all included in the capital cost estimation.

Operations and Maintenance Costs

The operation and maintenance associated with a biogas facility involve the activities to keep the equipment and digester working properly, disposal fees, worker salaries, water and power consumption, and other consumables. Keeping the equipment and digester working properly involves maintaining all the requirements discussed in the anaerobic digestion section as well as limiting odors, cleaning the digestion tank periodically, facilitating the reception and pretreatment of feedstocks, and preserving a safe facility. The gas utilization systems would require maintenance of the gas upgrading equipment to keep them working properly. The combined heat and power engine would require regular maintenance such as oil changes and new filters. All equipment would have to undergo occasional safety checks. The labor required at the biogas facility would be minimal. Other than the occasional tank cleaning and system maintenance, all the labor needed at the site would include loading the digester, removing inorganics from the feedstocks, and maintaining system stability. Operation and maintenance costs are estimated to be similar to the costs incurred at the MSU biogas facility. This includes $50,000-$80,000 per year plus labor costs. Labor costs will be estimated at $50,000 a year for a single operator.

An additional expense for the facility is the collection of the grass clippings from the UI. This is a waste cost that the UI does not currently undergo because the grass is not collected. This is estimated at $15.34 per ton of grass collected. This cost is represented by an equipment cost estimate of $14.37 per ton of grass and a labor cost estimate of $0.97 per ton of grass collected.

The last operation cost included in this section is on-site energy usage. Energy is required for tank mixing, pumping, system automation and control, etc. The on-site energy usage is estimated to be similar to the MSU facility of 10-20%. For simplicity, this will be average to an annual 15%. The CHP system would supply this power directly from the internal combustion engines. The RNG system, however, would have to purchase energy from the grid to power the facility. This energy purchase is estimated to be 15% of the total energy that could be produced from the CHP system. This introduces an expense for the RNG alternative that is not applied to the CHP alternative. The complete annual operation and maintenance costs are summarized in the table below.

Table 19: Annual operation and maintenance costs

Equipment operation and maintenance	$65,000.00
Labor cost	$50,000.00
Collection cost per ton	$15.34
Grass collected (tons)	1,543
Grass collection cost	$23,670
On-site energy usage estimated at 15% of CHP production potential (kWh)	291,626
Purchase price ($ per kWh)	$0.069
Annual on-site energy usage cost	$20,122
Yearly operation and maintenance cost	**$158,792**

Income and Avoided Costs

The primary avoided cost a biogas facility introduces is waste management costs. This cost was determined to be $48.91 per ton as that is the in-house cost to the University of Idaho for managing composting operations. It can be assumed that this savings is only applied to the tonnage that is converted to biogas since composting is still a necessary step for the solid digestate. It is assumed that the savings for the City of Moscow would be similar, so this applies to all the feedstocks considered in the study. The avoided waste management costs on an annual basis is illustrated in the table below.

Table 20: Avoided waste management costs

Feedstocks reduced by facility (tons per year)	4,122
Current waste management cost per ton	$48.91
Avoided waste management cost	**$201,625**

Income from the facility comes from selling the liquid digestate as a fertilizer. The liquid digestate contains a high amount of nitrogen and phosphorus that is comparable to industry fertilizers. The table below predicts the annual income from this digestate. The fertilizer cost data is taken from (United States Energy Information Administration, 2017). It is assumed that liquid digestate will provide 72% of the nutrients provided by a mineral fertilizer, and thus can sell for 72% of the cost of an organic fertilizer.

Table 21: Annual liquid digestate income

Liquid digestate (gal)	828,786
Liquid digestate (ft^3)	110,793
Estimated selling price ($ per ft^3)	$0.42
Annual liquid digestate income	**$47,033**

Other avoided costs include electricity costs at the UI or natural gas costs at the Steam Plant depending on the alternative chosen. Additional savings come from reduced transportation fuel costs due to waste reduction on-site. The calculated annual saved mileage was calculated to be 381 miles in the biogas production capability section. This introduces relatively insignificant savings. This is due to the introduced waste transportation from moving grass clippings to the facility as well as transporting customer self-hauled yard waste from Latah Sanitation to the Dairy Center. Because of this, fuel savings were not considered.

There must be a method to transport the produced RNG is to be used at the UI Steam Plant. The local utility, Avista, has natural gas lines throughout the City of Moscow that could be used to transport the produced RNG to the UI Steam Plant by selling the RNG to Avista at a slightly reduced price from the normal UI natural gas rates. This helps Avista by making a profit from buying and reselling the RNG as well as introducing a new renewable energy to their portfolio. It also benefits the UI by eliminating the need to invest heavily in RNG transportation lines. Alternatively, the UI could construct a piping system from the Dairy Center to the Steam

Plant but, this alternative was not considered for this study. Table 22 below illustrates the annual avoided natural gas costs for the UI by using the RNG.

Table 22: Annual avoided natural gas costs

Current price paid for natural gas ($ per therm)	$0.60
Therms produced	273,012
Annual natural gas costs avoided	**$163,807**

Alternatively, if a CHP system was used instead of an RNG system, the electricity produced could be sold to Avista. This would benefit Avista by adding an additional renewable energy source to their portfolio. This would benefit the UI and City of Moscow by having a facility able to provide base-load power and can power homes and/or the UI from the organic waste. Table 23 shows the electricity capacity of the biogas facility and the income potential.

Table 23: Annual avoided electricity costs

Energy exported to grid (kWh)	1,652,546
Electricity cost per kWh	$0.069
Electricity costs avoided	**$114,026**

Furthermore, savings come from future potential carbon credits and the ability to handle all organic city wastes in one location. Collaboration between Latah Sanitation Inc., the City of Moscow, and the UI would be compulsory for this facility to operate. The facility presents savings to all parties but to take advantage of economies of scale, all local feedstocks must be utilized.

Payback Analysis

This section integrates both the costs and benefits illustrated in the previous sections to determine the economic feasibility of the proposed biogas facility. The CHP and RNG alternatives are compared side by side below to show the differences in capital and avoided costs.

Table 24: Economic comparison between RNG and CHP

	RNG	**CHP**
Capital investment	$6,228,681	$7,719,081
Operation yearly operation costs	$158,792	$138,670
Waste disposal costs avoided per year	$201,625	$201,625
Liquid digestate income per year	$47,033	$47,033
Electricity costs avoided	N/A	$114,026
Natural gas costs avoided	$163,807	N/A
Yearly net income*	**$253,673**	**$224,014**

*Not considering capital investment loan repayment

These yearly expenses, savings, and incomes were extrapolated for 30 years to determine the payback period of the two alternatives. This forecast was made with the assumption that the operation and maintenance costs would follow an inflation rate similar to the yearly consumer price index for energy services of 2.8%. The RNG alternative was assumed to inflate similarly to the yearly consumer price index of natural gas of 3.8% and the CHP alternative would follow the yearly consumer price index of electricity of 2.2% (United States Department of Labor, 2018). Using these assumptions, the figures below were obtained for both the RNG and CHP alternatives.

Figure 9: RNG payback analysis

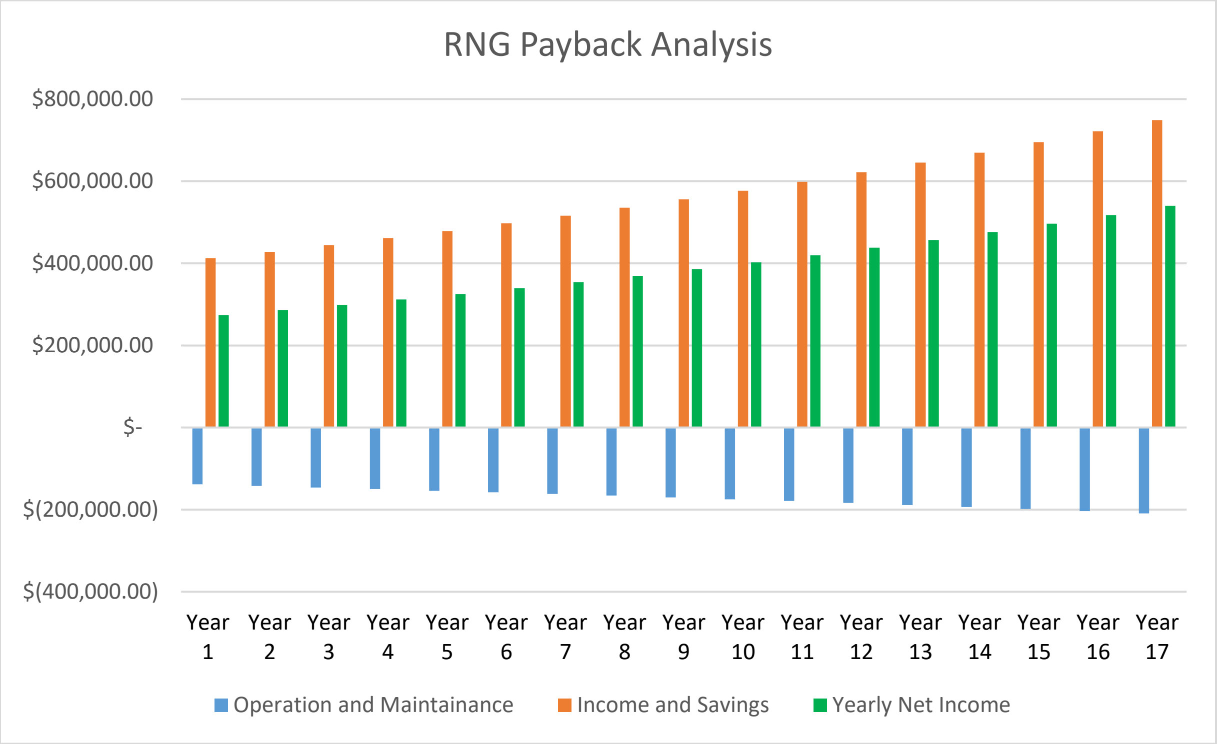
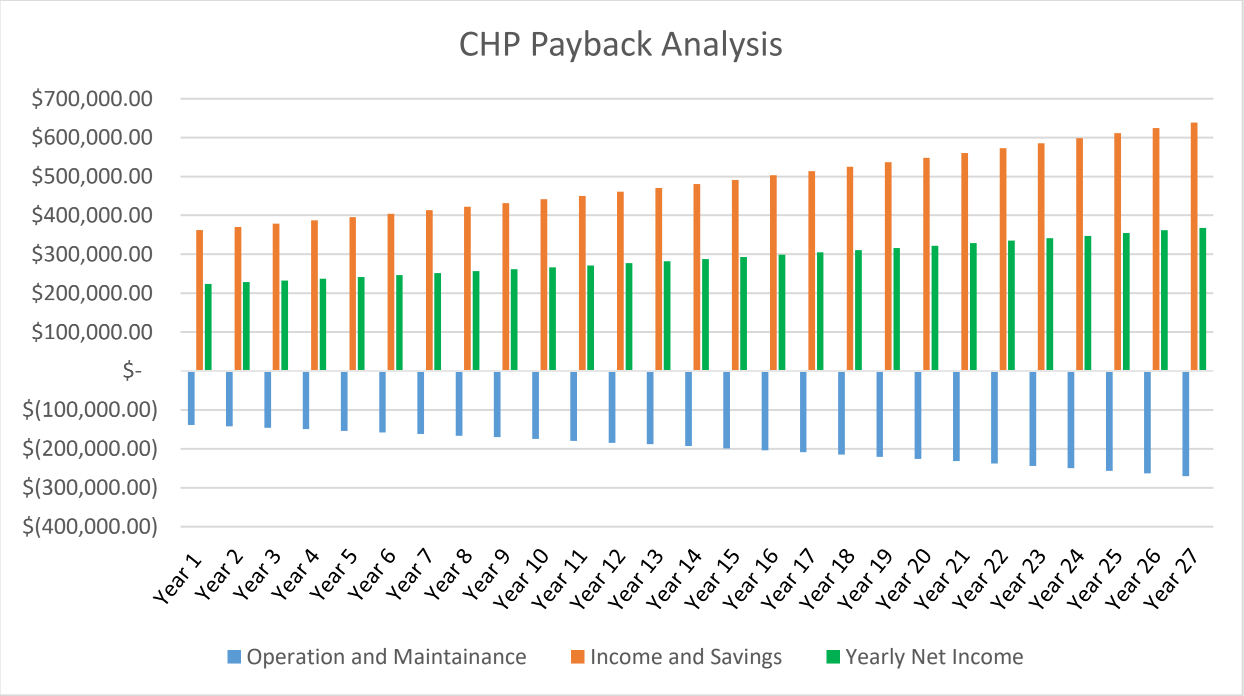


Figure 10: CHP payback analysis



These figures illustrate the projected cash flow in the proposed biogas facility over the payback period. The payback period assumes that each year's net income would be completely applied to the capital cost loan. In this way, the data reveals that the RNG facility would have a payback of 16.92 years while the CHP facility would have a payback of 26.71 years.

Summary and Next Steps

Dictionary.com defines feasibility as "capable of being done, effected, or accomplished." In the context of the definition, this study has revealed that it is feasible to operate a co-digestion biogas facility in Moscow, Idaho but not without its challenges. The payback period for both alternatives is significant but this is considering no additional support in construction costs such as government grants. The RNG alternative resulted more feasible than CHP merely due to the CHP's high investment cost and low electricity costs in Moscow, Idaho. This study resulted in the payback period for an RNG facility to be 16.92 years while the CHP facility would take almost 10 years longer at 26.71 years.

Some benefits were difficult to monetize such as increasing the UI competitive edge by offering a new power plant as a basis for research opportunities as well as potential future governmental carbon credits. Moreover, the study also considered the City of Moscow's waste which is currently managed separately from the UI. Collaboration between the two entities would be necessary for the facility to take advantage of economies of scale, generate more biogas, and recognize the payback period given in this study.

A biogas facility could offer many benefits to the UI and Moscow, Idaho sustainability. These benefits include:

- Management of all city organic waste on one site.
- Carbon neutral renewable energy generation in the form of electricity or a renewable natural gas.
- Reduced weed seed fertilizer production that can assist in nitrogen cycle management on cropland.
- Landfill avoidance by converting 4,122 annual tons of organic waste to biogas.
- Avoided waste management and energy costs as well as fertilizer income.
- Increased sustainability and waste awareness throughout the community.
- Decreased odors from the organic waste sources.
- Decreased carbon emissions from switching to a renewable energy.

However, the proposed facility does not come without its challenges. Some of the challenges discovered by the study include:

- The feedstocks contain a large percentage of solids so dry anaerobic digestion may have to be utilized although this study considered wet anaerobic digestion.
- Long payback periods for RNG and especially the CHP alternative.
- Lack of literature on a co-digestion facility that has utilized all the proposed feedstocks in a single operation.
- Lack of a method other than modeling to quantify biogas production from the co-digested feedstocks.

Many assumptions were made throughout this study to determine feasibility. As such; they were made with the intent of being as accurate as possible to the real-world application. The next steps in the process of determining feasibility will be to verify that these assumptions are accurate. This step would involve running lab tests to confirm the biogas production characteristics assumed in this study are accurate. Next, a pilot scale anaerobic digestion facility should be constructed to further confirm the feedstocks available can produce the determined amount of biogas. The digestate can then be tested for fertilizer characteristics and the digestate marketplace can be analyzed. The biogas facility would export energy to the city grid so the local utility, Avista, would have to support the facility. In conclusion, it is feasible to operate an anaerobic digestion facility to Moscow, Idaho to produce biogas but financial assistance will be necessary to decrease payback periods and financial risk.

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