ENGINEERING AND FINANCIAL ANALYSIS OF A WASTEWATER PLANT UPGRADE

by

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A Thesis

Submitted to the Faculty of Purdue University

In Partial Fulfillment of the Requirements for the degree of

Master of Science

School of Engineering Technology

West Lafayette, Indiana

May 2020

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To my family for their unwavering support and love.

ACKNOWLEDGMENTS

I would like to express my profound gratitude to my advisor, Dr. Anne Lucietto for providing me the opportunity to pursue graduate school and for her constant unwavering support and guidance of my master's studies and research.

I would also like to extend my appreciation to the rest of my committee: Prof. Nancy Denton, Dr. Anthony Sparkling, and Mr. Tim Healy. As well as to Mr. Mark Moore for allowing me to be a part and pursue this research topic as part of the upgrade project at the Wastewater Treatment Plant.

Lastly, I would like to thank my family for their constant support and affection throughout my life and for always pushing me to pursue my dreams.

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LIST OF ABBREVIATIONS

BOD = Biochemical Oxygen Demand

BMP = Biomethane Potential Test

CH4 = Methane

CO2 = Carbon Dioxide

CWA = Clean Water Act

DO = Dissolved Oxygen

EPA = Environmental Protection Agency

GAAP = Generally Accepted Accounting Principles

GASB = Government Accounting Standards Board

H2S = Hydrogen Sulphide

NH3-N = Ammonia Nitrogen

P = Phosphate

pH = “p” for the word power and “H” for the symbol of the element Hydrogen

ROI = Return on Investment

RSI = Required Supplementary Information

sCOD = Soluable Chemical Oxygen Demand

SI = Supporting Information

tCOD = Total Chemical Oxygen Demand

TKN = Total Kjeldahl Nitrogen

TS = Total Solid

TSS = Total Suspended Solids

VFA = Volatile Fatty Acids

VS = Volatile Solids

VSS = Volatile Suspended Solids

WWTP = Wastewater Treatment Plant

ABSTRACT

Municipal wastewater treatment plants treat wastewater such as domestic and industrial sewage and recirculates the clean water back into nature's waterways. However, the wastewater treatment process is costly and complex. The cost of running a municipal wastewater treatment plant is funded via ratepayer fee dollars from customers and therefore receives a fixed budget for which to run the plant according to environmental standards. A local initiative was established to upgrade a Midwestern municipal wastewater facility to utilize biomass renewable energy to a greater extent than what is used by the wastewater facility. The first phase of the initiative tested the suitability of utilizing organic substrates from local industrial plants with the potential to produce larger amounts of biogas via anaerobic digestion. The analysis evaluated the technical and financial viability of utilizing biomass technologies to help power the facility efficiently and economically. The financial and technical analysis will include a cost-benefit analysis by comparing current and forecasted natural gas demand and costs for running heating the WWTP to biogas produced by the anerobic digesters. The results of the research study found that the industrial waste substrates are suitable for anaerobic digestion and yield a higher biogas potential than what is currently used for anaerobic digestion by the WWTP. The initial financial analysis found it is feasible and economical, for at least certain months of the year, for the WWTP to refrain from purchasing natural gas and instead utilize the produced biogas.

CHAPTER 1: INTRODUCTION

Chapter 1 introduces the purpose of wastewater treatment plants and presents an overview of the research case study which includes the: problem, purpose, significance, scope of study, limitations and delimitations. The first part of the introduction presents the need and significance of wastewater treatment plants and their value to the environment.

The Earth is covered by approximately 70% water, with just 3% of that water viable for human consumption (Spellman, 2014). The 3% consumable water is further divided with two thirds comprising of frozen glaciers and just 1% available for consumption. The remaining 97% is comprised of saltwater or used for agricultural uses (Spellman, 2014). Water is essential for a variety of usages in daily life such as for drinking, washing, farming, industrial power plants, battling fires, etc. However, through the various demands for water over time, the supply of freshwater is becoming scarce (Spellman, 2014). The once consumable freshwater has since become contaminated with diseases and pollutants through various uses and as such becomes sick water. The term sick water was used by the United Nations in 2010 to address the need for transforming contaminated water leaking into the environment from causing harm to a clean, safe, and economical resource (Spellman, 2014). Furthermore, by transforming the sick water into a safe resource, once again helps contribute to reversing the concern over scarcity of freshwater.

Wastewater Treatment Plants (WWTP) treat wastewater such as sewage, chemical effluent, and other materials. These plants are used to process, purify, and recirculate clean water back to the environment. The purification process of WWTP is important for the environment as it prevents water pollution, spread of diseases and harm to wildlife and natural resources (United States Environmental Protection Agency. Office of Wastewater Management, 2004). Each WWTP operates differently from one another depending upon the quality and quantity of wastewater received.

The WWTP are often owned, operated, and managed by local municipal government agencies. Although, the plants are managed by professionals in the field of wastewater management, the onsite management is often controlled by a board of elected directors who set policy, budgets, plan for expansion or upgrades, make decisions for large purchases, assign rates for ratepayers and control overall direction of the operation (Spellman, 2014). Municipal

WWTPs are funded from a combination of sources such as: local taxes, federal grants, and/or usage fees for water and wastewater customers (Spellman, 2014).

The allocation of funds for WWTP can be complex. Municipal funding is distributed among several city services rendering some services such as WWTPs with limited funds for operations and potential upgrades. This creates a challenge for operating a WWTP in compliance with the environmental standards for waste and contaminant removal while on a fixed budget (United States Environmental Protection Agency, 2019a). The National Pollution Discharge Elimination System (NPDES), is an example an environmental standard program established by the Clean Water Act (United States Environmental Protection Agency, 2019a) which issues permits for facilities (industrial and municipal) which discharge directly into water bodies of the United States (Drinan & Spellman, 2013a). The NPDES compliance monitoring takes place mainly at the state level with main objective of the NPDES program is to address significant problems and to promote compliance to the rules and regulations for wastewater management (United States Environmental Protection Agency, 2019b).

The United States Environmental Protection Agency (EPA) manages the CWA and NPDES programs, which work with federal, state, and tribal regulatory partners to monitor and verify compliance with clean water laws and regulations to protect human health and the environment (United States Environmental Protection Agency, 2019b).

1.1 Research Case Study

A recent initiative for a Midwestern municipal wastewater treatment facility to utilize local industrial waste substrates to produce additional biomass fuel in order to help heat the plant was established. The initiative was proposed due to certain equipment undergoing possible upgrades and/or replacement to which may run on fuel derived from biomass. This research case study on examined the potential of producing more biogas energy to help power the municipal wastewater treatment plant more efficiently via a renewable energy source. The project looked into the suitability of utilizing industrial waste substrates with the potential to produce more biogas than is currently being produced. The methodology delved into the technical and financial viability of producing larger amounts of biogas using current equipment and the affect the increase will have on energy demand for the WWTP. A subsequent engineering and financial analysis was conducted on the suitability for future energy savings utilizing biomass energy.

1.2 Problem

The problem addressed by this study is that the operation and maintenance of a municipal wastewater treatment plant is complex, technical, and consequently costly (Balmér & Hellström, 2012). The WWTPs in general are not setup financially to generate cash profits and therefore there is no financial incentive for establishing a WWTP other than for environmental regulations. As such some WWTPs may tend to fall into disrepair or may not be able to treat wastewater properly due to having to depend upon limited resources for funding.

1.3 Purpose

The purpose of this research case study is to utilize additional biogas produced at the WWTP to help heat the WWTP. The WWTP produces a certain amount of biogas from their sludge/waste substrates and that biogas may be used to help heat the WWTP. Recently, waste substrates from local industrial plants have been found to potentially produce more biogas for the WWTP to use for heating purposes. This research study will look into whether the waste substrates from the local industrial plants do produce additional biogas. The subsequent financial analysis will investigate whether the additional power the WWTP expends to produce the higher amount of biogas will be offset by the lower costs associated with using that biogas instead of paying for natural gas to power the WWTP.

1.4 Significance

The significance of this research study is that the freshwater supply is slowly becoming scarce and WWTPs help to placate this scarcity by cleaning previously dirty water into clean water fit for the environment via providing a freshwater supply (Spellman, 2014). Furthermore, by utilizing biomass renewable energy technologies, the waste that was previously sent to landfills is now used to produce a renewable energy source to help reduce the energy demand and subsequent greenhouse gas emissions produced at the WWTP.

1.5 Research Questions

The problem addressed by this study is that the operation and maintenance of a municipal wastewater treatment plant is complex, technical, and consequently costly to run (Balmér & Hellström, 2012). The purpose of this project was to assess whether using additional biogas to help power the WWTP is a useful strategy in decreasing the plant's dependence on purchasing natural gas and the costs associated with purchasing that natural gas.

1. *Are the waste substrates from local industrial plants suitable for anaerobic digestion?*
   - *If so, do the waste substrates help to produce more biogas than what the WWTP is already producing?*
2. *Financially, how do the costs associated with producing* and *using biogas compare to the costs associated with heating the WWTP with the current fuel, natural gas?*
   - *Is it more expensive to produce biogas than it is to purchase natural gas?*
   - *Will the return on investment be better from using biomass renewable technologies or using equipment run on fossil fuels?*

1.6 Hypotheses

The usage of biomass renewable technologies are not currently capable enough to individually meet the heating demands of an industrial scale facility without the assistance of fossil fuels, notably natural gas.

1.7 Scope of Research Study

The research case study has two major sections: Biomethane Potential Test and financial analysis. The biomethane potential test section tests whether the industrial waste substrates are suitable for anaerobic digestion by testing the characteristics of the waste substrates. Next, the industrial waste substrates were tested in anaerobic digesters in varying amounts to ascertain how the substrates react during and after anaerobic digestion.

The financial analysis compared natural gas consumed to the amount of biogas produced by the anaerobic digesters. The analysis included how much natural gas is consumed by the entire WWTP and then how much the anaerobic digesters consumed. The cost for purchasing natural gas on a monthly and annual basis for the year 2019 was then determined. Next, a cost benefit analysis compared how much natural gas is consumed over a year to how much biogas was produced over a year. This cost benefit analysis showed whether biogas produced is comparable to the heating requirement of the WWTP and how much money may be saved by utilizing biogas instead of paying for natural gas to heat the WWTP. A final theoretical analysis was undertaken at the request of the WWTP, to determine how much biogas would be consumed by the higher methane yielding industrial waste substrates. The amount of biogas consumed allows for an insight into how beneficial the industrial waste substrates might be if and when they are used to help produce biogas for the WWTP.

1.8 Cost Benefit Analysis

The study's cost benefit analysis was examined by reviewing the costs for purchasing natural gas versus the heating costs associated with producing biogas from the anaerobic digesters for the wastewater plant analyzed for this research study.

1.9 Limitations

The potential increase in heating demand for running the anaerobic digesters with the industrial waste substrates cannot be determined at this time. The heating content of the industrial waste substrates is unknown and would require further in-depth analysis beyond the scope of this research study. As such, the costs associated and/or the amount of natural gas and/or biogas required to meet this increase in heating demand cannot be determined at this early stage.

The electrical consumption of the anaerobic digesters cannot be determined because the individual amounts of electric consumption by individual equipment cannot be ascertained. The WWTP uses two meters for metering the electrical consumption of the plant. The meters cover the primary and secondary sections of the WWTP, but it cannot be determined which piece of equipment is drawing the most electricity. It may be assumed certain equipment use more electricity than another but for the purposes of accuracy in this research study such assumptions cannot be employed based on speculation.

The data used for comparing natural gas consumption and biogas production costs were based on the average daily cost for the year 2019. As this research study is a preliminary look into ascertaining whether the industrial waste substrates are even suitable for anaerobic digestion for the purpose of producing additional biogas, a year's worth of data was enough for a comparison. The comparison was to see whether the current production of biogas is even close to the amount of natural gas consumed by the anaerobic digesters. Therefore, a year's worth of data was suitable for an initial inspection of natural gas consumption versus biogas production.

Individual data for daily or monthly demand of the natural gas consumption for heating the anaerobic digesters is not available and therefore the natural gas consumption for the anaerobic digesters is based on biannual values. The natural gas consumption data used for the results section of this research study is for the entire WWTP. The amount of natural gas consumed by just the anaerobic digesters is based on two heating demand values for the Summer months and Winter months, respectively. The Summer months include April to September and the Winter months include October to March. The Summer and Winter heating requirements are 50.1 million Btu/day and 24.3 million Btu/day, respectively. As such, it was assumed each day for the designated Summer and Winter months the anaerobic digesters will consume those exact values of heat per day. Therefore, the comparison of anaerobic digester consumption to biogas production may not be a precise comparison. However, for the purposes of a general comparative overview of consumption versus production it is adequate.

The financial intricacies of the municipality the WWTP investigated for this research study resides within is limited in the data available for public scrutiny. For the purposes of a general cost comparison between natural gas consumption and anaerobic digester production, the accounting methods used by municipality were not investigated due to the limited financial analysis scope of this project. However, the accounting methods used by the municipality is still an important consideration as it has significant influence on future decisions regarding the financial nature of the WWTP.

1.10 Delimitations

The delimitations of the research study investigated only certain aspects of the comprehensive BMP tests that were conducted and analyzed the natural gas costs associated with heating the WWTP. The data used to analyze the, natural gas consumption/costs, biogas production, and anaerobic digester heating consumption just covered data from the year 2019. The forecasted costs associated with purchasing natural gas for the next five years (2020, 2021, 2022, 2023, and 2024) are based on projected inflation rates and may not represent the actual rates that will be used in the future. Furthermore, it is assumed for the next five years the natural gas consumption amount will remain the same as it was analyzed for the year 2019 for the purposes of determining projected annual costs.

The financial analysis was limited to the WWTP and did not include accounting methods used by the WWTP and/or municipality. This is due to certain financial data not being available for public scrutiny.

The BMP tests involved a comprehensive overview that tested each of the twelve parameters required for anaerobic digesters. However, for the scope of this research study the purpose is to ascertain whether the industrial substrates are suitable for anaerobic digestion and if so, how much biogas may they produce? Therefore, only pH, biomass, methane, and volatile solids data results from the BMP test was analyzed. The other BMP parameters tested were concerned with the chemical and biological makeup of the wastewater and its effect on the environment upon leaving the WWTP, which is beyond the scope of this research study.

Chapter 1 summarized the environmental benefits that wastewater treatment plants offer as well as an introductory framework overview of the main components of this research case study. The literature review will provide background information on each of the central concepts and processes that was analyzed for this research case study.

CHAPTER 2: REVIEW OF LITERATURE

Chapter 2 provides the literature review related to how a wastewater treatment plant operates, the key processes and equipment involved and relevant to this research case study. Additionally, concepts and processes related to governmental and municipal accounting practices that need to be considered when running a WWTP are also discussed.

2.1 Background

Wastewater is used water originating from various sources such as domestic, industrial, agricultural, medical, or transport activities. Municipal wastewater is collected via a system of sewers which collect wastewater from homes, businesses and industries and delivers the wastewater to a treatment plant. The treatment plant will treat the wastewater and then discharge the newly cleaned waster to water bodies, landfills, or to be reused (United States Environmental Protection Agency. Office of Wastewater Management, 2004). A municipal wastewater treatment facility is particularly challenging as the material flowing into the plant is comprised of varying physical and chemical characteristics. Industrial wastes for example, contain chemicals, dyes and highly toxic materials which at times require pretreatment before entering a public treatment system (Drinan & Spellman, 2013b). As a result, the origination and composition of the wastewater entering a WWTP is an important factor to account for in order to properly treat the wastewater in accordance to environmental standards.

2.2 History of Wastewater Management

The history of wastewater management traces back to early human history dating approximately between 3500 – 2500 BC with the Mesopotamian Empire. Progress over time for waste management developed methods of expelling waste from homes to sewers where waste was either sold for agriculture use or remained in cesspools (Lofrano & Brown, 2010). The early 19th century, toilets were installed in homes and were typically connected to cesspools instead of sewers (Lofrano & Brown, 2010). For densely populated areas the cesspools created a difficult environment to live in. Threats to public health became apparent with outbreaks of diseases that were traced back to well-water supplies contaminated by human waste from cesspools (Lofrano

& Brown, 2010). It was then necessary for all toilets for densely populated areas to be connected directly to storm sewers (Lofrano & Brown, 2010). However, this merely transferred sewage from grounds near homes to nearby bodies of water and thusly creating a new problem of surface water pollution (Lofrano & Brown, 2010).

Stream self-purification is a natural process of helping to dilute small amounts of sewage by discharging it into a flowing body of water (Lofrano & Brown, 2010). Though, for large quantities of sewage expelled at once, stream self-purification is not adequate enough to prevent pollution. Therefore, it became apparent to treat or purify wastewater to a certain degree before disposing into bodies of water (Lofrano & Brown, 2010). The late 19th and early 20th centuries, construction of centralized sewage treatment plants began primarily in the United States and the United Kingdom. These early plants received the sewage and subjected it to a combination of physical, biological, and chemical processes to remove some or most of the pollutants before expelling the water into a nearby bodies of water (Lofrano & Brown, 2010). Simultaneously, in the 1900s, to prevent treatment plants from becoming overloaded during periods of rainy weather, a new sewage collection system was designed to separate storm water from domestic wastewater (Lofrano & Brown, 2010). The middle of the 20th century saw increased concern for the environmental quality of the wastewater and led to stricter regulations of wastewater disposal practices (Lofrano & Brown, 2010). The passage of the Clean Water Act in 1972 established stricter regulations for wastewater treatment and helped to develop subsequent advanced treatment purification processes such as using microorganisms and aeration to remove contaminants.

2.3 How a Municipal Wastewater Plant Works

The wastewater treatment plant system described here refers to typical systems used in the United States of America. Wastewater is first drained to the WWTP by the main sewer systems. Once the wastewater reaches the WWTP, the wastewater undergoes an initial preliminary treatment stage. The preliminary treatment stage removes grit, small and large objects from the wastewater. The objects are removed using screens which capture the debris and objects as the wastewater flows through. Some WWTPs use a device called a comminutor or barminutors which combine the functions of a screen and grinder. These devices will capture and shred the objects which will later be removed in a primary settling tank. Once the wastewater passes through the screen it will proceed to a grit chamber where small debris such as sand, grit and small stones will settle to the bottom. The removal of these small objects is very important as the objects may cause operating problems by clogging pumps and other equipment. Some WWTPs will have another finer screen after the grit chamber in order to further remove any small debris to prevent any possible damage to equipment for later processes (United States Environmental Protection Agency. Office of Wastewater Management, 2004). The objects removed by the screens and grit chamber will then be transported for disposal.

Once the large and small objects are removed from the wastewater, the next process will be primary sedimentation. Though, the wastewater is mostly free of large and small objects the wastewater still contains dissolved organic, inorganic, and suspended solids. Suspended solids are minute particles that will be removed by sedimentation or gravity settling, chemical coagulation, or filtration (United States Environmental Protection Agency. Office of Wastewater Management, 2004). The wastewater will enter the sedimentation tank where the velocity will be decreased, and the suspended solids will slowly sink to the bottom. The accumulation of these solids is called primary sludge. The removal of the primary sludge is done by various means, such as with mechanical equipment.

The following treatment stage is called secondary treatment. The secondary treatment stage processes remove up to 90% of the organic matter, using biological treatment processes (United States Environmental Protection Agency. Office of Wastewater Management, 2004). The most common methods utilized are growth processes and suspended growth processes. Attached growth processes (or fixed film), are effective for removing biodegradable material from the wastewater (United States Environmental Protection Agency. Office of Wastewater Management, 2004). This process works by having microbial growth on the surface of stone or plastic media whereby wastewater passes over the media with air. Attached growth processes use trickling filters, bio-towers, and rotating contractor. The trickling filter is comprised of a bed of media made up of rocks or plastic and ranges from three to six feet deep. The media allows for large numbers of microorganisms to attach and grow forming a microbial growth or slime layer known as biomass. During the treatment process, the microorganisms use the oxygen from the air to consume most of the organic matter from the wastewater and thereby cleaning the wastewater (United States Environmental Protection Agency. Office of Wastewater Management, 2004).

The suspended growth process, unless additional treatment is provided, removes biodegradable organic and organic nitrogen-containing material by converting ammonia nitrogen to nitrate (United States Environmental Protection Agency. Office of Wastewater Management, 2004). The suspended growth process comprises of the microbial growth being suspended in an aerated water mixture, where air is allowed in to allow oxygen. The units used by the suspended growth process "include variations of activated sludge, oxidation ditches and sequencing batch reactors" United States Environmental Protection Agency. Office of Wastewater Management, 2004). Suspended growth processes hasten the aerobic microorganisms to break down organic matter in the wastewater by providing a rich aerobic environment. Aeration tanks are used to breakdown the organic matter in the wastewater by mixing the wastewater with air. The microorganisms for several hours are acclimated to the wastewater while in suspension (United States Environmental Protection Agency. Office of Wastewater Management, 2004). The increased growth of the microorganisms and excess biomass are then removed by settling before the wastewater is discharged or treated further. The increased growth of the aerobic bacteria can be returned to an aeration tank to be mixed with incoming wastewater. Upon leaving the aeration tank, the treated wastewater then flows to a sedimentation tank where excess biomass is removed. Parts of the biomass is recycled back to the aeration tanks, while other parts of the biomass and settled solids are removed from the system. The removed biomass and settled solids are either treated before disposal or reused as biosolids (United States Environmental Protection Agency. Office of Wastewater Management, 2004).

2.4 Organic Material Pollutants

Biochemical Oxygen Demand (BOD) refers to the amount of oxygen required by aerobic microorganisms to decompose organic materials (Drinan & Spellman, 2013c). The BOD is important to the design and operation of a WWTP as it relates to the filtration and purification of the wastewater.

Water quality depends upon the presence of dissolved oxygen (DO) with a higher value of DO resulting in better water quality for wildlife. When untreated sewage enters into the bodies of water, the oxygen microbes consume the oxygen in the water as food and thus reduces the available oxygen in the water. The result of this oxygen depletion harmfully affects the aquatic life living in the water. Therefore, wastewater that has undergone the secondary treatment phase removes the biodegradable waste of which the microbes consume using available D.O. from the surrounding water and contributes to helping the environment.

2.5 Biogas

Biogas is a renewable energy source produced by the biological breakdown of organic matter in the absence of oxygen (Abbasi, Tauseef & Abbasi, 2012). The gas is produced via anaerobic digestion or fermentation of organic materials such as biomass, municipal waste, etc. The composition of biogas is primarily 40-70% methane with the rest being mostly carbon dioxide and small amounts of other gases (Abbasi, Tauseef & Abbasi, 2012). The generation of biogas may be simplified down to a four-stage process. The first stage is the breakdown of large protein macromolecules, fats and carbohydrate polymers through hydrolysis to amino acids, long-chain fatty acids, and sugars (Abbasi, Tauseef & Abbasi, 2012). The second stage is the acidogenesis stage of fermenting the first stage end products "to form volatile fatty acids, principally lactic, propionic, butyric, and valeric acid" (Abbasi, Tauseef & Abbasi, 2012). The third stage is acetogenesis where the bacteria consume the fermented products to generate acetic acid, carbon dioxide, and hydrogen. The fourth stage, methanogenic organisms consume acetate, hydrogen, and some carbon dioxide to produce methane. The overall biogas yield and methane content varies for different substrates (Abbasi, Tauseef & Abbasi, 2012). The combustion with oxygen, of methane, hydrogen and carbon monoxide gases allows for biogas to be used as a fuel to generate electricity and/or heat.

2.6 Anaerobic Digestion

Anaerobic digestion is a useful naturally occurring biological process for reducing waste and producing renewable bioenergy (Fermoso, Carliell-Marquet, Esposito, van Hullebusch & Collins, 2018; Alepu & Wang, 2016). The anaerobic process naturally occurs in soils, sediments and other anoxic environments that cycle carbon and other nutrients which converts organic matter into a methane-rich gas (Collins, et al., 2018). Anaerobic digestion is most suitable for WWTPs due to various factors such as: being able to produce a useful renewable biofuel, versatility for a variety of process configurations, and reducing greenhouse gases (Sanz & Köchling, 2019; Collins, et al., 2018). This naturally occurring process can be replicated in closed reactors called digesters, by cultivating and controlling the microorganisms found in these environments (Hornung, 2014)

The microorganisms that degrade the organic materials are situated into three categories: strict aerobes, facultative anaerobes, and obligate anaerobes (strict or aerotolerant). Strict aerobes are the microorganisms commonly used for WWTP and actively use free molecular oxygen to degrade soluble organic compounds found in the wastewater (Hornung, 2014). Strict aerobes cannot survive in anaerobic conditions (Hornung, 2014). Facultative anaerobes survive in the presence or absence of molecular oxygen (Hornung, 2014). Obligate anaerobes are divided into strict anaerobes which cannot grow in the presence of oxygen and aerotolerant which do not use oxygen to grow but can tolerate oxygen (Hornung, 2014l Kim & Gadd, 2008).

The anaerobic digestions process is comprised of four key phases: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Each phase utilizes distinct groupings of microorganisms which use intracellular or extracellular enzymes to break down compounds (also called substrates) in the biomass process (Hornung, 2014). The substrates are used for cell growth and energy supply, the end results of each phase are then used as a substrate for the microorganisms for subsequent phases (Hornung, 2014). The growth rates of any particular community, if inhibited, can impact the overall rate and efficiency of the digestion process (Hornung, 2014). Anaerobic digestion is a sequential process whereby the slowest phase determines the overall rate of the process (Hornung, 2014).

The first phase of anaerobic digestion, hydrolysis, is where biodegradable materials are broken down for bacteria to then convert these substrates into monosaccharides, amino acids, and long chain fatty acids (Hornung, 2014; Vavilin et al., 2008). The second phase is called acidogenesis, where the products from the hydrolysis phase are broken down to produce, carbon dioxide, alcohols, and volatile fatty acids (Hornung, 2014; Srirangan, Akawi, Moo-Young & Chou, 2012). The third phase is called acetogenesis where acetogenic bacteria is used to convert the product of acidogenesis into acetic acid, carbon dioxide, hydrogen and water. The final phase, methanogenesis converts the acetic acid, hydrogen, and carbon dioxide into methane, carbon dioxide, and water (Hornung, 2014).

2.6.1 Key Process Factors for Anaerobic Digestion

The anaerobic digestion process comprises of the following key process variables which must be maintained in order to preserve the production and quality of the end products of biogas and digestate and are as follows (Hornung, 2014):

- Temperature
- pH
- alkalinity
- nutrients and trace elements
- total solids and volatile solids
- organic loading rate
- hydraulic retention time

The temperature within the anaerobic reactor has a great impact on the growth and survival of the microorganisms. The optimal temperature varies depending upon the type of organisms and can range from approximately 12^{o}C to 55^{o}C (Hornung, 2014). The pH of the anaerobic process also has an effect on the growth and survival of the microorganisms. A pH of greater than 9.5 or below 4.0 cannot be tolerated by microorganisms. The low pH values have been found to inhibit the methanogenic bacteria and as a result affect the production of methane gas. The optimum pH range is between 6.5 and 7.5 (Hornung, 2014). The alkalinity of a substrate provides a buffer to ensure that the pH changes do not have a damaging effect on the biochemical reactions (Hornung, 2014). A good buffering capacity is approximately 1000 – 5000 mg/l (Hornung, 2014).

Nutrient and trace elements affect the microbiological growth during anaerobic digestion. The key nutrients required for anaerobic digestion are: nitrogen, sulfur, phosphorus, magnesium, calcium, sodium, and organic nutrients (i.e., amino acids, purines, and vitamins). These nutrients are often present in agricultural and municipal wastewaters, though they may be absent in industrial wastes and thus supplementation may be necessary (Hornung, 2014).

Total solids content may vary considerably for particular waste streams. The operational considerations may require increased energy to mix a waste with a high solids content (>40%) and increased vessel size "for a waste with a low solids content but high-water content" (Hornung, 2014). The volatile suspended solids (VSS) present are often used as indicators for biomass concentration (Hornung, 2014). The organic loading rate (OLR) is "the rate at which the digester receives organic mass" (Hornung, 2014) and affects the optimization of the anaerobic digestion process. The OLR is described either as "chemical oxygen demand (COD), which is a measure of the oxygen equivalent of organic compounds in solution, or as volatile solids (VS)" (Hornung, 2014). The COD is primarily used for liquid substrates and VS is used for high solid biomass substrates.

The h retention time refers to the required contact time the substrates have with the microbiology within the digester to breakdown the organic material to acceptable levels. The retention times are solid retention time (SRT) and hydraulic retention time (HRT). The SRT is "the average time solids remain in the digester" (Hornung, 2014). The HRT is the average time liquid sludge remains in the digester (Hornung, 2014). A shorter time for HRT and longer time for SRT have been known to yield better process efficiency and reduce carbon footprints and costs (Hornung, 2014).

2.6.2 Types of Substrates

Anaerobic digestion utilizes many different types of organic materials. The basic substrates found in varying concentrates are predominantly carbohydrates, proteins and lipids (Hornung, 2014). The most common organic materials include sewage sludge, agricultural residues, food wastes, and purpose grown energy crops.

Sewage sludge or municipal wastewater is comprised from domestic residences, effluents from industrial processes and storm water runoff. Municipal wastewater treatment processes produce large quantities of sludge of which the disposal or treatment accounts for approximately 50% of the overall cost of the wastewater treatment (Hornung, 2014; Li, Champagne & Anderson, 2011). The sludge is rich in carbon and nutrients which may be converted to energy, composted, or used as fertilizer for agricultural uses. The sludge is commonly processed via anaerobic digestion as anaerobic digestion reduces sludge volume, limits odors, destroys pathogens, and produces biogas that can be used for energy (Hornung, 2014). Sewage sludge is retrieved during the treatment of wastewater when the solids are separated from the wastewater through either primary settlement or biological treatment.

Agricultural waste is found from the processing of crops or from livestock. This waste is usually composted however environmental effects have come about in the form of odors, leaching of nutrients into groundwater, pests, and risk of pathogens to human health. Biomass is an alternative disposal method for agricultural waste though quality and availability of the waste would need to be considered before undergoing the biomass process.

Food waste is found from a variety of domestic, commercial, and industrial sources. The composition as a result varies depending upon its origin and season. The disposal of food waste or application to anaerobic digestion can be problematic due to its high moisture content, high number of volatile solids, and high biodegradability. Anaerobic digestion facilities which process food waste need to increase trace elements or reduce ammonia content by blending or co-digesting feedstocks. (Hornung, 2014).

Purpose grown energy crops are crops grown for biogas production. These crops have a high oil content, high productivity and good photosynthetic efficiency compared to terrestrial crops. The oils may be extracted and converted to biofuels and can be co-digested to enhance biogas production of other substrates (Hornung, 2014).

2.6.3 Types of Sludge

Sludge is the solid by-products obtained from the wastewater during different treatment stages (Sperling, 2007). The two main types of sludge extracted from the WWTP are: primary sludge and secondary sludge (Sperling, 2007). Primary sludge is comprised of the suspended solids and organics that were filtered out via primary sedimentation from the water during the primary treatment process. Secondary or biological sludge is obtained from the secondary treatment process after microorganisms consumed the biodegradable materials in the wastewater while in the aeration tank.

There are six main stages for obtaining and disposing of the sludge. The first stage is thickening, where the aim is to reduce the water content of the sludge and thereby its volume. The second stage is stabilization, where the biodegradable organic matter of the sludge is removed to reduce the odors during processing and disposing of the sludge. The third stage is the conditioning preparation process of adding chemical products to increase the dewatering capability of the sludge. The fourth stage is dewatering of the sludge, done either by natural or mechanical methods. Dewatering removes water and reduces the volume of the sludge to help with transportation and ultimate disposal of the sludge. The penultimate fifth stage is disinfection. Disinfection removes the pathogenic organisms and makes the sludge safe for potential agricultural usages. The sixth and final stage is final disposal of the sludge to be used either for agricultural usages, fuel (biogas), landfill or incineration (Sperling, 2007).

2.6.4 Key Parameters for Biomass

The anaerobic digestion process for biomass further depends upon evaluating biochemical and physical characteristics of the substrates. The following parameters are important in determining the suitability of a substrate for anaerobic digestion (Hornung, 2014):

- "Total Solids (TS) and Volatile Solids (VS)
- Nutrient composition (Nitrogen (N), phosphorus (P), and potassium (K))
- Biogas and methane (CH_4) yield on fresh mass (FM) and volatile solids (VS) basis"

The collection and storage of the substrates can influence the biochemical and physical characteristics of the substrates in the form of moisture content and materials. For example, the moisture content may be affected by the time of season the substrate was collected. Materials may be in the form of plastic packaging for food waste or straw in agricultural waste. Trace compounds such as antibiotics or pesticides may also affect the characteristics of the substrates (Hornung, 2014).

In addition to assessing suitability for anaerobic digestion, it is also important to determine a substrates' characteristics after undergoing anaerobic digestion.

2.6.5 Anaerobic Digestion Products

The end products of anaerobic digestion are digestates and biogas. Digestate is comprised of undigested fibrous material which, depending upon its composition, may be used for a variety of uses such as for agriculture land usage. Biogas is comprised of gases made up of predominantly methane and carbon dioxide. The biogas can be then be burned to produce heat and electricity to either run or optimize a plant (Hornung, 2014).

2.7 Biomethane Potential Test

A biomethane potential test is an important component when using a material for anaerobic digestion. Bio-Methane Potential tests (BMP) are used to measure the amount of methane production from different liquid and solid organic materials (Holliger et al., 2016). The BMP tests are performed in a laboratory environment and last approximately 30 days. The results from a BMP test reveal methane or biogas that can be anaerobically converted from a concentration of organics in a substrate (Holliger et al., 2016; Kaparaju, Ellegaard & Angelidaki, 2009). Once this is known the results can be used to determine the potential efficiency of the anaerobic process for a specific waste (Holliger et al., 2016). There are various methods/treatment processes that are used for BMP tests.

The financial aspects of running of a Municipal WWTP are described next. The financial aspects to be covered include sources of funding, accounting practices involved, and the process of performing a financial evaluation of a WWTP.

2.8 Financial Analysis of a Municipal WWTP – New System

The financial aspects of a wastewater treatment plant are important considerations to the administration of any plant. Municipal wastewater treatment plants receive funding from the government and customers. The customers are billed/charged primarily via a rate dependent upon the water usage used by the customer payers/user fees to help run the wastewater plant. Further, wastewater must be treated according to local regulations. Failure to treat wastewater properly, may result in fines to the WWTP. Therefore, it is imperative to utilize the funds appropriately and in a way that can be understood by the rate payer, customer, user, etc. It should be stated that each area of industry, government entity, and other entities such as non-for-profits account for their funding and expenditures in different ways.

The cost of running the equipment for the WWTP depends upon the quality of the wastewater received. Wastewater from a source that manages chemicals, toxic compounds, etc. will require a higher demand on the WWTP equipment to properly treat the toxic pollutants. The next main factor refers to how much water is processed per day and how fast is it processed. The equipment and processes needed to attend to these two main factors affect the operations cost of running a WWTP. The economic feasibility of operating a WWTP is best represented by conducting a cost-benefit analysis, especially when inspecting the viability of equipment upgrades (Stamatelatou & Tsagarakis, 2015; Molinos-Senante, Hanley, Hernández-Sancho & Sala-Garrido, 2015).

2.8.1 History of Accounting

The first known evidence of accounting practices dates to ancient civilizations in Mesopotamia, Egypt, and Babylon where governments kept records of their finances (Giroux, 2017a). Various rudimentary forms of accounting were used though during the Medieval time period brought to light an evolved method of accounting called double-entry bookkeeping believed to have been invented in the Genoa-Venice-Florence area (Giroux, 2017a). A vast commercial revolution had begun which saw many a merchant increasing their wealth. Techniques in bookkeeping were created by these merchants to meet the expanding and growing complexity of their business.

The practice of accounting and bookkeeping is credited to Luca Pacioli, who is considered to be "The Father of Accounting and Bookkeeping" (Giroux, 2017). Luca Pacioli's important contribution to the field of accounting was his 1494 published book, *Summa de Arithmetica, Geometrica, Proportioni et Proportionalite*. The book summarized existing mathematical knowledge and included a section on the accounting and recording system used in Venice, Italy at the time (Giroux, 2017). Luca Pacioli's book was believed to have provided the first description of double-entry bookkeeping (Giroux, 2017a) and emphasized other important points including mathematics and a systematic way to understand transactions, notably double-entry bookkeeping (Giroux, 2017).

Accounting practices continued to evolve during the Enlightenment movement in Europe and the subsequent Industrial Revolution. The growth of manufacturing firms, railroads, transportation companies, etc. required further advanced accounting techniques still in use today that were developed by several individuals, among which were Andrew Carnegie, Du Pont, and Donaldson Brown (Giroux, 2017b; Giroux, 2017c).

2.8.2 Government Accounting

Accounting is the process of recording financial transactions for a business. The accounting process comprises of assembling, analyzing, classifying, and recording a business's transactions which are then sent to oversight agencies, regulators, and tax collection entities (Genito, 2013). Government accounting accounts for all government entities such as: federal, state, county, municipal, and special purpose (Bragg, 2018). As an overview, government accounting maintains strict control over expenditures which allocates funds for various types of programs (Bragg, 2018). The financial statements used in accounting provide a summary of the company's financial transactions, operations, financial position, and cash flows over an accounting period.

The assembling aspect comprises of gathering documents which support a transaction such as purchase orders, invoices, billing statements, bank statements, etc. (Genito, 2013). The transaction documents are then analyzed to understand who and what was involved, and when, where, and why the transaction took place and the value assigned to the transaction (Genito, 2013). A comprehensive chart of accounts is then used by the government to properly classify the components of the transaction and then record as journal entries (Genito, 2013). The effect on each account is entered in the general ledger which comprise of a list of balances for each activity (Genito, 2013).

2.8.3 Financial Reporting

The financial reporting process compiles and summarizes the detailed information that was assembled, analyzed, classified, and recorded during the accounting process into a usable form for decision making (Genito, 2013). The three types of financial reporting are: internal, special-purpose external, and general-purpose external financial reporting (Genito, 2013). Internal financial reporting is used by management who specifics the format and timing of reports to meet managerial needs and preferences (Genito, 2013). Special purpose external financial reporting is used by individuals outside the government for certain legal or contractual requirements, including grantor requirements or as specified by state regulatory bodies (Genito, 2013).

2.8.4 General Purpose External Financial Reporting

General purpose external financial reporting is used by individuals who rely upon information contained within the reports but does not have direct access to the jurisdiction's financial information (Genito, 2013). General purpose external financial reporting is governed by generally accepted accounting principles (GAAP). The three communication methods used for general purpose external financial reporting are: display, disclosure, and supporting information

(Genito, 2013). Display communication provides the "items that are reported as dollar amounts on the face of financial statements if they both 1) meet the definition of one of the seven financial statement elements and 2) can be reliably measured. The seven financial statement elements for state and local governments are assets, liabilities, inflows of resources, outflows of resources, deferred inflows of resources, deferred outflows of resources, and net position" (Genito, 2013). Assets are resources the government controls via legal ownership or contractual rights. Liabilities are obligations to sacrifice resources which the government cannot avoid due to legally enforceable contracts or third-party legislation and must involve a party external to the government (Genito, 2013). A constructive, or inferred liability, may be invoked if social, moral, or economic consequences arise which force the sacrificing of resources. However, commitments such as public education, are not considered liabilities (Genito, 2013). A government's acquisition of net assets applicable to the reporting period is referred to as inflows of resources (Genito, 2013). Acquisition consists of new resources or resources currently under the government's control becoming newly available which result in either a net increase in assets or net decrease in liabilities (Genito, 2013). A government's consumption of net assets applicable to a reporting period are referred to as outflows of resources. Consumption consists of consuming or using up existing resources or consuming a resource as it is being acquired. Consumption may result in either a net decrease in assets or a net increase in liabilities (Genito, 2013). A government's acquisition of net assets (inflows of resources) applicable to a future reporting period (deferred) is referred to as deferred inflows of resources (Genito, 2013). Deferred outflows of resources refer to the government's consumption of net assets (outflows of resources) applicable to a future reporting period (deferred) (Genito, 2013). Last, net position refers to the residual of all other elements featured in a financial statement (Genito, 2013). The government equivalent of the accounting equation is defined as:

$$(Assets + Deferred\ outflows\ of\ recources) - (Liabilities + deferred\ inflows\ of\ resources) = Net\ Position$$

Disclosure is the second method of communication which includes three types of information included in financial statements: descriptions of the policy underlying amounts, detail or explanations concerning amounts presented, and information about potential financial statement elements not qualifying for recognition (Genito, 2013). Supporting information (SI) provides operational, economical, and historical context for the financial statements (Genito, 2013). Required supplementary information (RSI) is used for presenting mandated supporting information (Genito, 2013). Supplementary information is presenting information that is not mandatory (Genito, 2013). The SI and RSI must both possess a clear and demonstrable link to the financial statements or notes to the financial statements. The RSI is required by GAAP and must be essential and objective while SI is optional under GAAP and is useful but not essential. However, SI must follow relevant authoritative standards if presented in connection with GAAP financial statements (Genito, 2013).

The information presented in the financial statements, notes or supplementary information must meet the essential characteristics for inclusion for general purpose external financial reporting and are: understandability, reliabilities, relevance, timeliness, consistency, and comparability. Understandability means a person who has a reasonable comprehension of government and public finance activities and fundamentals of governmental financial reporting (Genito, 2013). Reliability means the information presented is verified, unbiased, and faithfully reflects a transactions economic content (Genito, 2013). Relevance means the information presented should affect how a user assesses a problem, condition, or event (Genito, 2013). Timeliness means the information is presented soon after the decision making. Consistency refers to utilizing the same accounting method from one period to the next (Genito, 2013). Comparability means the accounting standards and policies are consistently applied from period to period and from one entity to another so as to allow the user to compare financial statements from prior periods and those of other governments (Genito, 2013). The changes from prior periods affecting the comparability of financial information should be explained in the notes and provide detailed information (Genito, 2013).

2.8.5 Government Funds

A fund is an accounting body with a self-balancing set of accounts for recording financial resources, liabilities, and operating activities which are separated to attain targeted objectives (Bragg, 2018). The government utilizes funds to maintain tight control of their resources and the design of funds allows the monitoring of resource inflows and outflows and the remaining amount of funds available (Bragg, 2018). The separation of resources into multiple funds allows the government to closely monitor resource usage and therefore minimize risk of overspending or spending in government unauthorized areas (Bragg, 2018).

2.8.6 Financial Statement Audit

The Government Accounting Standards Board (GASB) is the primary organization responsible for creating and updating government accounting standards (Bragg, 2018). The GASB identifies a wide array of individuals which include, but are not limited to, legislators, municipal bond insurers, rating agencies, citizen and taxpayer groups, and the general public (Genito, 2013). The GASB further identifies three primary groups of users to include the citizenry, legislative and oversight bodies, and investors and creditors (Genito, 2013). The purpose of the financial statement audit is to provide necessary assurance that the financial statements are presented in accordance with GAAP (Genito, 2013).

2.9 Evaluation of WWTP

The financial evaluation of a municipal wastewater plant can be complex and when upgrading a facility with the intent of increasing power efficiency needs to be carefully considered. A financial analysis of a wastewater plant will usually investigate the private costs and benefits. The economic analysis will look at the broader costs and benefits for society and include information for public policy decisions to support any upgrades to the wastewater plant (Hernández-Sancho, Lamizana-Diallo, Mateo-Sagasta & Qadir, 2015) The purpose of a WWTP is to clean sewage water and recirculate the water back into the environment. However, the costs associated with running the WWTP are high and with the high costs it can be difficult to justify paying for a service with no economic benefits. Also, if the WWTP has a poor performance of cleaning the sewage water for the environment the WWTP may face backlash by undergoing intense State and Federal inquisition resulting in a Federal Consent Decree, or State Agreed Order, a legally defined agreement of actions to be taken and penalties for infraction if the terms of the decree/order are not met (United States Environmental Protection Agency, 2019b). Additionally, if the WWTP abiding by compliance standards and adequately executing the cleaning of the sewage water, the WWTP still need consider and pursue methods to reduce its own carbon footprint and contribution to greenhouse gases by decreasing or finding renewable methods to help with this.

Biomass technologies are currently being employed to help power WWTP more efficiently via the burning of biogas to help heat and power the WWTP. The biogas is a product of anaerobic digestion which in of itself is a process of helping to reduce the amount of waste to disposal. However, the testing, process, and utilization of anaerobic digestion can be costly and must be justified as a potential long-term financial benefit.

The financial analysis used in this research study included a basic overview of the following items: cost of running the WWTP over a 12-month time span and the future energy costs of running the WWTP with the high energy yielding waste substrates.

Overall, the literature review provided a background and introduction to each of the key concepts related to how a municipal wastewater treatment plant works and operates from a technical and accounting perspective. The concepts and processes described in the literature review relate to the key areas that were tested and analyzed for the methodology and results of this research case study.

CHAPTER 3: RESEARCH METHODOLOGY

The methodology for this research case study comprises of two main sections: biomethane potential test and the financial analysis. The biomethane potential test consists of two phases. The first phase tested the industrial waste substrates to ascertain the chemical characteristics and whether the characteristics are suitable for anaerobic digestion. The second phase tested the varying amounts of industrial waste substrates in anaerobic digesters to evaluate how the substrates react during and after testing. The financial analysis methodology comprised of comparing the natural gas amount consumed by the WWTP to the amount of biogas produced by the anaerobic digesters used at the WWTP. The costs associated with purchasing natural gas for the WWTP and anaerobic digesters was also analyzed to ascertain potential cost savings from utilizing the produced biogas in lieu of purchasing natural gas.

3.1 Reliability

The methodology conducted for the technical and financial analysis adhered to the official and accepted practices ruling each test. The biomethane potential test was conducted by a University research laboratory and conducted each test according to the rules and regulations set forth governing biomethane potential tests. The financial and technical analysis adhered to known accounting equations and principles and conducted via computer software and double-checked by hand calculations. The reliability of the tests is high and can be replicated by following the methodology set forth for each test and process.

3.2 Validity

The biomethane potential test, conducted by the University research team abided by the rules, regulations, and procedures as stated in the Standard Methods for the Examination of Water and Wastewater Methods for each facet of the biomethane potential test (Clesceri et al., 1998a).

The financial statements referring the energy bills for the WWTP were obtained from the WWTP of whom obtained the bills from the municipality. The amounts of the energy and costs associated for consumption were taken verbatim from the accounting statements. The energy amounts and data related to equipment were provided by the WWTP and were not altered in anyway.

3.3 Biomethane Potential Test

Local industrial plants near the WWTP generate food waste byproducts from their industrial processes that may have viability for anaerobic digestion and thereby useful as a biogas to help power the WWTP. A BMP test is used to understand the biodegradability of the industrial byproducts and its suitability and impact on the anaerobic digesters. The WWTP and an associated engineering consulting firm obtained three different types of samples to be BMP tested and comprise of: corn starch, primary sludge and waste activated sludge. The waste cornstarch was mixed with the WWTP's waste activated sludge and raw sludge. Once the starch was mixed with the waste activated and raw sludge, the new combination was mixed with digested sludge in order to measure methane gas production. The BMP test was conducted by a Purdue University research laboratory in the Department of Agricultural and Biological Engineering and conducted in two phases.

The first phase of BMP testing comprised of a "liquid sample analysis of diluted substrates, inoculum, and digester feed. The BMP test conducted utilized four types of substrates (S1, S2, S3, and SM). The four substrates refer to the three samples provided by the WWTP with SM referring to an equal mix of all three samples.

3.3.1 Phase 1

Phase 1 of BMP testing consists of preparing the substrates, inoculum, and digester feed. A total of six liquid samples were taken from the diluted substrate, inoculum, digester feed, BMP influent, and BMP effluent and tested in triplicate for:

- pH, TS, TSS, VS, VSS, tCOD, sCOD, Alkalinity, TKN, VFA, Ammonia-Nitrogen, and Phosphate.

The sample substrates were then prepared into liquid samples comprising of: 4 diluted substrates (S1, S2, S3, and SM), Inoculum (digestate), and Full-scale digester feed composed of primary sludge and waste activated sludge (PS: WAS). Table 1 shows an overview of phase 1 test. Phase 1 of the BMP test took place in April 2019. The digester WAS (waste activated sludge) and inoculum were received together and stored in a refrigerator at 3°C (Celsius). Also, on the same day received were the three industrial waste substrates, S1, S2, and S3, which were stored at room temperature. The samples were then prepared, characterized and calculated. The WAS and inoculum were also sampled and characterized twice.

Table 3.1: Phase 1 Test Overview

Type of Liquid Samples	Analysis	Number of Samples	Number of Trials	Analysis	Subtotal
Diluted Substrates (S1, S2, S3, SM)	pH, TS, TSS, VS, VSS, tCOD, sCOD, Alkalinity, TKN, VFA, Ammonia-Nitrogen, and Phosphate	4	3	12	144
Inoculum (Digestate)	pH, TS, TSS, VS, VSS, tCOD, sCOD, Alkalinity, TKN, VFA, Ammonia-Nitrogen, and Phosphate	1	3	12	36
Full-scale Digester Feed (PS: WAS)	pH, TS, TSS, VS, VSS, tCOD, sCOD, Alkalinity, TKN, VFA, Ammonia-Nitrogen, and Phosphate	1	3	12	36

3.3.1.1 Phase 1-Sampling Technique

The equipment used for testing was: an oven, pH meter, and spectrophotometer. A pH meter measures the acidity or alkalinity of a solution at a given temperature (Thermo Fisher Scientific, Inc., 2014). The term pH is an acronym where “p” refers to the word power and “H” refers to the Hydrogen element symbol (Thermo Fisher Scientific, Inc., 2014). A neutral solution will have a pH of 7 meaning the activities of hydrogen and hydroxide ions are equal (Thermo Fisher Scientific, Inc., 2014). A pH below 7 means the solution is acidic due to the activity of the hydrogen ion is greater than the hydroxide ion. A pH above 7 means the solution is basic or alkaline due to the activity of the hydroxide ion being greater than the hydrogen ion (Thermo Fisher Scientific, Inc., 2014).

A spectrophotometer is an optical instrument used for measuring the intensity of light relative to wavelength (Burgess, 2017). Since each substance reflects and absorbs light differently a spectrophotometer can be used to know exactly how much light is absorbed by the substance. This knowledge can then be used for identifying and quantifying different materials (Burgess, 2017).

The lab test protocol methods for testing total solids, total suspended solids, and volatile suspended solids, adhered to the Standard Methods for the Examination of Water and Wastewater Methods (Clesceri et al., 1998a). The lab test protocol methods for testing total solids used Method 2540B (Clesceri et al., 1998b). Total suspended solids were measured using Method 2540D (Clesceri et al., 1998c). Volatile solids and volatile suspended solids both were measured using Method 2540E of the Standard Methods for the Examination of Water and Wastewater Methods (Clesceri et al., 1998d).

The substrate and inoculum characterization were characterized after collection. To ensure homogeneity, the particulate samples were thoroughly mixed with a magnetic star bar. The soluble samples were filtered with either a 0.2μm cellulose acetate filter or a 0.45μm cellulose acetate filter. The substrates were diluted with DI (deionized) water. The dilutions were performed on a mass basis of gram per gram basis and used a high precision mass balance (4 decimal places). Table 2 shows each of the parameters that were tested, the equipment used to measure, and the standard (if used) method used for measuring.

Table 3.2: Phase 1 BMP Test Parameters

Item to be Measured	Equipment Used	Standard Method (if applicable)
pH	Model 60, Jenco Digital pH Meter	N/A
Total Solids (TSS, mg/L)	Oven	Method 2540B
Volatile Solids (VS, mg/L)	Oven	Method 2540D
Volatile Suspended Solids (VSS, mg/L)	Oven	Method 2540E
Total Chemical Oxygen Demand (tCOD, mg/L)	Spectrophotometer (Hach DR 3900)	N/A
Soluble Chemical Oxygen Demand (sCOD, mg/L)	Spectrophotometer (Hach DR 3900)	N/A
Alkalinity (mg $CaCO_3$/L)	Spectrophotometer (Hach DR 3900)	N/A
Total Kjeldahl Nitrogen (TKN, mg/L)	Spectrophotometer (Hach DR 3900)	N/A
Volatile Fatty Acids (VFA, mg Ac/L)	Spectrophotometer (Hach DR 3900)	N/A
Ammonia Nitrogen (NH_3-N, mg/L)	Spectrophotometer (Hach DR 3900)	N/A
Phosphate (P or PO_4^{-3}, mg/L)	Spectrophotometer (Hach DR 3900)	N/A

3.3.3 Phase 2

Phase 2 comprised of testing the influent BMP samples for fifteen anaerobic reactors based on instructions from the WWTP and associated engineering firm. Initially, fifteen BMP influent samples were tested for pH, TS, and tCOD. Next, the influent BMP was tested in fifteen 1000-mL anaerobic reactors for 30 days. Lastly, fifteen reactor effluent liquid samples were tested in duplicate for: pH, TS, TSS, VS, VSS, tCOD, sCOD, Alkalinity, TKN, VFA, Ammonia-Nitrogen, and Phosphate. The digestate characterization was performed in order to verify the TS and VS of digester #13. The associated test results were then reported to the WWTP and consulting engineering firm.

The Phase 2 testing began on May 17, 2019 which was also the same day the laboratory received the samples from the WWTP. Two control substances were used as a standard control and variable control. Cellulose was used for the standard control and the digester feed was used as the variable control and are referred to in the Phase 2 tests as, A0 and A02, respectively. Cellulose is commonly used as a control substrate because it is high in quality and purity, economical, in relatively simple to calculate the theoretical BMP (Filer et al., 2019).

The three industrial waste substrates were tested at different COD levels as designated by the engineering firm, and have assigned letters: S1 (A), S2 (B), S3 (C), and SM (D). This nomenclature was used throughout the data results to assign which substrate is which and at which COD levels. The COD levels were measured due to COD having an environmental effect upon leaving the WWTP. A lower COD of the effluent is desired though due to the limited scope of this research the substrates was not be analyzed via the COD levels as the purpose of this research study is just to ascertain digester suitability and subsequent potential biogas and methane production.

3.4 Financial and Technical Analysis

The financial analysis and technical analysis investigated the current and future energy demand of the WWTP and the current and future energy costs for running the WWTP. The anaerobic digesters are the focus of this research study and thus warranted an individualized look into the energy demand and cost of running the digesters.

The financial analysis consisted of two main parts: return on investment and cost benefit analysis. Microsoft Excel was used to help perform financial calculations, develop graphs and charts to then compare the data for analysis. The WWTP provided the current energy bills for running the plant. Additionally, a proposal to replace certain equipment related to the anaerobic digesters has been proposed. The cost associated for purchasing the new equipment, installation, and future maintenance costs were analyzed as well.

The technical analysis comprised of analyzing the current energy demand of the entire WWTP and also specifically analyzing the energy demand of the anaerobic digesters. Future energy demand of the anaerobic digesters utilizing the higher biogas producing substrates were forecasted mathematically using a combination of computer software and calculations by hand.

The technical analysis comprised of analyzing the current heating demand of the entire WWTP and also analyzing the heating demand of the anaerobic digesters. Future heating annual costs for demand values were calculated based on projected inflation rates for the energy sector. These inflated rates may then use by the WWTP to determine whether it will be more economical to produce additional biogas at a higher heating demand or to continue purchasing natural gas. Additionally, the heating demand currently consumed, and the amount of biogas produced by digesters may also share insight into whether it would wise to use biogas produced by the digesters during certain times of the year and purchase natural gas for the remaining months of the year.

Overall, the results from the financial and technical analysis were compared to current energy demand and costs for the WWTP to forecasted energy demand and costs to show whether utilizing this additional biogas is economically feasible and viable for the long-term. Additionally, whether using the renewable biogas will ultimately result in a lower energy profile via demand and costs for the WWTP.

3.4.1 Cost benefit analysis

The cost benefit analysis utilized a calendar's year worth of data over the year 2019. The data for natural gas included consumption for the entire WWTP and the amounts used for heating the anaerobic digesters along with the associated costs. The data for the anaerobic digesters also included how much biogas the digesters are currently producing. All data for the year 2019 was presented on a monthly basis to ascertain trends over a course of a year.

Additionally, forecasted amounts based on projected inflation rates, for purchasing natural gas for the next 5 years was also calculated and compared to biogas production costs. The current and forecasted costs associated with purchasing natural gas were then compared to the costs of running the anaerobic digesters. The natural gas consumption and biogas production amounts were compared to deduce if the digesters are producing enough biogas to meet the current heating demand for the WWTP. In addition, the costs for purchasing natural gas and the costs for heating the anaerobic digesters were also compared to ascertain how expensive it is to purchase natural gas and produce biogas.

The results of the cost benefit analysis will show whether the current production of biogas is comparable to the natural gas consumption required not only by the anaerobic digesters but also the entire WWTP. Furthermore, theoretical biogas production amounts for the industrial waste substrates were also conducted. Although, any increase in heating demand required for handling these more volatile waste substrates for anaerobic digestion cannot be determined for this research study, recommendations may be made for the WWTP. The recommendations included discuss if it would be advisable to use biogas for the entire or parts of the year, rather than purchasing natural gas.

The overall purpose of the methodology set forth is to first prove whether the industrial substrates are suitable for anaerobic digestion. Once the proven the industrial substrates are suitable for anaerobic digestion, the next section will view how the substrates behave during anaerobic digestion. Finally, the financial analysis section will look into the monthly and annual amount of natural gas consumed by the whole WWTP and the anaerobic digesters over the course of the year 2019. As well as the costs associated with purchasing the natural gas over the year 2019. The natural gas amounts and costs will then be compared to the amount of biogas produced by the anaerobic digesters.

CHAPTER 4: RESULTS

The results shown consist of two sections: results of the BMP test and the current and forecasted energy consumption and cost for the WWTP. Overall, the intent of this work is to answer the research questions of whether the industrial waste substrates are fit for anaerobic digestion; and if so, how much additional gas (biogas) may be generated such that it equals or surpasses the demand of natural gas purchased from the utility company. The current breakdown of gas at the WWTP is comprised of approximately 65% methane (CH_4) and 35% carbon dioxide (CO_2). Though, less than 1% is made up of nitrogen and some amount of hydrogen sulphide and ammonia. The goal of anaerobic digestion is to maximize the amount of methane for use to produce biogas. Therefore, BMP results of the industrial waste substrates showing high levels of methane (at least 65%) production, is favorable.

The first section of the results comprises of select results from the biomethane potential test (BMP) to ascertain whether the industrial substrates have the potential for anaerobic digestion. The results presented comprise of a brief insight into whether the industrial substrates are at all suitable for anaerobic digestion and if so, what would the methane production potential represent. The results with thus show the pH levels, VS, and methane production.

The second section included the energy usage and cost associated with electricity and natural gas the WWTP requires for normal operation. The data encompass only at a year's worth of data for the year 2019. This is due to data availability and because this research study is the beginning of a much larger project and as such 2019 is a baseline year of which to grow from for this developing project.

Additionally, three hypothetical scenarios involving the industrial waste substrates and their potential to produce additional biogas was conducted as a form of recommendation for the WWTP. The recommendation offers an initial look into how the industrial waste substrates may be used and in what quantities to yield the best results for biogas production. Although, the additional potential of biogas is a benefit, the anaerobic digesters still rely on natural gas to be heated and therefore it needs to be ascertained whether the additional cost associated with the extra heating demand is worth the additional biogas production. In addition to suitability for anaerobic digestion, the BMP tests also show the biological characterization of the substrates and how they may interact with the environment upon expulsion from the anerobic digesters. When the substrates enter the anaerobic digesters only a certain percentage is used for digestion and the rest of the substrates are taken out of the digesters to either be transported to landfills or for agricultural usage. Therefore, the BMP results also show how volatile these industrial substrates are to ascertain whether the substrates might be sent to either landfills or for agricultural usage. Agricultural usage often uses the sludge (substrates) as fertilizer and as such if the sludge has high amounts of volatile compounds it would be harmful to crops being grown.

4.1 BMP Test

The entirety of the BMP test was performed by a professor and their research group from the Department of Agricultural and Biological Engineering at Purdue University. The laboratory then provided the WWTP and the consulting engineering firm the BMP test results. The BMP test is used to verify whether the industrial waste substrates are suitable for anaerobic digestion and if the substrates upon leaving anaerobic digestion adhere to environmental guidelines. Therefore, the results from the comprehensive BMP test showcase whether the industrial substrates meet the key process parameters to be suitable for anaerobic digestion.

The entirety of the BMP test results discussed in this research study were provided via Microsoft Excel file containing all data results by the laboratory and is displayed as shown exactly as provided by the laboratory. The Phase 1 test results show the pH and volatile solids values of each of the substrates and the WWTP's digester feed and inoculum. The Phase 2 test results show how the substrates react while in the anaerobic digesters over the entire test period.

4.1.1 Phase 1 Test Results

Phase 1 of the BMP test was to prepare the four substrate samples provided. Each test was completed three times to verify: pH, TS, TSS, VS, VSS, tCOD, sCOD, Alkalinity, TKN, VFA, Ammonia-Nitrogen, and Phosphate. Due to the bounds of this research study focusing on just an overview of anaerobic digester suitability and the amount of methane produced, the results shown here will only be for pH and VS result values. The other parameters, although equally important, are more concerned with the quality of the sludge upon leaving (effluent) the anaerobic digesters and to be within the EPA guidelines for waste removal. The pH of a substance has direct bearing on all parameters and is a strong indicator for suitability for anaerobic digestion as a substance is too acidic or too basic will cause problems within the biological process and subsequently harm the anaerobic digesters. The VS parameter is considered an indicator of the amount of organic matter present in a certain amount of wastewater, activated sludge, and industrial wastes (Clesceri et al., 1998d). The organic matter is what is burned during anaerobic digestion and from which methane is generated from the digestion of the organic compounds. Therefore, methane productivity can be measured regarding the number of volatile solids (VS) burned (Goswami, n.d.)

The results of the Phase 1 Batch 1 tests are shown in Table 3. Also included in Table 3 are the result values for each of the three trials, the average values of the three trials, standard deviation, and the coefficient of variation (CV). The industrial waste substrates provided to the WWTP were labeled by the plant they originated from and are referred to as: Industrial FD, AGG1, and AGG2. The Industrial FD is composed of cornstarch. The AGG1 substrate is made of primary sludge and AGG2 is made of waste activated sludge. For phase 1 the industrial waste substrates are referred to as S1, S2, and S3, respectively. The test substrate SM refers to an equal mix of all three industrial waste substrates.

The term digester feed refers to a combination of primary sludge and waste-activated sludge provided by the WWTP. The term inoculum refers to the anaerobic digestate or effluent from the anaerobic digesters provided by the WWTP.

The samples from Table 3 were all received by the BMP testing lab on April 3, 2019. The four substrates (S1, S2, S3, and SM) were diluted with 5% DI water. The optimum pH levels for anaerobic digestion are 6.5 to 7.5. The pH values shown below for the four substrates are below 6.5 indicating the samples, S1, S2, S2, and SM are acidic. The digester feed (WAS) and inoculum were each tested twice; first on April 3, 2019 and again on April 12, 2019. The pH levels for both the digester feed and inoculum both degraded from the first test on April 3 to a lower value on April 12, indicating that over time the samples become more acidic. Furthermore, the volatile solids for the digester feed samples increased for the second test, whereas for the inoculum the volatile solids increased for the second sample. The coefficient of variation shows the degree of variability among the data sets. For the substrates, S1 and S3 have the least amount of variability compared to S2 and SM.

Table 4.1: Phase 1 Batch 1 results for pH and Volatile Solids

		Digester feed (WAS)	Digester feed (WAS)	Inoculum	Inoculum	S1 @ 5%	S2 @ 5%	S3 @ 5%	SM @ 5%
Date		4/3/19	4/12/19	4/3/19	4/12/19	4/5/19	4/5/19	4/5/19	4/5/19
pH	*#1*	6.81	5.47	7.12	5.63	6.51	6.24	6.17	6.33
	n	1	1	1	1	1	1	1	1
Volatile Solids (mg/L)	*#1*	25943	24431	15556	19271	44065	42056	51639	46735
	#2	25920	24133	16007	17265	44376	42874	52120	47325
	#3	25718	24030	15481	17055	44500	40678	51606	48685
	average	25860	24198	15681	17864	44314	41869	51788	47582
	stdev	123	208	284	1224	224	1110	288	1000
	n	3	3	3	3	3	3	3	3
	CV	0.005	0.009	0.018	0.068	0.005	0.027	0.006	0.021

A second batch of substrates were received and tested for the same parameters as used for Table 4. For the second batch, the digester WAS, and inoculum were received on April 29, 2019 and the three substrates (S1, S2, and S3) were received on April 3, 2019. The samples were prepared and analyzed from April 29, 2019 to May 6, 2019 and the test results are found in Table 4 which show just pH and Volatile Solids results for the Phase 1 Batch 2 test results. The test dates for S1, S2, S3, and SM were not specifically provided though the entirety of test for Batch 2 was completed from April 29, 2019 to May 6, 2019.

The pH values for Batch 2 when compared to that of Batch 1, are higher with all pH values above 6.5 unlike Batch 1. The volatile solids values for all substrates tested are also higher than what was found in Batch 1 from Table 3. The volatile solids values for Digester feed and Inoculum are lower than that of S1, S2, S3, and SM indicating that these industrial substrates contain more volatile organic compounds than what is presently processed by the WWTP.

Table 3.2: Phase 1 Batch 2 results for pH and Volatile Solids

Parameter and Note		Digester feed (WAS)	Inoculum	S1 @ 5%	S2 @ 5%	S3 @ 5%	SM @ 5%
	Date	4/29/19	4/29/19				
pH	*#1*	7.07	7.41	6.68	6.59	6.58	6.66
pH meter calibrated to 7.0 before testing.	*n*	1	1	1	1	1	1
Volatile Solids (mg/L)	*#1*	30506	15630	45363	47624	53449	48538
	#2	29917	15277	NA	48020	52847	48583
	#3	29660	15682	45250	49206	53557	48461
	average	30028	15530	45306	48283	53284	48527
	stdev	433	220	79	823	383	61
	n	3	3	2	3	3	3
	CV	0.014	0.014	0.002	0.017	0.007	0.001

4.1.2 Phase 2 BMP Test Results

The data for Phase 2 is represented via graphs which show the overall results of the BMP test. The Phase 2 test was completed to verify if the industrial substrates were suitable for use in the WWTP. The industrial substrates were speculated prior to testing to be volatile enough to produce additional methane. However, the degree to the volatility of the industrial substrates needs to be BMP tested to not only ascertain anaerobic digester suitability but also that the substrates upon leaving the anaerobic digesters are within the environmental regulatory bounds. Though, the concern for anaerobic digester suitability will only be covered in this section. Furthermore, due to certain circumstances, some samples were required to begin testing again and therefore the actual test period was increased from 30 days to 41 to 47 days".

Phase 2 of the BMP test includes two sets of results related to gaseous products (which include biogas and methane) and production rates, and characterization of the digestate. The influent samples were tested in 15 anaerobic digesters for 30 days. Next, the 15 reactor effluent liquid samples were then tested in duplicate for: pH, TS, TSS, VS, VSS, tCOD, sCOD, Alkalinity, TKN, VFA, Ammonia-Nitrogen, and Phosphate. Due to the limited scope of this research study only the pH and VS data results will be discussed as it relates to methane production.

The laboratory received the samples from the WWTP on May 17, 2019 and began Phase 2 testing on the same day. Two control substances were used as a standard control and variable control. Cellulose was used for the standard control and the digester feed was used as the variable control and are referred to in the Phase 2 tests as, A0 and A02, respectively. The three industrial waste substrates were tested at different COD levels and have assigned letters: S1 (A1, A2, A3), S2 (B1, B3), S3 (C1, C2, C3), and SM (D1, D2, D3, D4, D5). The COD levels tested for each substrate and overall testing parameters were also influenced by the engineering firm to test for specific instances. The results found in the figures and graphs relate to the entire BMP test period.

Figure 1 refers to the digester liquid pH over the entire test period. From the data the pH levels mostly remained above 6.5 and below 7.5. There was an instance when few instances when substrates S2 and S3 yielded a higher pH value at 33 days. Though for the remaining days the pH values stayed within the realm of 6.5 to 7.5. Table A.1 found in the Appendix comprises of the entire numerical data results that were used to develop the graph in Figure 2.

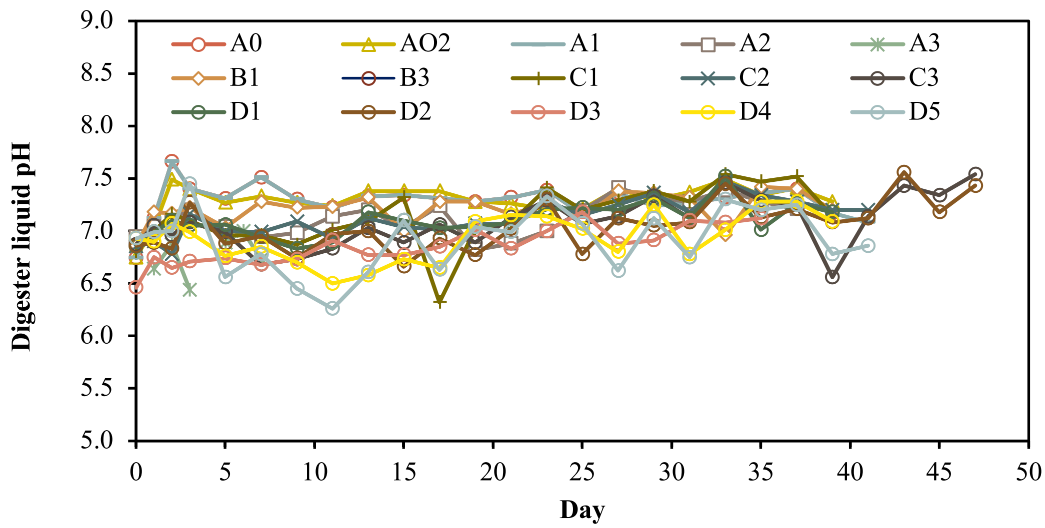

Figure 4.1: Digester liquid pH levels over entire test period

Figure 2 shows the cumulative biogas production (mL) over the entire test period. As shown, many of the samples stayed constant with C3 (S3-75% COD) increasing quite a bit over the test period. The substrate C3 is the WAS sludge from the industry plant and is tested at 75% COD. The COD is an indicator for how the effluent water upon leaving the anaerobic digesters will affect the environment. A high amount of COD in a material means a greater amount of oxidizable organic material in the sample. Therefore, with the high potential amount of biogas production from C3 is positive for the WWTP in producing biogas however these high amounts of COD mean it could be harmful upon leaving the digesters if not burned and/or treated to reduce the severity. Table A.2 found in the Appendix comprises of the entire numerical data results that were used to develop the graph in Figure 2.

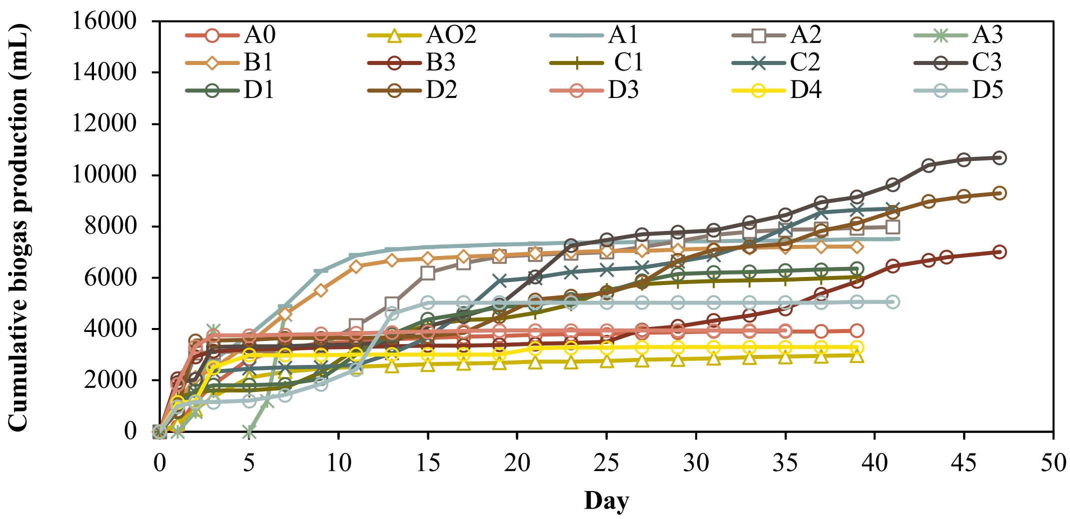

Figure 4.2: Cumulative biogas production (mL) over entire test period

Figure 3 shows the cumulative methane production (mL) of the samples over the entire test period. Similar to Figure 2, C3 increases over the span of the test period. The samples B1, A2, and D2 were promising in showing increase in methane production after Day 10 in the digesters. Table A.3 found in the Appendix comprises of the entire numerical data results that were used to develop the graph in Figure 3.

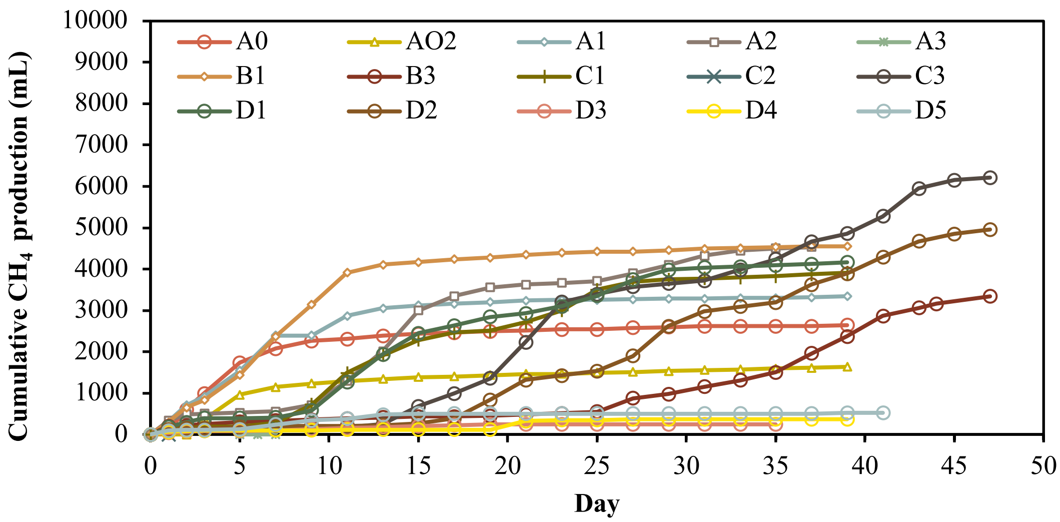

Figure 4.3: Cumulative CH4 production (mL) over entire test period

Figure 4 shows the VS levels (mg/L) of the samples in the digesters at the end of the test period. Sample D5 from digester #15 is noticeably higher followed by B3 (S2) and D3 (SM) and D1 (SM). This indicates that the mixture (SM) of all three substrates is volatile and may need to be pretreated prior to anaerobic digestion in order to reduce the number of volatile solids. The substrates upon leaving the digesters will be transported to one of several destinations, among these are: landfills, incineration, or agricultural use. As such, the amount of VS indicates the number of organic compounds within the substrates and therefore may be harmful to the environment upon leaving the digesters. Though, a high VS indicates a good measure for the anaerobic digesters since VS is directly related to methane production this may not be a good indicator for the environment. Table A.4 found in the Appendix comprises of the entire numerical data results that were used to develop the graph in Figure 4.

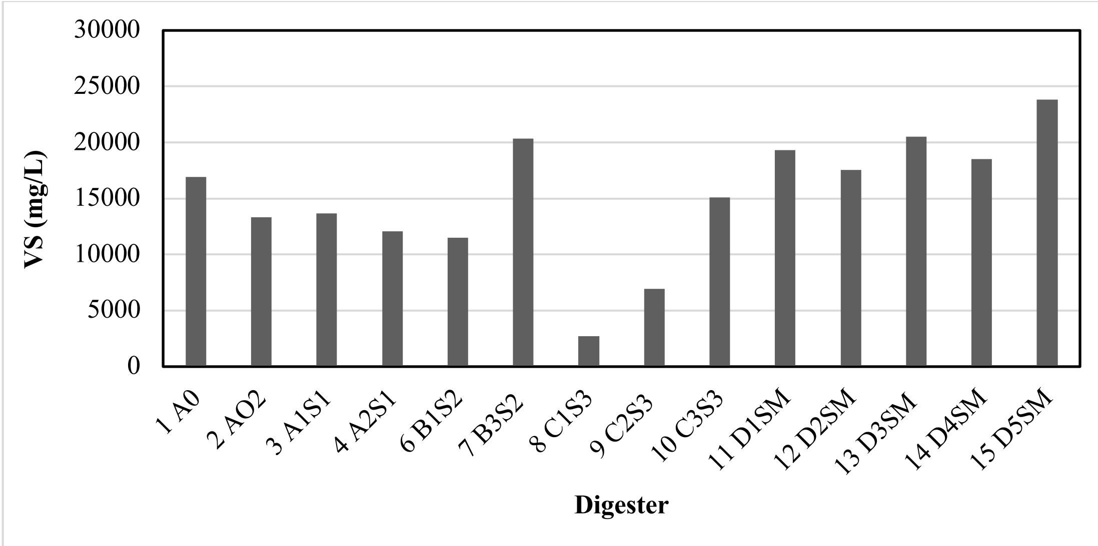

Figure 4.4: Volatile Solids (mL) of substrates at end of test period

4.2 Energy and Cost

The equipment directly linked to the anaerobic digesters require both electricity and heat to operate. Anaerobic digesters run on heat powered by natural gas. Although electricity is used to startup the digesters and is used for monitoring the equipment, adjustment to the controls, etc. However, due to the scope of this research study, the electrical consumption of the anaerobic digesters will not be analyzed. The main components for basis of comparison are between the natural gas consumption the WWTP buys from a provider and the amount of biogas produced by the anaerobic digestion.

There are two main components for the comparison between the natural gas and digester gas: amount of gas and costs associated. The first component analyzed the current natural gas consumption by the WWTP, and the costs associated on a monthly basis over the course of twelve months. The natural gas provider charges the WWTP fixed rates based on certain amounts of gas consumed. As such, forecasted amounts based on inflation rates for the next five years were calculated in order to view future natural gas costs. The current and forecasted costs associated with purchasing natural gas was then compared to the biogas produced by the anaerobic digesters.

The second component analyzed the natural gas consumption used for heating the anaerobic digesters and the amount of biogas generated by the anaerobic digesters on a monthly basis over the course of twelve months. The consumption and production rates were compared to view whether the anaerobic digesters are net zero regarding natural gas consumption and production.

To carefully analyze the available data the following sections evaluated electric usage, natural gas consumption, and digester biogas production. Graphs are provided to illustrate energy consumption of the WWTP, how much gas is consumed and the resulting production of biogas. The last analysis provided the increased yield by the addition of industrial substrates to anaerobic digestion, which aides in the production of biogas. Therefore, contributing to the capacity to heat WWTP which is expected to offset the costs associated with the purchase of natural gas.

4.2.1 Natural Gas

The natural gas provider has three locked prices for the WWTP dependent upon how much the WWTP consumes. The first locked price is the bulk gas price at \$3.79. The second locked price is the amount the natural gas provider charges the WWTP for the first 250 Dekatherms used at \$1.609. The third locked price is the amount the natural gas provider charges the WWTP for every Dekatherm used that is above the initial 250 Dekatherms at \$0.729. Table 5 shows the volume of natural gas consumed by the WWTP and the costs for each month over the span of twelve months from January 2019 to December 2019. The WWTP provided data for the meter reading date and volume of natural gas consumed measured in Dekatherms. Microsoft Excel was used to calculate the costs associated with the consumption of the natural gas for each month. The amounts were calculated using Equations 1, 2, 3, 4, and 5. Equation 1 shows the formula used to find the bulk gas price based on the entire daily natural gas consumption amount. Equation 2 is the formula used for calculating the cost for the natural gas volume consumed that is less than 250 or equal to 250 Dekatherms. Equation 3 is the formula used to find the amount of natural gas volume consumed that is above 250 Dekatherms. Equation 4 is the formula for calculating the cost for each additional Dekatherm used above the initial 250 Dekatherms. Equation 5 is the formula for calculating the entire total cost for consuming a certain amount of natural gas.

$$Bulk\ Gas\ (\$) = \$3.79 * Total\ Amount\ of\ Natural\ Gas\ Consumed\ (Dekatherms) \quad (1)$$

$$Amount\ used\ above\ 250\ Dekatherms = \quad (2)$$
$$= Total\ Amount\ of\ Natural\ Gas\ Consumed\ (Dekatherms) - 250\ Dekatherms$$

$$First\ 250\ Dekatherms\ (\$) = \quad (3)$$
$$= \$1.609 * Total\ Consumption\ under\ and\ including\ 250\ Dekatherms$$

$$Above\ 250\ Dekatherms = \quad (4)$$
$$= \$0.729 * Amount\ used\ above\ 250\ Dekatherms$$

$$Total\ Cost\ (\$) = \quad (5)$$
$$= Bulk\ Gas(\$) + First\ 250\ Dekatherms(\$) + Above\ 250\ Dekatherms(\$)$$

Table 4.3: WWTP monthly natural gas consumption and cost

Meter Reading Date	Volume (Dekatherms)	Amount above 250 Dekatherms	Bulk gas = \$3.79/Dekatherm	\$1.609 for first 250 Dekatherms	\$0.729 above initial 250 Dekatherms	Total (\$)
		250	\$3.79	\$1.609	\$0.729	
1/2/19	1020.23	770.23	\$3,866.67	\$402.25	\$561.50	\$4,830.42
2/1/19	1627.42	1377.42	\$6,167.92	\$402.25	\$1,004.14	\$7,574.31
3/1/19	1606.15	1356.15	\$6,087.31	\$402.25	\$988.63	\$7,478.19
4/1/19	1193.53	943.53	\$4,523.48	\$402.25	\$687.83	\$5,613.56
5/1/19	45.60	-204.40	\$172.82	\$73.37	\$0.00	\$246.19
5/31/19	19.26	-230.74	\$73.00	\$30.99	\$0.00	\$103.98
7/1/19	217.63	-32.37	\$824.82	\$350.17	\$0.00	\$1,174.98
8/1/19	15.45	-234.55	\$58.56	\$24.86	\$0.00	\$83.41
9/1/19	35.65	-214.35	\$135.11	\$57.36	\$0.00	\$192.47
10/1/19	35.65	-214.35	\$135.11	\$57.36	\$0.00	\$192.47
11/1/19	972.94	722.94	\$3,687.44	\$402.25	\$527.02	\$4,616.72
12/2/19	2344.21	2094.21	\$8,884.56	\$402.25	\$1,526.68	\$10,813.48
					Total Cost	\$42,920.21

To locate trends for how the natural gas consumption may appear for the foreseeable future (approximately 5 years from and including 2020 to 2024). A 3-point moving average was used for the natural gas consumption to view the trend representing consumption over the year 2019. Table 6 shows the natural gas date the meter was read, the volume of natural gas consumed at that point in time, and the accompanying 3-point moving average values.

Table 4.4: Annual natural gas consumption and trend

Meter Reading Date	Volume (Dekatherms)	3-Point Moving Average
1/2/19	1020.23	1417.93
2/1/19	1627.42	1475.70
3/1/19	1606.15	948.43
4/1/19	1193.53	419.46
5/1/19	45.60	94.16
5/31/19	19.26	84.11
7/1/19	217.63	89.58
8/1/19	15.45	28.92
9/1/19	35.65	348.08
10/1/19	35.65	1117.60
11/1/19	972.94	
12/2/19	2344.21	
Total Consumption	9133.72	

The forecasted rates the WWTP will be paying for the next 5 years including 2020 to 2024 are shown in Table 7. The projected inflation rates (Duffin, 2019) for the years 2020, 2021, 2022, 2023, and 2024 are shown below along with the adjusted natural gas rates the WWTP will pay for those years. Table 8 shows the new annual costs, using the inflation rates from Table 7, for purchasing natural gas for the years 2020, 2021, 2022, 2023, and 2024. From Table 8 it can be shown that the project annual costs increase by approximately $1,000 for every year assuming consumption amounts stay constant.

Table 4.5: Forecasted natural gas inflation rates

Year	2019	2020 (2.73%)	2021 (2.27%)	2022 (2.23%)	2023 (2.23%)	2024 (2.24%)
Percent Inflation		1.0273	1.0227	1.0223	1.0223	1.0224
Bulk Gas	$3.790	$3.893	$3.982	$4.071	$4.161	$4.255
First 250	$1.609	$1.653	$1.690	$1.728	$1.767	$1.806
Above 250	$0.729	$0.749	$0.766	$0.783	$0.800	$0.818

Table 4.6: Forecasted natural gas annual costs

	2019	2020	2021	2022	2023	2024
Natural Gas Annual Cost ($)	$ 42,920.21	$ 44,088.52	$ 45,094.08	$ 46,101.51	$ 47,119.94	$ 48,182.17

4.2.2 Anaerobic Digestion

The biogas produced at the WWTP is composed of approximately 65% methane gas and the remaining amount of 35% is carbon dioxide. The biogas produced from the anaerobic digestion occurs via the volatile solids which lets off methane and that methane is the primary source of biogas. Volatile Solids (VS) is an indicator for the potential of methane production. Volatile solids are made up of organic matter which when undergone the breakdown during anaerobic digestion gives off methane. Therefore, the higher the amount of VS, the greater the amount of methane production and thereby biogas. Currently the anaerobic digesters at the WWTP under observation, processes approximately 40,000 pounds per day (lbs./day) of dry weight, volatile solids spread across four anaerobic digesters.

The higher energy yielding industrial waste substrates under consideration, account for approximately 13 to 18 cubic feet of gas per pound of volatile solids. Table 9 shows the heat demand for the anaerobic digesters over the course of a calendar year (12 months). The heat used for the anaerobic digesters is fueled by natural gas. The values of heat demand are based on approximate values over the Summer and Winter months. The Summer months' value is comprised of, up to and including April to September and have an approximate heat demand of 24.3 million Btu/day. The Winter months' value is comprised of, up to and including, October to

March and require an approximate heat demand of 50.1 million Btu/day. For comparison to the natural gas consumption, the heat demand values of Btu/day were converted to Dekatherm/day by dividing the Btu/day values by 1,000,000 to obtain the Dekatherm/day values (Hofstrand, 2008). Once the Dekatherm/day values were determined, the cost for heating the anaerobic digesters can then be determined by utilizing the same cost value Equations 1, 2, 3, 4, and 5, used for the natural gas calculations.

Table 4.7: Heat demand for the anaerobic digesters

Month	Heat Demand (Btu/Day)	Dekatherm/ Day	Amount over 250 Dekatherm	Bulk gas = $3.79/ Dekatherm	$1.609 for first 250 Dekatherms	$0.729 above initial 250 Dekatherms	Total ($)
			250	$ 3.79	$ 1.609	$ 0.729	
January	50,100,000	50.1	-200	$ 189.88	$ 80.611	$ -	$ 270.490
February	50,100,000	50.1	250	$ 189.88	$ 80.611	$ -	$ 270.490
March	50,100,000	50.1	-200	$ 189.88	$ 80.611	$ -	$ 270.490
April	24,300,000	24.3	224	$ 92.10	$ 39.099	$ -	$ 131.196
May	24,300,000	24.3	-200	$ 92.10	$ 39.099	$ -	$ 131.196
June	24,300,000	24.3	224	$ 92.10	$ 39.099	$ -	$ 131.196
July	24,300,000	24.3	-200	$ 92.10	$ 39.099	$ -	$ 131.196
August	24,300,000	24.3	224	$ 92.10	$ 39.099	$ -	$ 131.196
September	24,300,000	24.3	-200	$ 92.10	$ 39.099	$ -	$ 131.196
October	50,100,000	50.1	250	$ 189.88	$ 80.611	$ -	$ 270.490
November	50,100,000	50.1	-200	$ 189.88	$ 80.611	$ -	$ 270.490
December	50,100,000	50.1	250	$ 189.88	$ 80.611	$ -	$ 270.490
	Total Consumption	446.4				Total Cost	$ 2,410.114

Next, the amount of biogas produced over the calendar year 2019 by the anaerobic digesters is shown in Table 10. The volume of gas production was provided by the WWTP in the units of cubic foot of gas (cfh) daily for the entire twelve months of 2019. The values were then summed for the entire month and the monthly totals are shown in Table 10. To compare to the natural gas consumption from Table 6 the biogas production, cfh, was converted to Dekatherms by using Equation 6 (Hofstrand, 2008):

$$X\ Dekatherm = \frac{[(X\ cfh) * (1{,}027\ Btu)]}{1{,}000{,}000} \tag{6}$$

A 3-point moving average was used to show the trend of biogas production and the amount of biogas produced over the calendar year 2019 and can be shown in Figure 5.

Table 4.8: Anaerobic digester gas production

Month	Volume (cfh)	Dekatherms	3-Point Moving Average
January	1,874,250.00	1,924.85	2,118.42
February	1,906,400.00	1,957.87	2,390.64
March	2,407,530.00	2,472.53	2,644.24
April	2,669,430.00	2,741.50	2,556.17
May	2,647,220.00	2,718.69	2,293.40
June	2,150,240.00	2,208.30	2,016.66
July	1,901,860.00	1,953.21	1,784.42
August	1,838,830.00	1,888.48	1,640.02
September	1,471,830.00	1,511.57	1,589.25
October	1,480,060.00	1,520.02	1,652.54
November	1,690,510.00	1,736.15	
December	1,656,720.00	1,701.45	

4.2.3 Natural Gas vs. Anaerobic Digester

A side by side overview comparison of natural gas versus anaerobic digestion is shown in Table 11. The table comprises of showing the natural gas consumption and annual cost associated; compared to the anaerobic digesters production of biogas, consumption of natural gas, and the total annual cost for heating the anaerobic digesters.

From Table 11, it can be shown that over the course of the 2019 calendar year, the anaerobic digesters produce more biogas than the amount of natural gas the anaerobic digesters use. Additionally, the anaerobic digesters produce more biogas than what the WWTP consumes overall for natural gas. Indicating the WWTP may utilize biogas in lieu of purchasing natural gas for the majority of the year. Though, due to the high consumption for Winter months, notably December, it would still be wise to purchase natural gas.

However, when referencing Table 8 of forecasted annual costs for purchasing natural gas, it would be wise to consider utilizing more of the biogas produced than purchasing natural gas. The projected annual costs for natural gas increase by approximately $1,000 every year with 2024 at a project annual cost of $48,182.17. Although, the heating demand may fluctuate in the coming years it would be recommended to at least utilize the biogas produced for heating the anaerobic digesters as even with the potential heating demand by the industrial waste substrates the biogas production would still possibly be in excess of what will be consumed.

Table 4.9: Annual natural gas consumption vs. anaerobic digestion production and consumption

	Natural Gas	Anaerobic Digesters
Total Annual Production (Dekatherm)	N/A	24,334.64
Total Annual Consumption (Dekatherm)	9,133.72	446.4
Total Annual Cost ($)	$42,920.21	$2,410.11

To compare consumption and production, Figures 5 and 6, show the natural gas consumption and anaerobic digester biogas production, respectively. Figures 5 and 6 include the month, volume used/produced, and a 3-point moving average trend over the course of twelve months for the calendar year 2019. As shown, the months from May (5/1/19) up to and including October (10/1/19) have a lull period of natural gas consumption. The highest consumption of natural gas is for the month of December (12/1/19) followed by February (2/1/19) and March (3/1/19). To contrast, the anaerobic digesters produce a steady supply throughout the year with the largest amount of biogas produced during the months from March to July.

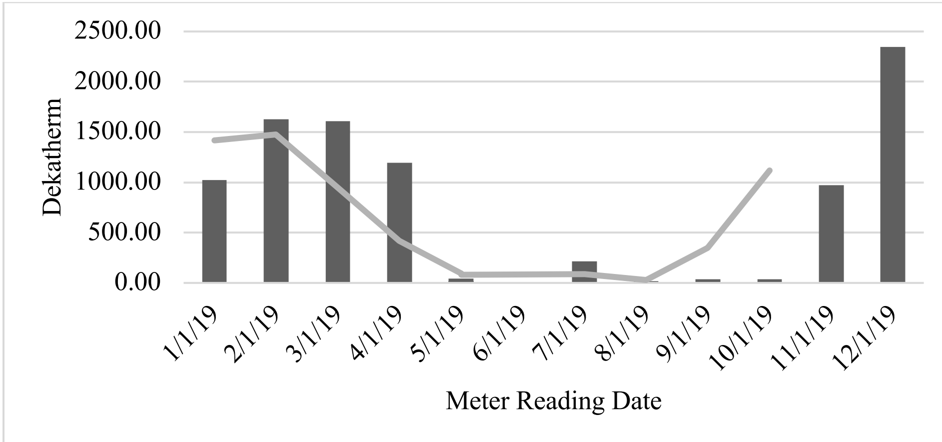

Figure 4.5: Annual natural gas consumption and trend

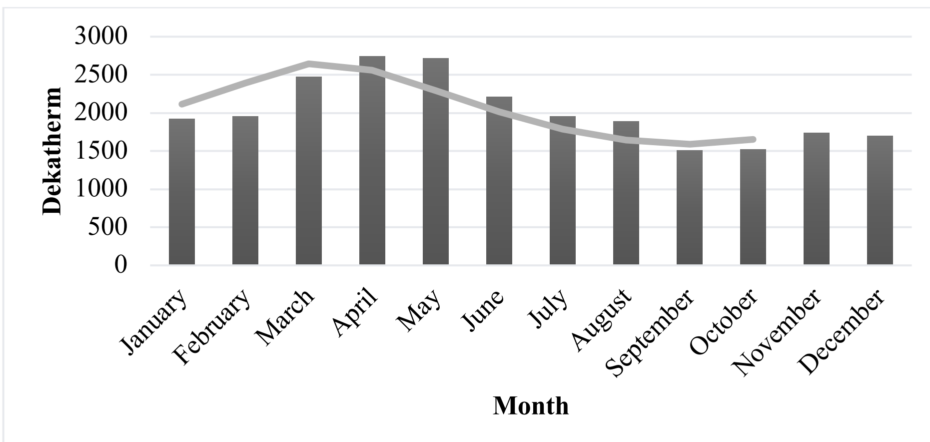

Figure 4.6: Anaerobic digester biogas production

4.2.4 Theoretical Scenarios

The anaerobic digesters used at the WWTP process approximately 40,000 lbs./day of volatile solids. The volatile solids are used to make methane which is then used to produce biogas. A certain percentage of the waste substrates used for anaerobic digestion is used to process the methane to produce biogas with the remaining unused percentage sent from the WWTP to a destination which may include are not limited to landfills or agricultural usage.

The three industrial waste substrates the WWTP had analyzed by BMP testing have a percent volatile solids average of approximately 99.8% volatile solids. As part of a recommendation to the WWTP to determine what amount of the industrial waste substrates may be added to the daily 40,000 lbs./day, three theoretical scenarios were used to determine how many pounds are used for anaerobic digestion. The three theoretical amounts to be processed per day by the anaerobic digesters are: 45000 lbs., 50000 lbs., and 55000 lbs. For the year 2019, the anaerobic digesters had an inputted digested sludge on average 63% and outputted approximately 47% of the digested sludge which will then be transported from the WWTP to landfills, agricultural usage, etc. For the theoretical scenarios involving the higher volatile industrial waste substrates, an input percentage of 99.8% and an output percentage of 45% was used where percentage values were provided by the WWTP. The percent difference between 99.8% and 45% yielding 54.8% means that 54.8% of the sludge is burned to produce biogas. The 45% leftover will be transported from the WWTP. Currently, the percent difference between 64% and 45% yields a difference of 18%, meaning only approximately 18% of the sludge going into the anaerobic digesters is actually used to produce biogas, resulting in approximately 7,200 lbs./day of the total 40,000 lbs./day actually used for biogas. The remaining 32,800 lbs./day is transported from the WWTP. Therefore, the higher yielding industrial waste substrates allows for a higher amount of the sludge to be burned to produce biogas and can be summarized in Table 12 for the three amounts of 45000, 50000, and 55000.

Table 4.10: Theoretical anaerobic digestion amounts

Amount to be Used for Biogas (lbs./day)	Percent In	Percent Out	Percent Difference	Amount Consumed (lbs./day)
45,000	99.80%	45%	54.80%	24,660
50,000	99.80%	45%	54.80%	27,400
55,000	99.80%	45%	54.80%	30,140

4.3 Discussion

The potential increased usage associated with producing more biogas at these larger amounts than the current 40,000 lbs./day may result in an increase in heating demand requirement. An exact value for the increase in heating demand and associated costs cannot be accurately surmised at this point due to limited data availability. Future work and insight into determining the heating values for the industrial substrates is required to properly calculate the projected increase in heating demand and thereby potential increase in costs associated. These costs may then be compared to the inflation values calculated in Table 8 to surmise whether it would be more cost effective to produce more biogas at a higher heating demand or continue purchasing natural gas. Additionally, the potential increase in greenhouse gas emissions from using additional natural gas to heat the anaerobic digesters would also need to be considered. Furthermore, whether using the produced biogas will decrease greenhouse gas emission would need to be further examined to determine whether the use of biogas is indeed environmentally friendly.

The costs associated for heating the anaerobic digesters with natural gas over the course of a year (2019) is $2,410.114 of the entire $42,920.21 amount for heating the WWTP with natural gas. Furthermore, other costs the WWTP may incur would also raise the budget for running the WWTP. Therefore, the $2,410.114 to heat the anaerobic digesters is a rather small amount when compared to entire amount for running the WWTP. Although, it is a small amount and could be saved by utilizing the biogas to heat the digesters, it is still promising that costs could be saved. This then leads to the possibility of other areas within the WWTP that may be analyzed to reduce costs. Alternative uses for biogas outside of utilizing it for the WWTP will need to be analyzed. This analysis will ascertain whether reusing the biogas for the WWTP is the most beneficial on a cost and environmental basis for the WWTP and public welfare. Moreover, certain equipment cannot run on digester gas without gas cleaning, which may require the WWTP to refrain from using the biogas and instead find external uses of which to utilize the biogas. The electric costs associated directly with anaerobic digestion cannot singularly be isolated. It may be correlated, using future data, to the level of anerobic digestion. Based on constant production levels the electric consumption is anticipated to remain stable. The only change will be in the additional heat demand required for a large volume of substrates to be processed in the anaerobic digesters over the same time period of digestion.

CHAPTER 5: SUMMARY, CONCLUSIONS, and RECOMENDATIONS

The overall results of this research study found that the industrial waste substrates, after an initial BMP test, are acceptable for anaerobic digestion; as shown by the substrates being within the acceptable pH levels. The pH levels of the substrates affect the parameters required for a substrate to be able to undergo anaerobic digestion. How basic or acidic a substrate is having a direct relationship to the other process parameters for a substrate to able to undergo anaerobic digestion. For the purposes of this research study, only the pH levels and methane production of the substrates were considered. However, the quality of the sludge upon leaving the anaerobic digesters are just as important as the sludge going into the digesters. The environmental guidelines for waste substrates need to adhere to certain guidelines as these substrates are often transported to landfills, incinerated, or used for agricultural usage as fertilizer. As mentioned, the presence of many microorganisms plays a role in the environment and can lead to harm. Therefore, with anaerobic digestion the process degrades the substrates volatility so that upon leaving the digesters the substrates are not as volatile as to harm the environment upon reaching the final destination.

As such, to assure of consistency of results, additional BMP tests should be undertaken to ascertain that the industrial substrates being processed will indeed consistently yield the same results each time the substrates undergo anaerobic digestion. Furthermore, the BMP test conducted adhered to test guidelines set forth by the engineering firm in order to ascertain the suitability of the substrates upon initial analysis. Therefore, to err on the side of prudency, it would be advisable to conduct another BMP test (preferably at a different location) to test for conditions different than the ones performed initially in order to glean a more encompassing look into how the higher volatility industrial substrates will react under certain conditions. A different location to conduct the BMP test would be helpful as even though every laboratory adheres to the standard procedures, miscellaneous methods not standardized may potentially alter the results.

The results of the BMP discussed in this research study did not view the results from the perspective of how these industrial waste substrates may impact the environment upon leaving the digesters. Therefore, future work will be to not only view the potential methane production from these substrates but also the substrates may affect the environment upon removal. In light of this, pretreatments may be needed to decrease the volatility of the substrates so that when they are expelled from the digesters they are not as harmful to the environment. Additionally, if such pretreatments are required it could add to the costs of the additional heating demand requirements.

The energy and financial analysis results show were quite promising for the future of biogas. The current production of biogas is nearly equal to the amount of natural gas the WWTP consumes over a year. Further analysis would need to evaluate additional previous years of energy consumption to determine energy trends, but the data for the year 2019 is encouraging. The theoretical scenarios for using the industrial waste substrates shows great potential for the WWTP to produce more biogas and potentially save on natural gas costs by utilizing this additional biogas in the future.

5.1 Recommendations

The amount of biogas produced by the anaerobic digesters was high enough that the WWTP could potentially store the biogas for use during the months the WWTP requires high amounts of natural gas such as in December. Although, the costs for biogas storage would need to be ascertained to determine if storage would be the most cost effective for the WWTP.

Additionally, with the addition of the industrial waste substrates the amount of biogas produced will increase and raise the heating demand requirement. Though, further insight would need to be undertaken in order to see how much the heating demand will rise. Once the new heating demand is determined, the costs and amount of natural gas and biogas required to meet that heating demand would need to be determined and compared.

Alternative uses of determining the use of the produced biogas may also be considered. The preliminary evaluation conduced in this research study found the biogas produced to be comparable to the natural gas consumed. However, various factors relating to the biogas still need to be considered such as gas cleaning, storage, transportation, etc. These factors once determined may change the recommendations presented. Additionally, tax incentives for industrial firm utilizing a renewable energy source may be considered for the future. The tax incentive benefits, if present, may neutralize any additional negative financial obligations related to storing and cleaning the biogas.

The research case study is part of a much larger project ongoing at the WWTP and the results of this research study, relating to utilizing biogas in a greater capacity in the future, is a promising proposition the WWTP may consider moving forward.

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APPENDIX A. BMP RESULTS

Table A.1: Phase 2: BMP pH test results

Day	0	1	2	3	5	7	9	11	13	15	17	19	21	23	25	27	29	31	33	35	37	39	41	43	44	47
#1 'A0 (Standard Ctrl-Cellulose)	6.74	7.12	7.66	7.40	7.31	7.51	7.30	7.22	7.33	7.34	7.31	7.28	7.32	7.39	7.16	7.36	7.24	7.27	7.32	7.36	7.40	7.17	7.08			
#2 'AO2 (Variable Ctrl-WAS+Inoculum)	6.75	7.03	7.49	7.40	7.27	7.33	7.27	7.24	7.38	7.38	7.38	7.28	7.26	7.21	7.21	7.40	7.29	7.37	7.49	7.34	7.41	7.28	7.18			
# 3 'A1-S1 (25% COD)	6.88	7.02	7.29	7.20	7.17	7.33	7.18	7.20	7.31	7.28	7.33	7.04	7.04	7.10	7.11	7.42	7.32	7.26	7.50	7.11	7.19	7.23	7.17			
#4 A2-S1 (50% COD)	6.94	7.04	7.12	7.20	7.04	6.94	6.98	7.14	7.20	7.03	7.24	6.82	6.88	7.00	7.19	7.41	7.31	7.28	7.39	7.28	7.21	7.11	7.18			
#5 A3-S1 (75% COD) (First test, stopped after liquid overflow)	6.64	6.87	6.44																							
#5 A3-S1 (75% COD) (Second test, stopped after liquid overflow)	6.89	7.00	6.73																							
#6 B1-S2 (25% COD)	6.86	7.18	7.17	7.22	7.03	7.28	7.22	7.23	7.32	7.00	7.28	7.28	7.16	7.26	7.12	7.38	7.36	7.32	6.96	7.42	7.40	7.20	7.09			
#7 B3-S2 (75% COD)	6.86	6.81	7.11	7.00	6.96	6.71	6.83	6.86	7.07	6.96	7.18	6.94	6.90	6.90	7.09	7.24	7.44	7.34	7.55	7.42	7.42	6.98	7.02	7.12	7.30	7.39
#8 C1-S3 (25% COD)	6.80	7.00	7.16	7.10	6.96	6.96	6.87	7.01	7.09	7.32	6.32	7.02	7.08	7.41	7.20	7.29	7.38	7.28	7.54	7.47	7.52	7.14	7.07			
#9 C2-S3 (50% COD)	6.85	6.90	6.78	7.16	7.00	6.99	7.09	6.93	7.12	7.04	7.01	7.07	7.07	7.28	7.15	7.25	7.36	7.18	7.47	7.34	7.28	7.20	7.20			
#10 C3-S3 (75% COD)	6.87	7.05	6.96	7.08	6.99	6.68	6.73	6.83	7.03	6.89	7.06	6.89	7.13	7.29	7.07	7.14	7.33	7.12	7.46	7.29	7.25	6.56	7.14	7.43	7.34	7.54
#11 D1-SM (25% COD)	6.85	6.99	7.1	7.05	7.06	6.94	6.83	6.89	7.18	7.1	7.03	7.04	7.08	7.21	7.22	7.2	7.31	7.12	7.52	7.01	7.26	7.18	6.89			
#12 D2-SM(50% COD)	6.86	6.89	6.83	7.27	6.88	6.95	6.74	6.97	7	6.66	6.93	6.77	7.02	7.3	6.78	7.12	7.05	7.08	7.45	7.13	7.21	7.08	7.12	7.56	7.18	7.43
#13 D3-SM (75% COD) (First test, stopped after liquid overflew)	6.9	7.15	6.9																							
#13 D3-SM (75% COD) (re-started test)	6.46	6.75	6.65	6.71	6.74	6.68	6.73	6.91	6.77	6.77	6.85	7.01	6.83	7	7.18	6.88	6.91	7.1	7.08	7.12						
#14 D4-SM(150 %COD)	6.93	6.9	7.07	6.99	6.76	6.85	6.7	6.5	6.58	6.73	6.65	7.09	7.15	7.14	7.02	6.8	7.25	6.78	7.01	7.28	7.28	7.09	7.08			
#15 D5-SM (50 %COD)	6.93	6.99	7	7.45	6.56	6.78	6.45	6.26	6.61	7.1	6.63	7.04	6.99	7.33	7.07	6.62	7.12	6.75	7.3	7.2	7.25	6.78	6.86			

Table A.2: Phase 2 cumulative biogas production (mL) over entire test period

Day	0	1	2	3	5	7	9	11	13	15	17	19	21	23	25	27	29	31	33	35	37	39	41	43	44	47
#1 'A0 (Standard Ctrl-Cellulose)	0	1	3	6	11	18	27	38	51	66	83	102	123	146	171	198	227	258	291	326	363	402	443			
#2 'AO2 (Variable Ctrl-WAS+Inoculum)	0	1	4	10	21	39	66	104	155	221	304	406	529	675	846	1044	1271	1529	1820	2146	2509	2911	3354			
# 3 'A1-S1 (25% COD)	0	1	5	15	36	75	141	245	400	621	925	1331	1860	2535	3381	4425	5696	7225	9045	11191	13700	16611	19965			
#4 A2-S1 (50% COD)	0	1	6	21	57	132	273	518	918	1539	2464	3795	5655	8190	11571	15996	21692	28917	37962	49153	62853	79464	99429			
#5 A3-S1 (75% COD) (First test, stopped after liquid overflow)	0	1	7																							
#5 A3-S1 (75% COD) (Second test, stopped after liquid overflow)	0	1196	4562																							
#6 B1-S2 (25% COD)	0	1196	5758	5758	5758	5758	5758	5758	5758	5758	5758	5758	5758	5758	5758	5758	5758	5758	5758	5758	5758	5758	5758			
#7 B3-S2 (75% COD)	0	1196	6954	12712	18470	24228	29986	35744	41502	47260	53018	58776	64534	70292	76050	81808	87566	93324	99082	104840	110598	116356	122114	122114	122114	122114
#8 C1-S3 (25% COD)	0	1196	8150	20862	39332	63560	93546	129290	170792	218052	271070	329846	394380	464672	540722	622530	710096	803420	902502	1007342	1117940	1234296	1356410			
#9 C2-S3 (50% COD)	0	1196	9346	30208	69540	133100	226646	355936	526728	744780	1015850	1345696	1740076	2204748	2745470	3368000	4078096	4881516	5784018	6791360	7909300	9143596	10500006			
#10 C3-S3 (75% COD)	0	1196	10542	40750	110290	243390	470036	825972	1352700	2097480	3113330	4459026	6199102	8403850	11149320	14517320	18595416	23476932	29260950	36052310	43961610	53105206	63605212	63605212	63605212	63605212
#11 D1-SM (25% COD)	0	766	1607	1823	1823	1850	2065	3003	3803	4382	4606	4846	4953	5158	5448	5885	6144	6207	6233	6278	6314	6359	6399			
#12 D2-SM(50% COD)	0	837	3548	3548	3593	3646	3646	3646	3673	3726	3861	4482	5150	5284	5411	5839	6687	7090	7223	7331	7823	8110	8561	8974	9181	9297
#13 D3-SM (75% COD) (First test, stopped after liquid overflew)	0	1469	4189																							
#13 D3-SM (75% COD) (re-started test)	0	1853	3332	3754	3754	3781	3816	3843	3870	3897	3923	3950	3950	3950	3950	3950	3950	3950	3950	3950						
#14 D4-SM(150 %COD)	0	1139	1184	2498	2990	2990	2990	3017	3017	3017	3017	3017	3248	3275	3275	3302	3302	3302	3302	3302	3302	3302	3302			
#15 D5-SM (50 %COD)	0	979	1156	1156	1201	1426	1855	2431	4617	5035	5035	5035	5035	5035	5035	5035	5035	5035	5035	5035	5035	5062	5062			

Table A.3: Phase 2 cumulative CH4 volume (mL) over entire test period

Day	0	1	2	3	5	7	9	11	13	15	17	19	21	23	25	27	29	31	33	35	37	39	41	43	44	47
#1 'A0 (Standard Ctrl-Cellulose)	0	72	603	990	1737	2073	2261	2310	2385	2428	2462	2490	2520	2544	2544	2577	2594	2621	2621	2621	2621	2642	2642			
#2 'AO2 (Variable Ctrl-WAS+Inoculum)	0	0	0	363	956	1143	1228	1296	1339	1383	1402	1432	1462	1462	1491	1513	1531	1554	1572	1592	1613	1634	1634			
# 3 'A1-S1 (25% COD)	0	319	701	914	1543	2390	2390	2869	3049	3121	3164	3199	3235	3253	3253	3266	3288	3288	3301	3301	3319	3343	3343			
#4 A2-S1 (50% COD)	0	333	487	501	523	556	713	1295	2011	2997	3346	3559	3627	3663	3709	3897	4101	4322	4446	4502	4529	4561	4592			
#5 A3-S1 (75% COD) (First test, stopped after liquid overflow)	0	99	143																							
#5 A3-S1 (75% COD) (Second test, stopped after liquid overflow)	0	0	0																							
#6 B1-S2 (25% COD)	0	290	648	830	1442	2369	3140	3909	4108	4170	4241	4276	4343	4389	4427	4427	4458	4496	4511	4531	4550	4550	4550			
#7 B3-S2 (75% COD)	0	203	219	256	302	329	358	386	409	431	431	451	482	510	546	872	978	1150	1308	1505	1959	2370	2866	3060	3162	3340
#8 C1-S3 (25% COD)	0	120	165	194	194	286	721	1489	1912	2283	2463	2508	2709	2994	3504	3687	3748	3776	3796	3827	3874	3911	3962			
#9 C2-S3 (50% COD)	0	120	133	187	257	282	287	357	690	1172	1970	2913	3015	3207	3301	3368	3563	3782	4162	4712	5245	5345	5382			
#10 C3-S3 (75% COD)	0	104	109	110	125	125	153	179	243	680	993	1352	2230	3196	3392	3574	3652	3722	3978	4234	4663	4854	5274	5953	6152	6214
#11 D1-SM (25% COD)	0	176	296	393	393	412	578	1270	1938	2445	2636	2846	2928	3100	3356	3741	3978	4034	4057	4093	4124	4163	4195			
#12 D2-SM(50% COD)	0	111	149	149	174	206	206	206	227	272	385	833	1313	1422	1531	1898	2615	2972	3093	3190	3629	3886	4294	4669	4850	4957
#13 D3-SM (75% COD) (First test, stopped after liquid overflew)	0	99	120																							
#13 D3-SM (75% COD) (re-started test)	0	39	67	84	84	103	132	155	177	197	222	244	244	244	244	244	244	244	244	244						
#14 D4-SM(150 %COD)	0	62	87	90	96	96	96	114	114	114	114	114	323	345	345	367	367	367	367	367	367	367	367			
#15 D5-SM (50 %COD)	0	91	108	108	123	238	343	379	483	500	500	500	500	500	500	500	500	500	500	500	500	523	523			

Table A.4: Phase 2: Volatile Solids end of digestate characterization results at end of test period

Day	1	2	3	4	6	7	8	9	10	11	12	13	14	15
	A0	AO2	A1S1	A2S1	B1S2	B3S2	C1S3	C2S3	C3S3	D1SM	D2SM	D3SM	D4SM	D5SM
#1	16840	13431	14226	12040	12731	24931	1810	6159	15205	19831	17548	21141	17597	23671
#2	17045	13240	13141	12088	10222	15808	3569	7676	15019	18816	17525	19907	19484	23951
Average	16943	13336	13684	12064	11477	20369	2690	6918	15112	19323	17537	20524	18541	23811
stdev	145	135	767	34	1775	6451	1244	1072	131	717	16	872	1334	198
n	2	2	2	2	2	2	2	2	2	2	2	2	2	2
CV	1%	1%	6%	0%	15%	32%	46%	16%	1%	4%	0%	4%	7%	1%