Assessing the Feasibility of Anaerobic Digestion at the Bridgewater, MA Wastewater Treatment Plant

A Major Qualifying Project Report Submitted to the Faculty of Worcester Polytechnic Institute in Partial Fulfillment of the requirements for the Bachelor of Science Degree

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Abstract

The Town of Bridgewater Wastewater Treatment Plant is designing a facility upgrade in cooperation with Stantec. As an alternative to landfill sludge disposal, our team worked with Stantec to evaluate the process of anaerobic digestion (AD). An AD system was designed with the physical, structural, chemical, and electrical elements of a reactor, using mass-balance calculations and modeling software such as Revit and GPS-X. We then performed an economic analysis to compare costs with and without AD. We concluded that although AD is feasible at this facility, it is costly. Despite high upfront investment, AD is an opportunity for small wastewater treatment plants to increase environmental sustainability by reducing solid waste and producing renewable energy.

Acknowledgements

Our team would like to thank everyone who has supported and advised our project throughout its course. Thank you to Stantec and its representatives that were attentive to our team and willing to assist with any questions we had throughout this project: Erica Lotz and Justin Motta. Thank you to the Stantec employees who lent their time and expertise: David Graham and Brian Shea. Thank you to the Bridgewater Wastewater Treatment Plant operators for their hospitality and enthusiasm during our site visit. Thank you to Professor John Bergendahl for his guidance and expertise on anaerobic digestion modeling. Finally, thank you to our WPI Architectural, Civil, & Environmental Department Advisors: Professors Leonard Albano and Suzanne LePage.

Authorship

For the authorship of this report, each team member focused on an area of the anaerobic digestion (AD) process. For each chapter of the report, each group member wrote subsections on what they had worked on throughout the term. Some team members' work all fit within one objective while others spanned multiple objectives. Marshall focused on the structural aspects of the AD reactor, including designing the building surrounding the reactor using Revit. Rachael focused on most of the modeling aspects of the AD reaction as well as sizing the AD reactor. Maia focused on the energy requirements of the system as well as options for biogas reuse. Evelyn focused on the different types of AD reactors, sludge disposal options, and overall discussion of the report. For the economic analysis, Rachael focused on maintenance and disposal costs. For installation costs, Marshall investigated building costs, and Evelyn focused on reactor costs. Maia focused on the editing and formatting of the overall report.

Capstone Design

The Civil, Environmental, and Architectural Engineering Department at Worcester Polytechnic Institute (WPI) has ABET-accredited programs in civil, environmental, and architectural engineering. Part of the requirements for ABET accreditation of a university program is a capstone project with a design component (ABET, 2021). WPI has chosen to fulfil this requirement by having students in this department complete a Major Qualifying Project (MQP) during their final academic year.

The Bridgewater Wastewater Treatment Plant (WWTP) is seeking to upgrade and add multiple processes to their current treatment train and overall site. These upgrades are essential for the longevity and wellbeing of the facility and the community it serves. Stantec was hired to design this system upgrade and has more than 90% of the design plan completed. Our MQP team worked with Stantec, a consulting and design firm, to consider alternative design options for the Bridgewater WWTP. We chose to focus on researching and exploring an alternative option for sludge disposal which involved designing an anaerobic digestion (AD) system to reduce the sludge produced and explore options of biogas energy reuse. We have considered the impacts of six real-world constraints on this project and have outlined them in this section.

Ethical

Our team followed the guidelines of the American Society of Civil Engineers Code of Ethics and, to the best of our ability, provided an unbiased analysis of this alternative design option. We also considered the resources and equity impacts of an AD with the nearby community in mind.

Health & Safety

During this project, we considered the public health risks of having AD near residential areas. In addition, we assessed this alternative in comparison to the public health risks of sludge being brought directly to a landfill with no AD treatment. Our team also worked to ensure that the structural components of the AD system would be constructed in a way that was is in accordance with the Code of Massachusetts Regulations (CMR) Section 780.

Constructability

Since one of the main components of our project was creating a structure with an AD reactor attached, our team had to consider different aspects of the construction process. This included limitations of the building site, as well as the various materials that we intended to use within our design. The Bridgewater plant was a smaller scale site, and therefore our design had dimensional constraints with regards to the reactor and building sizes.

Environmental

The primary focus of this project was to assess alternative design options for the Bridgewater WWTP, specifically whether any part of this project could be more environmentally sustainable. According to a cost-benefit analysis, Stantec has recommended that Bridgewater WWTP discontinue on-site composting and instead dispose of sludge in a landfill. Landfills present many serious environmental and health concerns. When AD is implemented, it effectively converts organic waste into renewable energy and reduces the amount of overall solid waste (EPA, 2021). The sustainability of AD falls in line with Massachusetts' goals for the state's sustainability plans produced and supported by the state.

Social & Political

When instituted in a community WWTP, AD has social and political implications. Controlling odors is one of the most difficult aspects of designing a WWTP. Although smells are not physically harmful, they are physiologically disturbing. Foul smells can waft into nearby neighborhoods and businesses, which causes objections between residents and their idea of a plant. As a benefit for residents and local businesses, AD can help reduce unpleasant odors. AD reactors provide immediate disposal of wastewater sludge, whereas unprocessed sludge in large quantities can cause odor and nearby water pollution.

Economic

To assess the economic constraints of this project, our team performed an economic analysis of the addition of an AD reactor to the Bridgewater WWTP. For this economic analysis, our team reached out to vendors and used industry data to estimate various costs of this system. We also considered the economic burden that this project would introduce by adding significantly to the up-front cost of upgrades to the current system. Upgrades and maintenance of this plant primarily rely on taxpayer contributions, so even if the long-term cost of the AD would be less than alternative disposal methods, residents in the Town may be more focused on the immediate cost of installation. Additionally, economic challenges may be a higher priority for taxpayers than the environmental implications of the project due to immediate impacts to livelihood.

Professional Licensure Statement

Becoming a professional licensed engineer is critical, as ethics and law are involved in nearly every civil and environmental engineering profession. The Fundamentals of Engineering (FE) and Principles and Practice of Engineering (PE) exams are necessary steps that need to be taken in order to become a professional engineer. Professional engineers are individuals that have attained the highest level of knowledge within their respective field and renew their licenses regularly in order to maintain the high standard. Since only professional engineers are allowed to approve engineering plans for public and private clients, these individuals carry greater authority and responsibility than unlicensed engineers. As a result, professional licensure is a necessary step to advance in a civil or environmental engineering career. Most of our contacts at Stantec are licensed as professional engineers. This has provided our group with insight as to what it means to be a professional engineer in the work force, as well as their real-life responsibilities.

Executive Summary

The Town of Bridgewater is a predominantly residential city located in Massachusetts with a well-developed water supply, storage, and distribution system. The municipality has owned and operated a wastewater treatment plant (WWTP) since the 1960s, which is designed to process 1.44 MGD and serves approximately 30% of the developed parcels in Town (Graham, 2020; Weston & Sampson, 2019). The Town is now looking to upgrade outdated systems and repair various processes that do not currently follow national discharge elimination standards. Stantec, a consulting and design firm, was hired to develop the designs for this renovation. Currently, sludge from the WWTP is mixed in a below-grade sludge storage tank and dewatered in a two-belt system, then composted and aerated to be used for land fertilization. Stantec's Preliminary Design Report (PDR) proposed to remove the on-site composting area and transition to trucking sludge off-site for treatment (Graham, 2020). As an alternative option of sludge processing, our team researched implementing an anaerobic digestion (AD) system to minimize the final amount of sludge and partially power the facility.

In the United States there are over 16,000 municipal WWTPs, about 20% of which use AD systems for sludge disposal (Eaton & Jutras, 2005). AD is a process through which naturally occurring microorganisms break down organic matter such as sludge in the absence of oxygen. AD results in the production of biogas that can be used for heating and electricity as well as a reduction of overall sludge volume (EPA, n.d.a.). The goal of this project was to assess the technical feasibility and practicality of implementing an AD system at the Bridgewater WWTP.

Our first objective was to design the physical AD reactor and structure. Utilizing a decision matrix based on determining factors of efficiency, maintenance, size, shape, solid composition, and temperature, our project focused on a basic complete mix system reactor. For designing the actual structure, the volume needed to be processed by the reactor was 162,900 gallons, calculated using the average daily flow rate of sludge from the current holding tank. Using site constraints, we estimated that the dimensions of the cylindrical reactor would be 26 ft in height and 36 ft in diameter. We determined that the best location for the AD reactor would be in the current administration building. We proposed that a new, two-floor administration building be built surrounding the AD reactor. If the reactor is included within the dimensions, the total square area of this building would need to be 56 feet by 67 feet. The basement of the building will contain pumps and a boiler. The first level of the building will contain a laboratory space, a bathroom, a SCADA control room, and an office space.

Our second objective was to calculate the quantity of byproducts from the AD reactor. Based on our calculations of methane produced at different BOD removal rates and sludge flow rates per day, our team estimated the amount of biogas produced to be between 155.48 and 233.22 ft^3/day. Currently the plant produces 350 tons of disposed sludge per year. With the addition of AD,

approximately 235 tons of sludge would be produced per year, which is approximately a 30% reduction of annual sludge production.

Our third objective was to assess the energy inputs and outputs of the system. The calculated value for heat energy required throughout the year is on average 725.52 kWh/day. A decision matrix was utilized to compare options for biogas usage, which resulted in the decision to use energy in a biogas boiler. A boiler will be necessary to heat the system, regardless of whether biogas is reused, and a boiler can be fueled with both biogas and natural gas. Based on the estimated amount of methane produced, it was determined that the biogas in a boiler could produce 9,000 kWh per year of thermal energy.

Our fourth objective was to perform an economic analysis for implementing an AD at the Bridgewater WWTP. Based on installation costs of the building, reactor components, contractor, and engineering fees, the estimated base installation costs for the AD reactor and adjoining building were $2,235,500. The annual cost of sludge transportation and disposal would be between $94,600 and $232,400 with AD, a decrease of $40,800 to $100,300 annually from landfilling alone. Even with the additional fees for maintenance and installation, the mean 20-year cost of implementing the AD would be approximately $1.5 million less than the cost of landfilling alone.

An additional cost our team considered was the environmental benefits of AD. According to a cost-benefit report by Stantec, the company has recommended that Bridgewater WWTP discontinue on-site composting and instead dispose of sludge in a landfill. Landfills and incinerators present serious environmental and health concerns. The current composting system, however, is labor intensive and expensive to upgrade. AD offers hope to the waste disposal community by converting waste into renewable energy and reducing the amount of overall waste (EPA, 2021).

Major limitations that impacted the results of this project include the limited timeframe and the collection of information. For example, we had difficulties receiving quotes from vendors and modeling software data. To mitigate some of these limitations, our recommendations are that if AD were to be considered practical, a pilot study should be performed in a lab. This study would help determine specific chemical components of byproducts.

After completing our analysis of an alternative option for sludge disposal at the Bridgewater WWTP, we have determined that while it is feasible to install an AD system at this location, the initial cost may be impractical for the plant. This is a substantial amount of money to add to a $30 million project and may not be possible with Bridgewater's WWTP project budget. While our proposal did not prove to be as practical as we had intended, we are grateful for the educational opportunities that this project provided us.

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(Eq. 1) $d(V_{liq} + V_{gas}) = 0 = q_{in} – (q_{out} + q_{gas}) +/- \sum biochemical\ reaction$

(Eq. 2) $V = Q \cdot \theta$

(Eq. 3) $D = 1.5H$

(Eq. 4) $V = \pi(\frac{1.5H}{2})^2 H$

(Eq. 5) $CH4 = 5.62[(So - Se)(Q)(8.34) - 1.42(Px)]$

(Eq. 6) $P_x = \frac{Y[(So-Se)(Q)(8.34)]}{1+(Kd)(\theta)}$

(Eq. 7) $Q = mC_p\Delta T$

Key Terms and Abbreviations

ABET	Accreditation Board for Engineering and Technology
AD	anaerobic digestion/digester
ADM1	Anaerobic Digestion Model 1
ASBR	anaerobic sequencing batch digester
BOD	biochemical oxygen demand
BSU	Bridgewater State University
CHP	combined heating and power
CMR	Code of Massachusetts Regulations
COD	chemical oxygen demand
CSTR	continuously stirred tank reactor
CWMP	comprehensive wastewater management plan
EGSB	expanded granular sludge bed
EPA	Environmental Protection Agency
FE	Fundamentals of Engineering Exam
GLSD	Greater Lawrence Sanitary District
GIS	Geographic Information System
GPD	gallons per day
HRT	hydraulic retention time
IWA	International Water Association
MGD	million gallons per day
MWRA	Massachusetts Water Resources Authority
MQP	Major Qualifying Project

NPDES	National Pollutant Discharge Elimination System
O&M	Operation and maintenance
PDR	Preliminary Design Report
PE	Principles and Practice of Engineering Exam
SCADA	supervisory control and data acquisition
SRFCW	State Revolving Fund Clean Water
SRT	solids retention time
UASB	upflow anaerobic sludge blanket
VEEBDO	Value Engineering Evaluation of Biosolids Disposal Operations
VFA	volatile fatty acids
VS	volatile solids
WPI	Worcester Polytechnic Institute
WWTP	wastewater treatment plant

1.0 Introduction

The Town of Bridgewater, Massachusetts has owned and operated a municipal wastewater treatment plant (WWTP) since the 1960s (Graham, 2020). This system has had several upgrades, most recently in 1987, but the Town is now looking to build new systems and repair various processes within the facility. These new upgrades are essential for the longevity and wellbeing of the facility and the community it serves. Stantec, a consulting and design firm with an office in Burlington, Massachusetts, was hired to develop the designs for this renovation. Part of the renovation includes the removal of the compost building on site which served to repurpose the sludge produced by the facility to be used in land applications. Our team researched and explored an alternative option for the compost building which involved creating an anaerobic digestion (AD) system to reuse the sludge, minimize the final amount of sludge, and partially power the facility. Our team worked with employees from Stantec and professors from the Civil, Environmental, and Architectural Engineering Department at Worcester Polytechnic Institute (WPI) to produce a design for this AD system.

Our goal for this project was to assess the technical feasibility and practicality of implementing an AD system in the Bridgewater municipal WWTP. To reach this goal, we defined and achieved the following four objectives.

1. Design the physical AD reactor and structure.
2. Calculate the quantity of byproducts from the AD reactor.
3. Assess the energy inputs and outputs of the system.
4. Perform an economic analysis for implementing an AD at the Bridgewater WWTP.

Once these objectives were reached, we determined that building an AD system at the Bridgewater WWTP is technically feasible but may not be economically practical.

2.0 Background

To achieve the goal and objectives set forth for this project, our team has researched aspects of anaerobic digestion (AD) to inform ourselves and the readers of the setting and any technical information about this project that may not be common knowledge. In this chapter, our team has set the context of this project in Bridgewater as well as describing what AD is, how it works, and what the benefits may be.

2.1 Stantec

Stantec is an international design firm with over 22,000 employees and 400 locations around the world. In Massachusetts alone, there are six different offices which provide their own variety of services, including but not limited to community development, landscape architecture, and geotechnical engineering (Stantec, n.d.). For this project, our team worked with a team from the Stantec Burlington, MA office.

2.2 The Town of Bridgewater

Geography

The Town of Bridgewater is located in Plymouth County, Massachusetts, in the Brockton metropolitan area, approximately 27 miles south of Boston. The Town is located at the intersection of Interstate 495 and Mass. Route 24, two major roads in the region. Figure 1 presents a map of the Town with location of the WWTP. There are multiple water bodies in the area, most notably the Town River as well as several lakes and ponds, and multiple wetland areas. There is also a state forest, town forest, and several conservation areas such as the Hockomock Swamp Wildlife Management Area. The wastewater treatment plant (WWTP) is located near a wetland area and treated wastewater is discharged into the Town River. (The Town of Bridgewater, 2021)

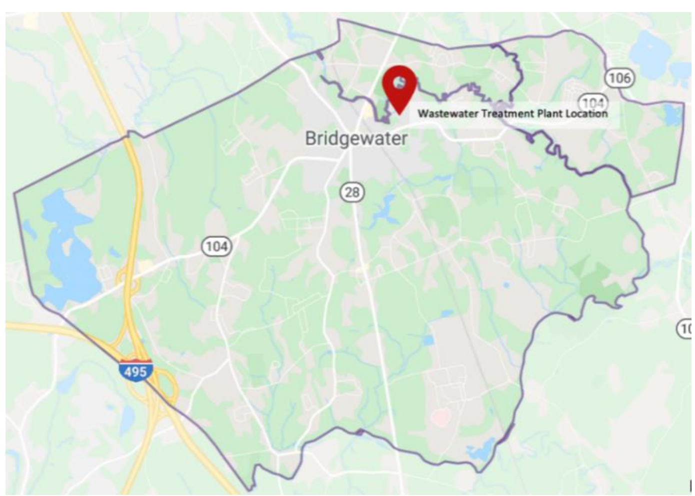

Figure 1. Map of Bridgewater, MA (Google Maps, 2021)

Government

The Town of Bridgewater is one of fourteen Massachusetts municipalities that have applied for and received a city form of government but have voted to retain "The Town of" in all official titles. Due to this, Bridgewater has a ‘city’ form of government, led by nine City Councilors: seven Precinct Councilors, two "at-large councilors," as well as an appointed Town Manager, Assessor, and Tax Collector. Due to this system of government, it is required that the Town Council must vote ⅔ of full council on all planning and financial decisions made about the WWTP. These votes are based on the opinions and ideas of the residents in the seven precincts, as well as the budget decided by the Town Manager and Assessor. (The Town of Bridgewater, 2021)

Demographics and Land Use

The land use in Bridgewater is predominantly developed residential. To support the growing population of homeowners in the area, residential use is continuously growing. This has halted commercial and industrial development in comparison to other nearby municipalities. The fastest growing population is college-age students, in connection with the nearby Bridgewater State University (BSU). BSU is a major public university enrolling nearly 11,000 students and contributes to the largest amount of sewer inflow in comparison to other nearby institutions such as the Bridgewater Correctional Complex or the Bridgewater State Hospital (United States Census, 2020).

2.3 Bridgewater WWTP Project

In December 2019, the Town of Bridgewater allocated money and resources to a Comprehensive Wastewater Management Plan (CWMP) performed by a private engineering consulting company, Weston & Sampson. This report analyzed how to improve the wastewater, drinking water, and stormwater treatment processes in Town (Weston & Sampson, 2019).

The Town has a well-developed water supply, storage, and distribution system. There is a centralized sewer system, which provides wastewater collection, treatment, and disposal for approximately 30% of the developed parcels in Town (Weston & Sampson, 2019). Of these developed parcels, nearly all receive municipal water service from the Bridgewater Water Department. Stormwater is managed with localized drainage collection systems that recharge the groundwater or flow to existing surface water via an outfall to the Town River. The CWMP report has determined that, in order to improve the Town’s water system, it is most important to focus mainly on wastewater issues with less emphasis on drinking water and stormwater issues (Weston & Sampson, 2019).

The main goal for the CWMP was to find the best solutions to Bridgewater’s wastewater management challenges. This included the following objectives:

1. Add extensions to the existing municipal sewer system.
2. Improve nutrient removal to comply with the Town's National Pollutant Discharge Elimination System (NPDES) permit.
3. Continued on-site system use and management
4. Re-rate plant for a nominal increase in flow with a commensurate increase in permitted flow.
5. Regulate future sewer extensions and connections to serve the identified needs areas and to allocate the remaining limited system capacity to a targeted development.
6. As the Town's major sewer user, BSU plans and sewer capacity needs should be agreed upon together with financial commitments for system capital improvements
7. Continue ongoing efforts to remove extraneous wastewater treatment plant flows through its Infiltration/Inflow identification and reduction program. (Stantec, 2021)

The Bridgewater WWTP is designed to treat 1.44 MGD of municipal wastewater and 20,000 GPD of sewage from Bridgewater residents (Graham, 2020). The treatment process removes nutrients and bacteria from the raw wastewater in accordance with the Town's NPDES permit. When raw wastewater initially enters the plant, it flows through a headworks system consisting of a comminutor and aerated grit removal system. These steps cut up larger material in the influent to less than 5/16-inch pieces and remove large debris to avoid damaging equipment along the treatment train. The influent is then combined with secondary sludge and ferric chloride (for phosphorus removal) before entering one of two primary clarifiers. Here settleable solids are removed from the base of the tanks, and scum is scraped off the surface of the water. Effluent from the primary clarifiers moves through four stages of biological treatment consisting of 14 rotating biological contactors (RBC) to remove biological oxygen demand (BOD) and to nitrify ammonia. Then, the water moves through one of two secondary clarifiers to settle out biological solids. This effluent then enters a chlorine contact tank for disinfection and is treated with sulfur dioxide for dechlorination prior to discharge to the Taunton River. Figure 2 shows the current flow of the WWTP. (Graham, 2020)

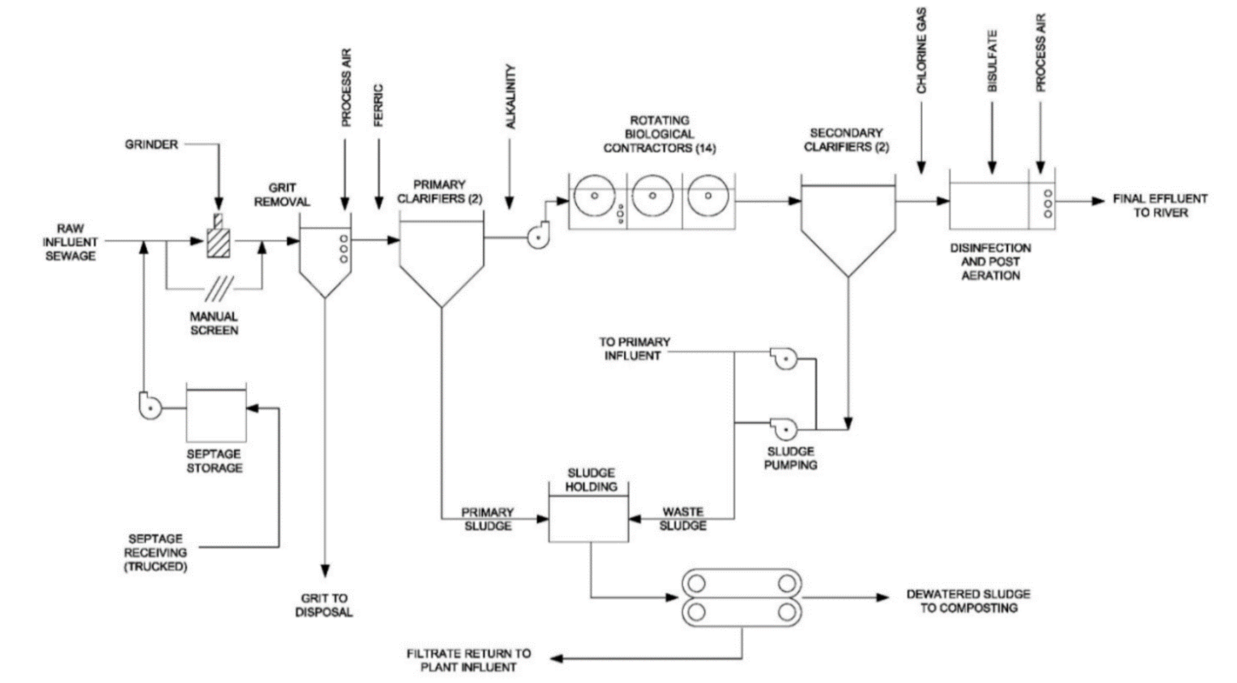

Figure 2. Current flow diagram of the Bridgewater WWTP (Graham, 2020)

Sludge from these processes is mixed in a below-grade sludge storage tank and dewatered in a two-belt system. Any residual water removed from this process is returned to the start of the treatment train for treatment, and the dewatered sludge is moved to an onsite composting area. The sludge is aerated and then reused for land fertilization. In Stantec's Preliminary Design Report (PDR), it is proposed to remove the on-site composting area and transition to trucking sludge off-site for treatment. (Graham, 2020)

2.4 Anaerobic Digestion Overview

AD is a process through which bacteria break down organic matter in the absence of oxygen. The organic matter used in AD can vary from animal manure to food waste to waste from restaurant grease traps (EPA, n.d.a.). In the case of the Bridgewater WWTP, wastewater sludge will be used as the input. Sludge is a byproduct of wastewater treatment and is typically reused for agricultural or other purposes, disposed of in a landfill, or incinerated. AD is an alternative option for sludge disposal that results in the production of biogas that can be used for heating and electricity and a reduction of overall sludge volume (EPA, n.d.a.). Figure 3 gives an overview of the AD process.

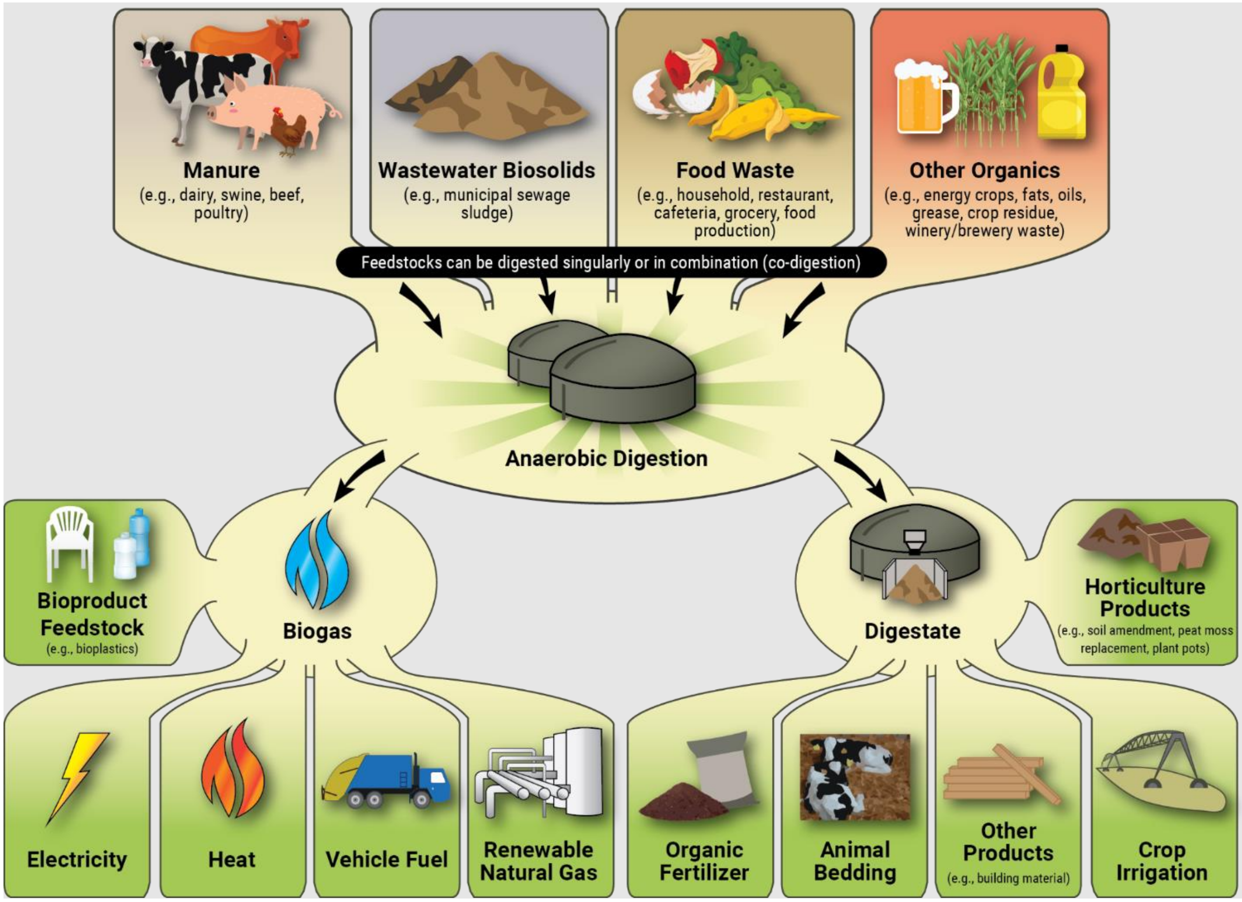

Figure 3. Overview of AD Process (EPA, 2021)

The process of AD has both chemical and biological components. The overall chemical process involves glucose in the influent sludge being broken down into carbon dioxide and methane; this is shown in the equation below.

$$C_6H_{12}O_6 \rightarrow 3CO_2 + 3CH_4$$ (Metcalf & Eddy, 1991)

This breakdown occurs through biological processes of microorganisms. These microorganisms, naturally present in the influent organic material, break down biodegradable material into biogas in the absence of oxygen. This occurs in four different steps: hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Stronach, 2012). Figure 4 shows the inputs and outputs of each step, which are explained further below.

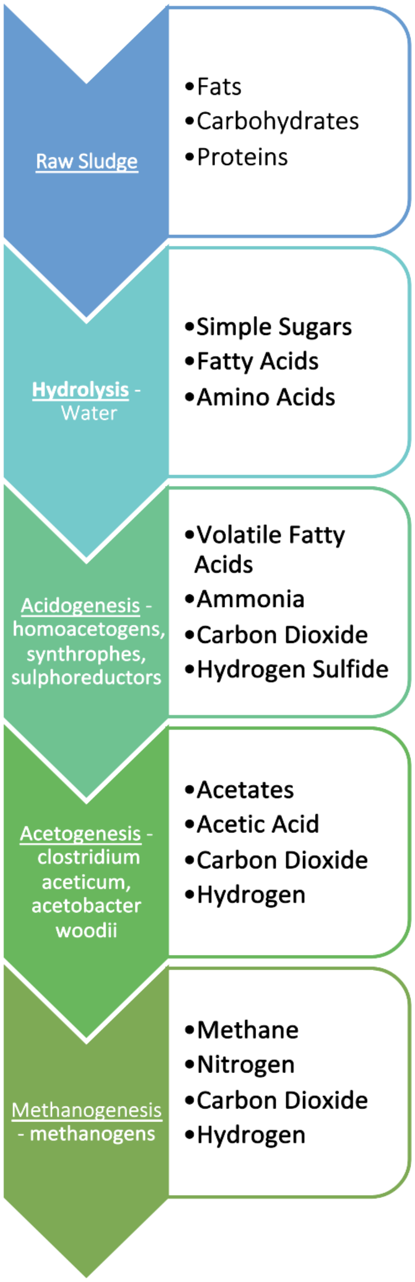

Figure 4. Biological AD Process (Narihiro, 2007; Stronach, 2012)

The first step, hydrolysis, is a chemical reaction in which water molecules are used to break the bonds of larger polymers. Sludge is typically composed of large organic polymers that are too complicated for bacteria to digest. The hydrolysis process breaks down these polymers into smaller constituent parts called monomers. Hydrolysis is sometimes performed in a separate reactor before the rest of the AD process (Tchobanoglous, 2014).

Once the biomass is in small enough parts to be broken down by microorganisms, the sludge is introduced to a chamber with fermentative bacteria. This begins the process of acidogenesis. Once acidogenesis is completed, acetogenesis occurs to convert VFAs into even simpler molecules. Finally, methanogenesis occurs which requires the most sensitive of the microorganisms involved in AD, methanogens. Methanogens require a pH between 6.5 and 8 and temperatures above 37 degrees Celsius or 98 degrees Fahrenheit (Narihiro, 2007). These microorganisms cannot be exposed to oxygen and have a slow regeneration time of 5 to 16 days (Narihiro, 2007).

2.4.1 Products of AD

The final byproducts of the AD process are biogas, digestate, and water. Biogas is the most desired product and contains a mix of mostly methane and carbon dioxide, as well as nitrogen, hydrogen, hydrogen sulfide, and oxygen (Weederman, 2015). Biogas can be used to provide heat and electrical energy, as discussed further in Section 2.6.

Any indigestible material that microbes cannot use, as well as dead bacterial remains, forms digestate. Digestate may be solid, liquid, or a mix of these phases, depending on the type of reaction chamber used in the AD process. Digestate may contain cellulose, minerals, heavy metals, and materials such as microplastics and silicones that could not be processed by either the wastewater treatment train or AD. Once an assessment of the materials present in the digestate is performed, there are many options for disposing of the waste (Lettinga, 1995). If the digestate is high in toxic elements such as industrial contaminants and complex chemicals, the digestate should be disposed of depending on the specific contaminants. If it is determined that there are not elevated levels of toxic material, oftentimes digestate is added into compost or dried into fertilizer pellets to be used as nutrients for plant growth (Tchobanoglous, 2014).

The final byproduct, water, originates from the moisture content of the original influent material, as well as water produced by microbes in the digestion reaction chambers (Lettinga, 1995). The volume of water vapor produced can be represented as a function of the temperature of the biogas. Depending on the type of chamber used, this water might also be combined with the leftover digestate, which could be dewatered. The wastewater extracted from the digestate typically has elevated levels of biochemical and chemical oxygen demand (BOD and COD, respectively). If released into nearby waterways, this can be harmful as it may cause eutrophication. To prevent this, reverse osmosis treatment is typically used on the leftover wastewater to remove BOD and COD, or wastewater can be pumped back to the original headworks of the WWTP. (Tchobanoglous, 2014).

2.4.2 Anaerobic Digestion Mass Balance

To better understand the flow of material (liquid, solid, and gas) in and out of the AD system, a mass balance was utilized. Figure 5 shows the variables in the mass balance and how they move through the system.

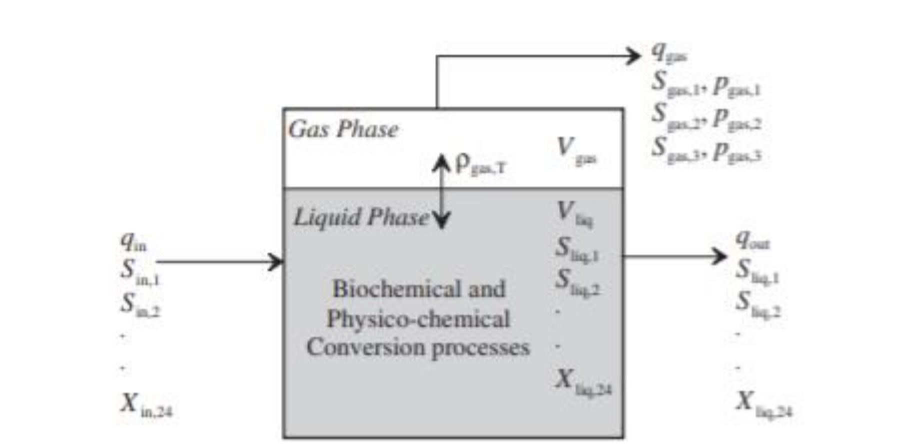

Figure 5. Typical Anaerobic Digester Mass Flow Diagram (Batstone, 2002)

Equation 1 provides the generalized equation for a mass balance of an AD system.

$$\text{(Eq. 1) } d(V_{liq} + V_{gas}) = 0 = q_{in} - (q_{out} + q_{gas}) +/- \sum \textit{biochemical reaction}$$

The mass balance for an AD reactor includes a reaction rate expression because there is a biochemical and physio-chemical reaction which occurs through the process of AD. This reaction changes the state and chemical composition of material within the system, which is important to note because the influent of AD is a solid-liquid slurry, and the effluent contains material in all three phases. Although the composition and state of the material changes during the AD process, the total amount of material going in and out of the system remains constant.

Another key parameter for the mass balance of an AD system is the amount of time the sludge takes to go through the system. In WWTPs, there are two retention times used to determine factors about the system such as size and efficiency: Hydraulic Retention Time (HRT) and Solids Retention Time (SRT). HRT refers to the amount of time it takes for wastewater to pass through a tank. SRT refers to the amount of time that solids or bacteria are maintained in the activated sludge system. In AD, HRT and SRT are nearly the same, with the ratio between them as $SRT/HRT \approx 1$ (Gerardi, 2002). An equivalent SRT and HRT mean that solids and liquids move throughout the reactor at the same rate, and the amount of time it takes for the sludge to move through the AD and the time that the sludge should stay in the tank for peak performance are equal. Equal times allow for simplified calculations when solving for chemical components.

2.5 Reactor Design

In general, anaerobic reactors require less energy to run than aerobic reactors, as the chamber requires no aeration. However, there is oftentimes a long startup and recovery time for anaerobic reactors. Additionally, specific nutrients, such as iron, nickel, and cobalt, are required for microbial growth, and their levels should be monitored for efficiency and optimal growth. Microbes are highly susceptible to their environment, so factors such as pH and temperature must stay within a specific range as well (Lettinga, 1995).

When choosing an anaerobic reactor, there are a wide variety of considerations and options for types of chambers to carry out the four steps of the process (EPA, 2021). There are three efficiency-rate categories that categorize the speed at which sludge is digested in relation to the amount of sludge produced. These AD systems can be passive, low, and high rate. If a system is passive, methane recovery is added to existing sludge treatment infrastructure. If a system is low-rate, sludge is the primary source of methane producing microorganisms. If a system is high-rate, methane forming microorganisms are added into the system to increase methane production efficiency.

An example of a passive system is a covered lagoon design. This design typically has two lagoon cells, as shown in Figure 6. The influent is added into the first cell in which AD occurs and biogas is captured under an impermeable cover. The second cell is used to store digestate and water. Covered lagoons are best used in meat production and other agricultural industry streams (Vandevivere, 2002).

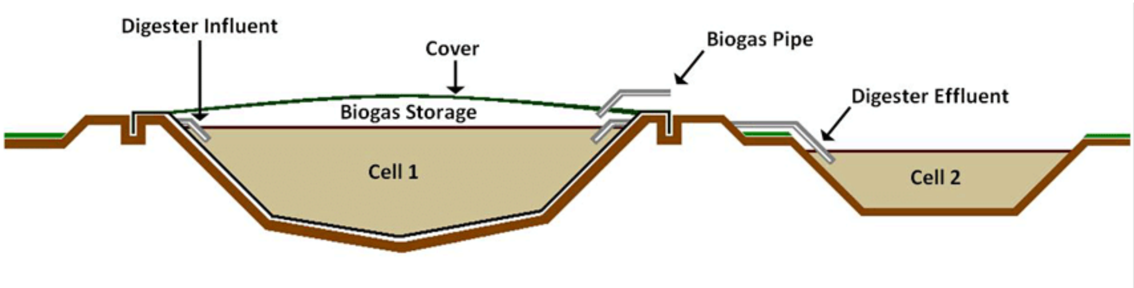

Figure 6. Covered Lagoon (Karim, 2013)

For low-rate systems, one option is a basic complete mix reactor, also known as a continuously stirred tank reactor (CSTR). In this reactor, sludge flows through the digester at a constant rate to displace digester volume, as shown in Figure 7. In the tank, sludge is heated and mixed continuously. Biogas production is maintained by adjusting the volume of inflow, and then using a separate pipe at the top of the tank to recover the biogas. There is also an effluent pipe at the base of the tank for digestate removal. (Vandevivere, 2002)

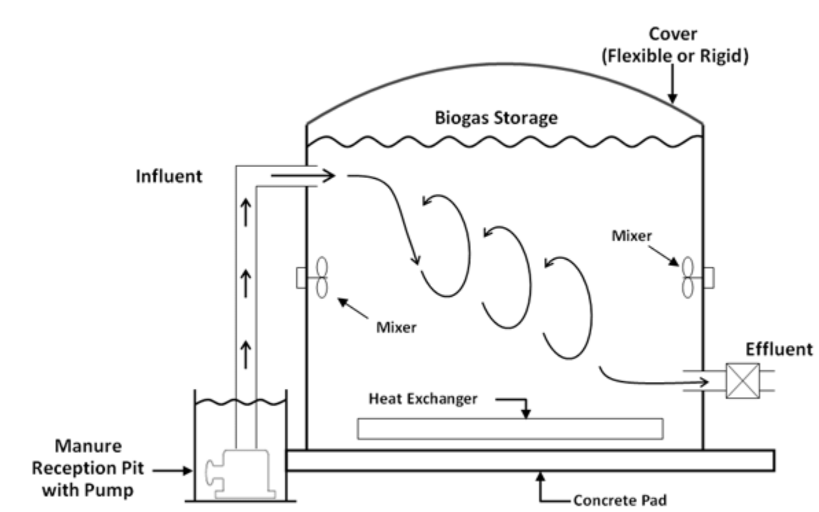

Figure 7. Continuously Stirred Tank Reactor (Bentley, 2012)

Another option for low-rate reactors is a basic plug-flow digester, shown in Figure 8. In this reactor, like in the CSTR, the sludge flowing into the digester displaces digester volume, and an equal amount of material flows out. However, the reactor is not mixed, and the contents move in a plug. Additionally, the tank is inclined in a way so that particles do not settle to the bottom (Vandevivere, 2002).

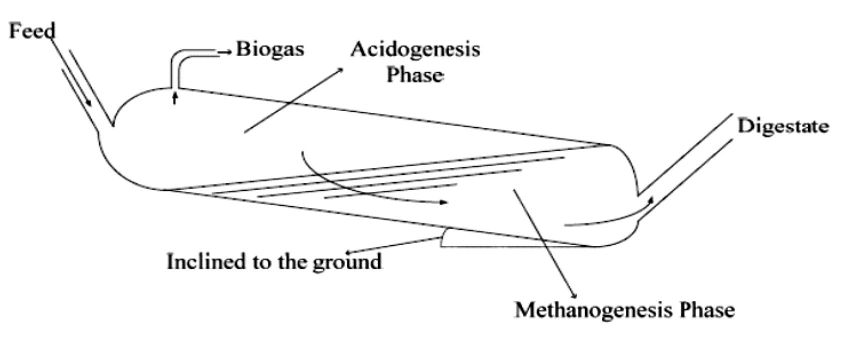

Figure 8. Plug Flow Reactor (Ramasta, 2014)

There are many additions that can be made to tanks for high-rate systems. One option is solids recycling, shown in Figure 9. Recycling can be added to a CSTR to recover the solid portion of the digestate and maintain a higher concentration of microorganisms in the system (Vandevivere, 2002).

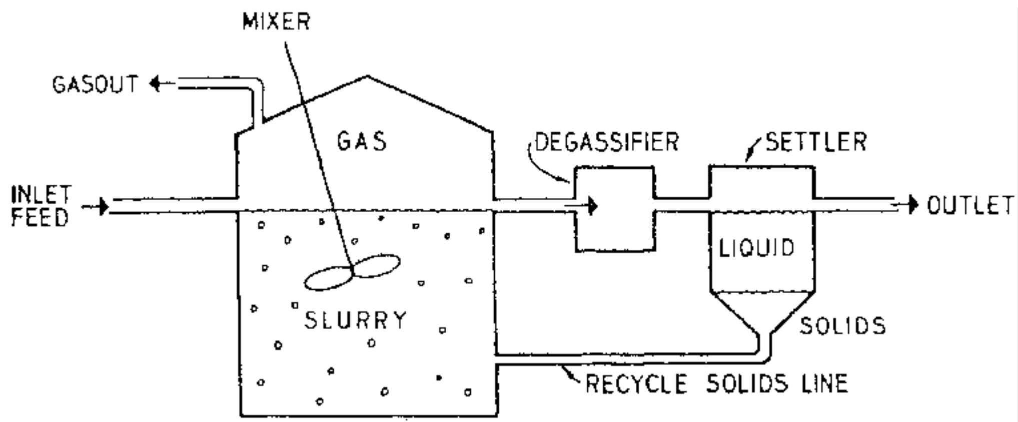

Figure 9. Solids Recycling in a CSTR (Vandevivere, 2002)

Other options for high-rate systems include fixed anaerobic filter reactors, anaerobic sequencing batch reactors, and sludge blanket reactors. Each of these reactors have features which increase the efficiency of a typical CSTR or PFR.

Regardless of what type of reactor is built, the digestate and wastewater in the effluent must have a post-treatment stage. Wastewater from AD must be treated prior to discharge due to high nitrogen protein, and organic content. This can be recycled back into the original WWTP influent, or a smaller treatment tank can be built (Lettinga, 1995).

2.6 Obtaining Energy from AD

One of the byproducts of AD is biogas, which is a renewable energy source consisting primarily of methane and carbon dioxide. There are many options for how to utilize this biogas, which are summarized in Table 1.

Table 1. Options for biogas usage

<table>
<tr><th colspan="2">Method</th><th>Effluent</th><th colspan="2">Advantages</th><th colspan="2">Disadvantages</th><th>Efficiency</th><th>Typical Size</th><th>Installed Cost (USD/kW)</th><th>O & M Cost (USD/kWh)</th></tr>
<tr><td colspan="2">Flare biogas[1]</td><td>CO2</td><td colspan="2">easy to do, reduces emissions of methane</td><td colspan="2">biogas is wasted (no advantageous byproducts)</td><td>N/A</td><td>N/A</td><td>[2]</td><td></td></tr>
<tr><td colspan="2">Biogas Boiler</td><td>Heat</td><td colspan="2">can run on both biogas & natural gas, no pretreatment needed, works with low gas pressures, boiler is already necessary to heat AD[3]</td><td colspan="2">biogas containing H_2S is highly corrosive & can degrade boilers[4]</td><td>75%</td><td>>15kW[5]</td><td>no additional cost to facility</td><td></td></tr>
<tr><td rowspan="5">CHP[6]</td><td>Reciprocating Engine</td><td rowspan="5">Heat & Electricity</td><td rowspan="5">highly efficient, can operate at a minimum of 50% capacity with little change in efficiency</td><td>most common CHP for WWTPs</td><td rowspan="5">impurities in biogas can degrade system mechanics, more suitable for larger plants</td><td>requires removal of water, particulates, sulfur compounds, and NH3</td><td>70-87%</td><td>10kW - 10MW</td><td>800 - 2900</td><td>0.008 - 0.025</td></tr>
<tr><td>Stirling Engine</td><td>low noise, no biogas pretreatment required, high thermal efficiency</td><td>low electrical efficiency</td><td>95%</td><td><200kW</td><td>1,000 - 10,000</td><td>0.01</td></tr>
<tr><td>Gas Turbine</td><td>very common for CHP</td><td>mostly used at large-scale power plants</td><td>65-71%</td><td>500kW - 300 MW</td><td>700 - 2,000</td><td>0.006 - 0.013</td></tr>
<tr><td>Micro-Gas Turbine</td><td>small, high power:weight ratio, short start up time</td><td>requires fuel with short combustion time, efficiency greatly decreases when operated at a partial load</td><td>64-72%</td><td>30 kW - 500 kW</td><td>1,100 - 3,200</td><td>0.008 - 0.02</td></tr>
<tr><td>Fuel Cell</td><td>high efficiency even in small systems, low emissions</td><td>expensive, not common in small WWTPs</td><td>62-75%</td><td>5 kW - 3 MW</td><td>3,000 - 10,000</td><td>0.01 - 0.045</td></tr>
<tr><td colspan="2">Sell biogas to national or local grid</td><td>Money</td><td colspan="2">potentially profitable opportunity for facility</td><td colspan="2">requires pretreatment of biogas to meet standards for renewable natural gas[7]</td><td>N/A</td><td>N/A</td><td>1,000 (for cleaning technology)[8]</td><td>profit of 0.22 - 0.39 USD/m^3 biogas sold[9]</td></tr>
</table>

[1] (BiogasWorld, 2021)
[2] Information in grey cells not available
[3] (Viswanathan, 2018; Beddoes, 2007)
[4] (Beddoes, 2007)
[5] (Krich et al, 2005)
[6] (Riley et al, 2020)
[7] (Tanigawa, 2017)
[8] (Wasajja et al, 2020)
[9] (Irena, 2017)

The first option is to flare the biogas to waste. This is often done by small WWTPs using batch reactors for AD because it is a low cost and easy way of preventing the release of methane into the atmosphere. Methane is a very powerful greenhouse gas in terms of its impact on the atmosphere. Burning methane yields carbon dioxide, which is also a greenhouse gas but has a much less severe impact on the climate. (BiogasWorld, 2021)

The next option is to use biogas to fuel a boiler to provide hot water for heating the building and system processes. This is very common in agricultural applications of AD, due to the need for heat and hot water on farms. Boilers are a highly efficient way of converting fuel to heat; however, it is important to note that the corrosive nature of biogas can cause degradation of system mechanics. Most biogases contain some level of H_2S, which, when burned, is converted to sulfur oxides (most commonly sulfur dioxide and sulfur trioxide). When effluent gases containing sulfur oxides cool to dew point, the water vapor in the gas combines with the sulfur oxides to form highly corrosive sulfuric acid. The sulfuric acid formed is the direct cause of degradation to boiler operations. To prevent this degradation and minimize operation costs associated with corrosion, boilers fueled by H_2S containing biogas should be run continuously at a temperature above dew point. Alternatively, biogas can be cleaned upstream of the boiler to remove H_2S. (Beddoes, 2007)

As another reuse method, biogas can be converted into electricity and heat using a combined heat and power (CHP) system. CHP works to capture and utilize heat energy, in the form of steam or hot water, that is typically lost in electricity generation systems, thus increasing the system's overall efficiency (Riley et al, 2020; EPA, n.d.b.). CHP systems can also typically operate down to half of their installed capacity without drastic decreases in efficiency, making them beneficial for facilities that may be producing an inconsistent amount of biogas (Riley et al, 2020). There are multiple prime movers that can be used in CHP such as engines, fuel cells, and microturbines. The prime mover chosen for a given facility depends on the facility's size, as well as the composition and heating potential of the biogas. Some prime movers also require pretreatment of the biogas to remove impurities, such as siloxanes, H_2S, and water vapor, that can cause mechanical degradation (Riley et al, 2020).

Another option for use of biogas produced by AD is to sell biogas to the national or local natural gas grid. Before being sold to the grid, biogas must be refined to meet industry standards (Tanigawa, 2017). This involves removal of carbon dioxide, water, and other trace gases to result in pure methane biogas, also known as renewable natural gas. If sold to the grid, a plant could earn between 0.22 and 0.39 USD per m^3 of biogas (Irena, 2017).

2.7 Biosolid Disposal

For any biosolid sludge waste emitted into the environment, a WWTP must follow regulations provided by the EPA. Because biosolids are an essential resource and should be safely used, The EPA created the Part 503 rule. This rule establishes specific requirements for the final use or disposal of sewage sludge when biosolids are applied to land to condition the soil or fertilize crops or other vegetation grown in the soil, placed on a surface disposal site for final disposal, or fired in a biosolids incinerator (EPA, 1994). Biosolids are defined as a primarily organic solid product produced by wastewater treatment processes that can be beneficially recycled. The Part 503 rule includes five subparts: general provisions, requirements for land application, surface disposal, pathogen and vector attraction reduction, and incineration (EPA, 1994). This rule applies to any plant that uses biosolids as fertilizer or incinerates this waste. Our group will be working heavily with biosolids, a byproduct of AD. Therefore, this rule is relevant to our area of work.

In addition to EPA regulations and because residuals can be re-sold for a profit, Massachusetts also has a residuals management program that regulates the beneficial reuse of biosolids. This program categorizes biosolids into 3 types: Type I, Type II and Type III. Type I biosolids meet very high quality and may be used as commercial fertilizers. Type II biosolids require additional MassDEP permitting to be applied to land. Type III biosolids typically have more chemicals and metals than Type II. Use of Type III biosolids is restricted and any application must be recorded on the deed to the parcel of land in which it is applied (MassDEP).

2.8 WWTP AD Case Studies

As discussed, there is a substantial amount of biosolids produced and a high energy demand from the wastewater treatment process. This combination of excess waste and high energy demand deems AD as an effective process for capturing energy from these biosolids for reuse throughout WWTPs. In the United States there are over 16,000 municipal WWTPs, about 20% of which use AD systems (Eaton & Jutras, 2005). Oftentimes, facilities that implement AD use any excess biogas energy to provide heat to the AD process. However, few WWTPs go the extra step of converting the biogas waste into electricity to power the facility or sell to the municipal power grid (Eaton & Jutras, 2005). Two New England facilities that have successfully implemented AD systems and use the biogas produced for electricity are the Essex Junction WWTP in Essex Junction, VT and the Greater Lawrence Sanitary District (GLSD) in North Andover, MA.

2.8.1 Essex Junction WWTP

Essex Junction, VT has a small WWTP with a design flow rate of 3.3 MGD and an average flow of 2 MGD (Eaton & Jutras, 2005). Following AD, this facility uses a CHP system consisting of two 30 kW microturbines. These turbines use the methane gas produced from AD to make electricity while also releasing thermal energy which heats the AD process. Microturbines produce fewer emissions than the alternative options of an engine or fuel cell and were chosen to ensure the WWTP was as sustainable as possible (Eaton & Jutras, 2005).

AD and CHP systems are not commonly seen at small WWTPs due to the extensive upfront cost of implementation. Essex Junction was aware of this but had been considering AD and CHP as an option for many years due to the environmental benefits of the system and the potential for long-term savings. In their planning, Essex Junction designated a 7-year pay-back time for the upfront costs, which the Town was able to obtain from Efficiency Vermont and other organizational funding available to the state. Additionally, the WWTP received funding from the Department of Energy Region 1, who hoped to inspire other WWTPs that could potentially develop similar systems. (Eaton & Jutras, 2005)

In developing the AD and CHP system at Essex Junction, there were few WWTP with similar systems for the proposed design to reference. In fact, this system was the first of its kind in New England. For more information about such processes, Essex Junction reached out to the WWTP in Lewiston, NY which had previously developed a similar AD system. Treatment plant operators found that the most difficult challenge in the AD and CHP process was the presence of siloxanes in the methane produced from AD. Siloxanes are compounds commonly found in shampoos that have the potential to turn to glass at high temperatures, which reduces the efficiency of heat exchangers and can cause failures in the system. Because of this challenge faced in Lewiston, Essex Junction determined it would be necessary to install a siloxane removal system upstream of the CHP to ensure that the methane was free of siloxanes. This further increased the implementation costs but led to a more efficient system. (Eaton & Jutras, 2005)

In the end, the system reduced the electricity demand of the WWTP and provides long-term cost savings to the Town. The system was found to be reliable 90% of the time with the most difficult issues stemming from the presence of moisture in the methane entering the microturbines. For other municipalities considering installing an AD and CHP system, Essex Junction recommends carefully analyzing the chemical composition of the methane gas produced from AD to determine steps that may be necessary prior to CHP, such as removal of moisture and siloxanes. Despite this challenge, the system has been effective overall and has saved the facility up to 40% on power costs each year since its installation. (Eaton & Jutras, 2005)

2.8.2 Greater Lawrence Sanitary District

Another example of a successful AD system is at the Greater Lawrence Sanitary District (GLSD). This WWTP in North Andover, MA processes sewage from approximately 168,000 piped sewer residents in 5 municipalities, while also accepting and treating sludge from over 30 other communities within and surrounding the Merrimack Valley. The plant processes a flow of 52 MGD and has the capacity to accept 100,000 GPD of trucked sludge. (*Rules & regulations*, n.d.)

GLSD has three AD reactors which are used to treat sludge and produce methane to support facility processing. Each digester has the capacity to hold 1.4 million gallons of sludge (about twice the size of an Olympic-size swimming pool) and 48,500 cubic feet of methane gas. The methane produced by the digesters is used to heat the boilers and heat exchangers needed for AD and is combined with natural gas to heat the buildings at GLSD.

In January 2020, GLSD improved their AD system by adding a fourth digester, incorporating food waste digestion, and implementing a CHP system. The addition of food waste into the AD process resulted in triple the production of biogas and the new CHP system can produce enough power to support all of the facility's power needs. (Cousens et al, 2020)

2.8.3 Anaerobic Digestion Around the World

In our research, we found that AD is not common at small WWTPs in the United States, however many other countries utilize AD to produce biogas at a wide range of size scales. The United States is the leading biogas producer in the world, but only contains 20% of all AD plants (Nikolausz, 2020). Comparatively, China is the third largest biogas producer in the world, but contains 40% of all AD plants (Nikolausz, 2020). This difference is primarily due to the number of small-scale AD plants in rural, developing parts of China, as well as the presence of AD plants in many Chinese WWTPs (Akhiar, 2020).

The use of domestic AD plants in many countries throughout Asia and Africa shows the range in size that AD plants can have. In 2004, there were nearly 15 million households in China producing and using biogas for fuel (Nes, 2006). Whereas, in 2017, the United States had only 2,200 total AD plants (Simet, 2017). This data indicates that the United States is primarily investing in AD plants that are on a large scale, but there is potential to invest in medium, small, and domestic AD plants that could increase the use of renewable energy throughout the country. All in all, AD technology is extremely diverse and can be as simple or complex as a system requires, particularly at WWTPs. AD is also a very accessible technology and could reduce the amount of fossil fuels being used throughout the world tremendously.

3.0 Methodology

The goal of this project was to assess the technical feasibility and practicality of implementing an anaerobic digestion (AD) system in the Bridgewater Wastewater Treatment Plant (WWTP). We defined a set of four objectives to guide our project and accomplish our goal.

Objective 1: Design the physical AD reactor and structure.

Objective 2: Calculate the quantity of byproducts from the AD reactor.

Objective 3: Assess the energy inputs and outputs of the system.

Objective 4: Perform an economic analysis for implementing an AD at the Bridgewater WWTP.

For each objective we followed a set of tasks that we completed to reach the objective. These tasks are detailed in the following subsections.

3.1 Objective 1: Design the Reactor

For our first objective we designed the physical AD reactor in terms of size, shape, and site constraints. We also designed a building to house the AD reactor and other administrative needs of the facility.

3.1.1 Determine Reactor Type

Initially, we analyzed options for reactor types based on the needs of the facility. This was done using a comparison chart detailing specifications of different reactor designs. We assessed how well specifications for a given reactor aligned with the sludge characteristics and needs of the facility. Those specifications that did were highlighted in green, and those that were not aligned were highlighted in red. This process allowed us to determine which reactor would be most beneficial for the Bridgewater WWTP.

3.1.2 Determine Reactor Size

Equation 1 was used to represent the variables entering and leaving the AD. Using a mass balance to better understand the AD process was useful to our team because we were able to delineate which variables we had data on and which variables we needed to find.

$$\text{(Eq. 1)}\ d(V_{liq} + V_{gas}) = 0 = q_{in} - (q_{out} + q_{gas}) +/- \sum \textit{biochemical reaction}$$

For the purposes of this system, the change in volume was set to 0 because the system is at steady state, which means there is theoretically no significant change in volume. The variables our team wanted to assess included q_{gas}, $S_{gas,x}$, q_{out}, and $S_{liq,x}$. Based on information that was provided to our team from Stantec and the Bridgewater WWTP, we had data for q_{in} and S_{in} for the liquid/solid stream. Our team was not able to use the mass balance equation to directly find the effluent streams because we could not adequately determine the reaction rate coefficient. The reaction rate coefficient is heavily dependent on various properties of the sludge, which we did not have access to. To find the effluent streams and concentrations, we used a variety of other equations and industry standards.

Since our team had the flow rate into the AD and decided to focus on a complete mix AD reactor (see Table 3), we used equations from the 1991 edition of the Metcalf & Eddy textbook *Wastewater Engineering* to determine the size and dimensions of the reactor. Equation 2 was used to approximate the volume of the tank.

(Eq. 2) $\boldsymbol{V = Q \cdot \theta}$

Where:

V = Volume of the tank in gallons

Q = Average sludge flow rate in gallons/day

θ = Average retention rate in days

Once the volume was calculated, the dimensions were defined using the standard ratio of diameter (D) to tank height (H), assuming the tank is a cylinder, given in Equations 3 and 4.

(Eq. 3) $D = 1.5H$

(Eq. 4) $V = \pi(\frac{1.5H}{2})^2 H$

3.1.3 Site Layout and Building Requirements

To determine where our AD reactor would be installed on the Bridgewater WWTP site, our group met with our Stantec contact, Justin Motta. In this meeting, we discussed advice regarding the best possible location for our AD reactor building, given his knowledge of the site, as well as the necessary requirements for the interior. We also discussed the dimensional constraints of the site once we determined which location would be ideal for the structure.

3.1.4 Building Design

After determining a location for the on-site AD facility, Revit was used to develop a preliminary structural design of the facility. Our group had previous experience with the 3D-modeling software Revit, and therefore we used this to create the basic structure of the reactor building. Revit was the ideal software to use in order to model the structure and layout of the AD building. The dimensional constraints of the surrounding area as well as the process of AD and the design of the preexisting administrative building were all considered. The design documents of the new administration building were used to determine the dimensions of the structure within the Revit model. The requirements for the building included a lab space, Supervisory Control and Data Acquisition (SCADA) room, office space, bathroom, and basement pump room with a boiler. The AD reactor tank also needed to be directly connected to the building. In addition, the building design satisfied the requirements set forth in the Code of Massachusetts Regulations (CMR) Section 780 (Mass.gov, 2021).

3.2 Objective 2: Calculate the Byproducts

For our next objective, we calculated the amounts of methane and digestate produced during the AD process. We also used a modeling software to outline the chemical processes and back up our calculations.

3.2.1 Calculate Methane Output

One of the key components of this system was the use of biogas as a renewable energy source, so determining the range of methane production from the proposed AD reactor was important for modeling this system. Equation 12-7 from *Wastewater Engineering* (Metcalf and Eddy, 1991) was used to approximate methane production. This is shown in Equation 5 below.

(Eq. 5) $CH4 = 5.62[(So - Se)(Q)(8.34) - 1.42(Px)]$

Where:

CH4 = Volume of methane produced at standard conditions (32 F and 1 atm) in ft^3/day

S_o = BOD influent concentration in mg/L

S_e = BOD effluent concentration mg/L

Q = Average sludge flow rate in MGD

The value 5.62 is the theoretical value for the conversion of the amount of methane and carbon dioxide in cubic feet of methane per pound of BOD oxidized. The value 8.34 is the conversion factor for BOD in pounds per million gallons of water.

Additionally, P_x is the net mass of cell tissue per day in pounds which can be calculated using Equation 12-8 in Metcalf and Eddy 1991, Equation 6 below.

(Eq. 6) $P_x = \frac{Y[(So - Se)(Q)(8.34)]}{1+(Kd)(\theta)}$

Where:

Y = Yield coefficient in lb cells produced/lb substrate removed

Kd = Endogenous coefficient in 1/day

Note: Both values for Y and Kd were estimated using Table 8-9 in Metcalf and Eddy 1991.

The values used in these calculations were obtained from the Bridgewater WWTP (Bridgewater WWTP, 2020).

3.2.2 Calculate Digestate Output

The solids output of the AD reactor, the digestate, was an important value to calculate to determine the reduction of material that would need to be landfilled. In the sludge entering the reactor, there are both volatile and fixed solids. The volatile solids (VS) are those that are partially converted to biogas through the chemical reactions of AD. The fixed solids travel through the reactor unchanged. To determine the volume of digestate exiting the reactor, the amount of influent fixed solids is added to the reduced amount of VS. In a typical AD reactor, VS are reduced by 40% to 60% (EPA Office of Water, 2006). To get a range of sludge reduction values, we calculated the effluent sludge volume at 40%, 50%, and 60% VS reduction. The value for the VS in the influent sludge was determined from the GPS-X model (which is discussed further in Section 3.2.3) of the upgraded WWTP made by Stantec employees. The value for the fixed solids was calculated by subtracting the amount of VS from the number of total solids, also obtained from the GPS-X model.

3.2.3 Model Biogas and Digestate Production

While most of the values for the parameters used in the equations for methane and digestate production could be assumed to be constant, we determined that some quantities were better represented through a range of possible values. Spreadsheets and a software program were used to produce different values quickly and easily for the variable parameters of the AD system. The software was also used to model the entire Bridgewater WWTP treatment train which allowed our team to easily compare the system with and without AD. This pre-existing model also gave our team values such as COD and TSS of influent sludge that were not available from the Bridgewater WWTP data. Lastly, software allowed our team to easily visualize the process and provide visuals in our report.

In order to determine the best program for our uses, we reviewed potential software programs that could model the actual AD process and determine the quantities of each byproduct. This was done through research of available software programs and recommendations from both Stantec employees and WPI professors. We also looked at the governing equations that made up the software programs available to find what our team needed. Table 2 gives a brief analysis of some of the different software programs our team considered.

Table 2. Overview of Modeling Software Options

Software	Key Points
GPS-X[10]	• Can model ADM1 as well as specialized models • Often used in classroom settings (educational and easy to use) • Used by Stantec
AQUASIM[11]	• Can model a variety of aquatic systems • Used in many professional research papers • Difficult to learn
BioWin[12]	• Focuses on reactions • Limited resources for learning software

Because the WWTP was already modeled in GPS-X by Stantec employees and we were able to receive full access to a temporary license, our team chose to use GPS-X. After making this decision, our team familiarized ourselves with the software and created a separate spreadsheet with equations used by GPS-X, parameters provided by Bridgewater WWTP, and calculations from equations provided earlier in this section. On GPS-X, we used the full model of the upgraded WWTP provided by Stantec employees as a point of comparison. Our first method of modeling the addition of the AD was to add the AD icon and parameters to the full model. This model was difficult to converge and did not produce usable values. To simplify the model, we used parameters from the Primary Clarifier in the full upgraded model and added these values to a separate model as the "influent sludge," that was fed into the AD reactor. This model did produce some reasonable values which were primarily used for comparison of our calculated values.

3.3 Objective 3: Assess the Energy

For our third objective we determined how much energy is required to run the system and compared this to the amount of energy that can be obtained from the biogas produced during the AD process. We also analyzed different options for converting biogas to energy.

3.3.1 Determine Heat Energy Input Required

To estimate the energy input required by the system, our team looked at the energy needed to heat the AD reactor. Heat energy used to heat the influent sludge was found using a modified version of Equation 7.

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[10] (Hydromantis, 2021)
[11] (Aquasim, 2021)
[12] (Envirosim, 2021)

$$\text{(Eq. 7) } Q = mC_p\Delta T$$

Where:

Q = heat energy required (J)

m = mass of sludge (kg)

C_p = Specific Heat Capacity of Water (J/(kg °C))

ΔT = Change in Temperature (°C)

Since we had previously decided to use a complete mix reactor operating at steady state, there will be a constant flow of sludge entering the system. Therefore, instead of having a mass of sludge in this equation, we had a mass flow rate. The value used for this equation was the average sludge flow rate to the AD reactor in gallons per day (converted to kilograms per second). This meant that the required heat energy was defined in Joules per second (rather than Joules), which is equivalent to Watts. We found three values for the heat energy required to heat the sludge using the minimum, maximum, and average sludge temperatures as initial values and heating to 100˚F (37.78˚C) (Bridgewater WWTP, 2020).

Once a value for the heat energy required was found in kilowatts, it was multiplied by 24 hours per day, since we are assuming the AD reactor will be constantly running. This resulted in values in units of kilowatt hours per day. These values are reported in Chapter 4: Results, in Table 7.

3.3.2 Assess Options for Biogas Usage

After determining an approximate range of biogas quantities produced during AD, we assessed options for its usage. Based on the options discussed in Section 2.6, six methods for biogas usage were chosen for comparison. These options were compared based on the amount of heat and/or electricity they can produce, the system's tolerance to biogas impurities, installation as well as operation and maintenance costs, the estimated annual cost savings that the method would provide to the WWTP, and the estimated time it would take to pay off the initial cost of the system. The amounts of heat and electricity were calculated using the amount of methane produced by the AD system that had previously been calculated, a conversion value of 10 kWh produced per cubic meter of methane, and the average thermal and electrical efficiency of each system (Inoplex, 2018). The system's tolerance to biogas impurities is linked to the need for biogas pretreatment. If a system has a low tolerance to biogas impurities, more extensive pretreatment is necessary. This information was adapted from Table 2 of Riley et al, 2020. The installation and operation and maintenance costs were calculated using values from Table 1 of this report. Cost savings were calculated by multiplying the total thermal and electrical energy produced from each system by the cost of heat and electricity, respectively, from Eversource (the utility supplier to the Town of Bridgewater) and subtracting the annual operation and maintenance cost for the system. Payback times were calculated by dividing the total installation cost of the system by the estimated annual savings. The costs of pretreatment technologies potentially needed for some CHP methods were not included in cost estimates. Methods with a low tolerance to biogas impurities are expected to have slightly higher initial installation costs as well as higher sustained operation and maintenance costs. All these factors were put in a table to compare each method (see Table 8). Aspects of each method that would positively impact the WWTP were highlighted in green and aspects that would have a negative impact were highlighted in red. The method with the most benefits to the facility was chosen.

3.3.3 Quantify Biogas Energy Production

Once a technology was chosen for biogas reuse, the amount of energy able to be obtained from the biogas was calculated. This was done using the previously calculated amount of methane produced from the proposed Bridgewater WWTP AD system, the conversion factor of 10 kWh of energy produced per cubic meter of methane, and the efficiency of the chosen biogas usage method.

3.4 Perform an Economic Analysis

To assess the practicality of the addition of an AD system to the upgraded Bridgewater WWTP, our team performed an economic analysis of the upgraded WWTP with and without the addition of an AD system. This analysis was an economic comparison that included the overall installation, transportation, disposal, and maintenance.

3.4.1 Determine Installation Costs

Building Costs

To calculate the total cost to build the structure, our group accounted for the different components that comprise the building, including the walls, ceilings, floors, doors, stairs and windows. We were able to research the average unit costs of these components based on the materials used and combined that with the total amount of material used in order to determine the total cost. We also considered the cost to demolish the current administration building to make room for the upgraded building.

Reactor Costs

Many general specifications of AD reactors can be found through research in scholarly journals that analyze efficiencies or other qualities. However, the cost of an AD reactor varies greatly based on the supplier of the reactor. Using Stantec’s contacts to connect with vendors, our team sent emails to four different suppliers of AD reactors with information about the reactor. This information included the following specifications determined from the modeling process:

- Overall WWTP processing rate (MGD)
- Available area for reactor footprint (ft^2)
- Percentage of total solids in influent sludge
- Tank size specifications (volume [ft^3], height [ft], diameter [ft])
- Minimum and maximum operating levels (ft)
- Average, minimum, and maximum raw sludge feed rates/AD reactor influent (GPD)
- Minimum and maximum sludge influent temperatures (°F)
- Minimum and maximum reactor operating temperature (°F)
- Average, minimum, and maximum heating required (kW and BTU)

From this information, WesTech Inc. and Dutchland Inc. responded with quotes that detailed cost information. Quotes with specific pricing for the necessary part of the system consisted of an industrial scale tank and the mechanical components necessary for the AD process, such as a tank cover, mixer, heat exchanger, and gas storage container. Additional vendors were contacted regarding the costs of the boiler needed to heat the AD reactor; however, we did not hear back from them with actual cost information.

3.4.2 Determine Disposal Costs

To assess and compare the costs of different disposal options, our team referenced the Value Engineering Evaluation of Biosolids Disposal Operations at Bridgewater WWTP Report (Graham, 2020). This report is essentially a cost-benefit analysis for the different disposal methods of sludge which included upgrading the compost facility, landfilling, reuse, and incineration (Graham, 2020). The report found a range of values for transportation, disposal, and overall annual cost for disposal as well as construction, maintenance, and overall annual cost and pay-back time for the compost facility upgrades. By incorporating this data and the calculations our team performed from Section 3.2.2 for sludge reduction from AD, we were also able to estimate disposal costs for the remaining sludge after AD. We then compared the annual and 20-year cost for the disposal options listed in the report and estimated cost of disposal with AD included.

3.4.3 Determine Operation and Maintenance Costs

Operation and maintenance (O&M) costs of the system include the energy required to run the system, repairs, electricity, and labor.

To find the energy input of the system, in kWh/day, required to heat the sludge was found using Equation 7. The cost of this energy was then determined using cost information from Eversource, the energy provider for Bridgewater. From the information on the Eversource site, we determined the cost of 1 kWh of natural gas to be $0.0284 (USD) (*Cost of Gas*, 2021). From this conversion, the cost of heat energy required per day, and annually, was found.

To determine O&M costs, our team referenced labor rates used in internal documents from Stantec (Graham, 2020). In this report, values were provided for the O&M costs of the proposed upgraded compost facility for a full-time operator and part-time mechanic. Knowing these operator rates, we researched and compiled a list of activities that may be involved in maintaining and repairing a municipal AD. Based on this list, we estimated the number of hours that may contribute to O&M costs based on the hours designated by Stantec that a mechanic would be on-site (Graham, 2020).

3.4.4 Calculate 20-Year Costs and Payback Times

Values for the 20-year cost of the different disposal methods without the AD reactor were calculated previously by Stantec employees with a range for each method that accounted for varying inflation percentages (Graham, 2020). For the AD reactor, the 20-year cost was calculated by multiplying all annual costs by 20 years, factoring in varying percentages of inflation, and adding the installation cost. The inflation percentages used for the AD reactor cost were the same as the inflation percentages used by Stantec (Graham, 2020). The mean values for the landfill 20-year cost and the AD addition 20-year cost were then compared.

4.0 Results

This chapter synthesizes our findings from the methods of physical design, chemical components, energy requirements, and cost analysis as described in Chapter 3.

4.1 Objective 1: Design the Reactor

4.1.1 Determine Reactor Type

To compare possible reactor types for the Bridgewater Wastewater Treatment Plant (WWTP) to use, our team assessed eight anaerobic digestion (AD) systems commonly used for processing wastewater. Table 3 compares these systems. Cells highlighted in green indicate factors that were beneficial to the facility, and cells highlighted in red indicate factors that were not ideal for this system. Background information for each type of AD can be found in Section 2.5 of this report.

Table 3. AD Reactor Type Comparison

System Name	Covered Lagoon[13]	Basic Complete Mix[14]	Basic Plug-Flow[15]	Solids Recycling[16]	Fixed Film Filter Digester[10]	Sequencing Batch Digester[17]	Upflow Sludge Blanket[18]	Expanded Granular Sludge Bed[19]
Acronym	CL	CSTR	PFR	SR	FF	ASBR	UASB	EGSB
System Type	Passive	Low Rate	Low Rate	High-Rate	High-Rate	High-Rate	High-Rate Sludge Blanket	High-Rate Sludge Blanket
Maintenance	Very Low	Low	Low	Average	High	Very High	High	Very High
Size	1-2 acres, 20 feet deep	Variable	50m^2	Variable	Relatively Small	430m^2	5m depth, 10-20 m width	Variable
Shape	Swimming Pool	Variable	5:1 length: height ratio	Variable	Variable	Multiple 30L Tanks	Rectangular	Cylinder
HRT (days)	30-60	20-30	15-20	10-25	<5	10 - 15	8 - 10 hours	1-6 hours
SRT	Same as HRT						30-50 days	40-100 days
Solid Composition	0.5% – 2%	3% – 10%	10% – 20%	3% – 10%	1% – 5%	<1%	< 5% – 10%	< 5% – 10%
Mix Type	PFR	CSTR	PFR	CSTR	PFR	Depends on reactor	PFR	PFR
Temperature	External environment	mesophilic (37–39 °C) or thermophilic (52–55 °C)						

[13] Karim, 2013
[14] Bentley, 2012
[15] Ramasta, 2014
[16] Moestedt, 2017
[17] Yoochatchaval, 2008
[18] Van, 2020
[19] Steele, 2013

System type is based on the energy that is required to run the system. The amount of energy that is given to the system determines the amount of biogas that is expelled in return. If a system is passive, methane recovery is added to existing sludge treatment infrastructure. If a system is low-rate, sludge is the primary source of methane producing microorganisms. If a system is high-rate, methane forming microorganisms are added into the system to increase methane production efficiency. The Town of Bridgewater runs on a significant amount of renewable energy, therefore the amount of energy required to run the WWTP is not of concern (Dave Graham, Personal Communication, November 4, 2021). For this reason, our team did not use system energy type as a determining quality.

Maintenance is determined through a variety of characteristics to give a rating of very low, low, average, high, and very high. These characteristics include the machinery required in each reactor, oversight required by operators, the number of media used in the reactor that must be tested, the number of steps required, and the number of functions that could go wrong and disrupt the system. The treatment operators prefer the new system to be as low maintenance as possible. For this reason, only reactors in the very low, low, and average categories were determined acceptable for our design.

Due to the protected wetlands surrounding the WWTP, there is limited size and space that allows room for an AD. For this reason, our team ruled out multiple size and shape options that would not be feasible given the site requirements. An acre or two of land required for covered lagoons, and multiple 30-liter tanks covering 430 m^2 required for sequencing batch reactors were determined to be too large for our specific WWTP design.

The sludge holding tank at the WWTP has an average solid composition of 3 – 4%. To bypass the dewatering process used by the current plant, it is best to find an AD reactor within this range.

Temperature must be regulated by the system because the AD process needs to be at least 100˚F to convert sludge into other constituents, such as methane. Since Bridgewater is in a colder region of the United States that has freezing temperatures for much of the year, a system must rely on an internal heating device, rather than the external outdoor temperature. For this reason, any system that relies on external temperatures cannot be considered.

Hydraulic and solid residence time (HRT and SRT, respectively), and mix type are all important to know for design considerations, but the number does not affect our overall decision of an AD reactor type.

Based on determining factors discussed above, our project focused on a basic complete mix system.

4.1.2 Determine Reactor Size

To approximate the size of the reactor, we calculated three different volumes based on the average flow rate, minimum flow rate, and maximum flow rate of sludge as reported by the Bridgewater WWTP (Bridgewater WWTP, 2020). These values can be found in Table 4. The retention time was estimated to be 20 days, based on our team's research on complete mix reactors and from the Stantec employees we worked with (Motta, Personal Communication, 2021).

Table 4. Reactor Volume [gal] at Different Sludge Flow Rates

Sludge Flow Rate	**Reactor Volume (gal)**
Average Flow Rate (8,143 gpd)	162,800
Minimum Flow Rate (1,786 gpd)	35,700
Maximum Flow Rate (12,626 gpd)	252,500

For designing the actual structure, the volume of the reactor was estimated using the average flow rate. Based on Equations 3 and 4, we estimated that the dimensions of the cylindrical reactor would be 26 feet in height and 36 feet in diameter.

4.1.3 Site Layout and Building Requirements

Our next step was to determine the location and layout of an AD at the Bridgewater WWTP. Our group's initial plan was to build the AD system in the current dewatering building; however, after further discussion with our Stantec contact, Justin Motta, we determined that the best location for the AD reactor would be in the current administration building. This was due to multiple reasons including the administration building's proximity to the sludge holding tank. Motta also recommended the different components that should be inside the building including a Supervisory Control and Data Acquisition (SCADA) control room, lab space, office space, bathroom, and basement pump/boiler room, all of which are in the final model, shown in Figures 10 and 11.

4.1.4 Use of Modeling Software

Figures 10 and 11 depict the structural components and layout of the building in Revit.

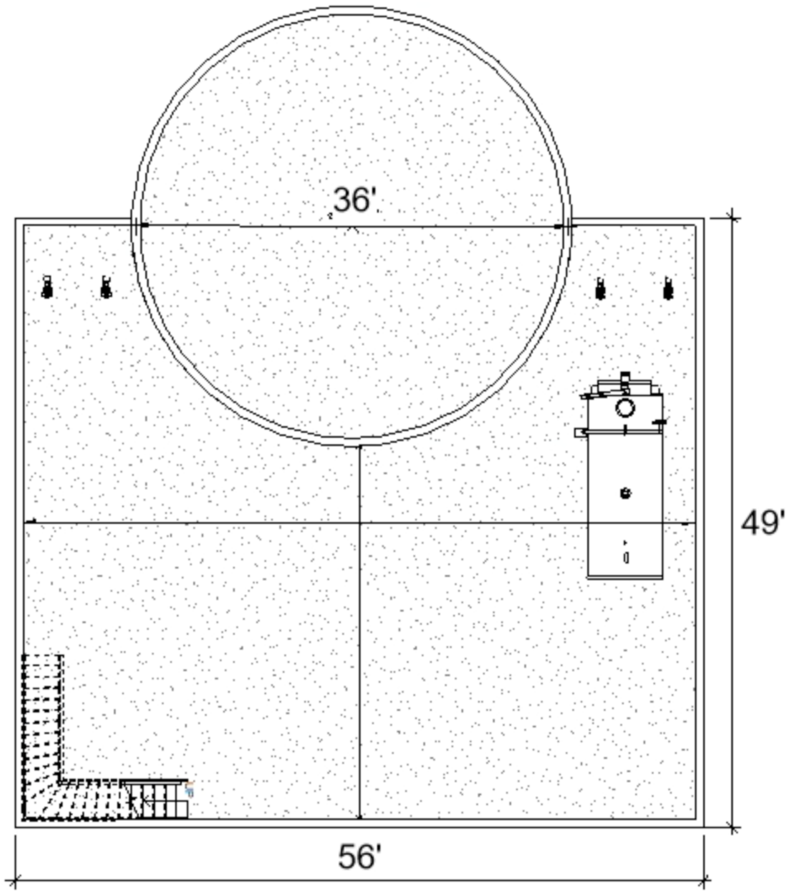

Figure 10. Basement Floor Plan

The basement, shown in Figure 10, contains pumps (not all are pictured) and a boiler (right side of the image). The cylindrical AD reactor has a height of 26 feet and a diameter of 36 feet. The dimensions of the building excluding the reactor are 56 feet by 49 feet. If the reactor is included within the dimensions, the total square area would be 56 feet by 67 feet. The basement and structure are supported by a concrete foundation. Concrete was the desired material to use as it is durable, water-resistant, and provides stabilization to the rest of the building. The reactor itself is also made of concrete in order to withstand the heat from within the reactor. All exterior walls are made of load-bearing brick for the purpose of the upper floors and roof being structurally stable. The stairs, which would be enclosed, are made of metal as this is an inexpensive material that is structurally stable. The building would be sprinklered in order to eliminate the risk of fires. Both the basement floor and 1st floor consist of concrete with a polyurethane coating in order to ensure toughness and durability.

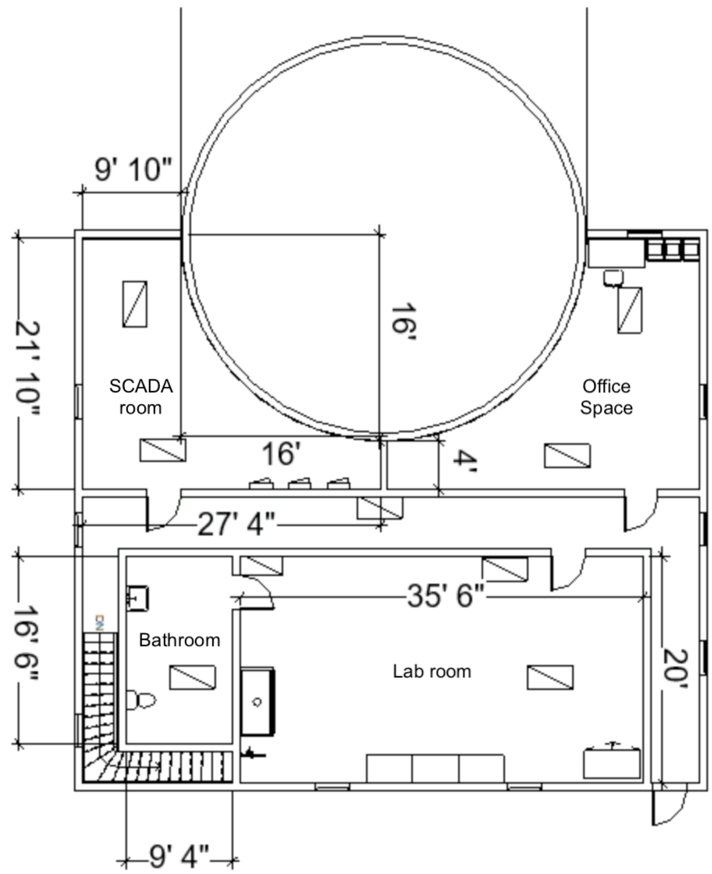

Figure 11. 1st Level Floor Plan

The first level of the building, shown in Figure 11, contains a 710 ft^2 laboratory space, a 154 ft^2 bathroom, a SCADA control room and an office space, both of which are roughly 280 ft^2. The square boxes with a line through them represent lights on the ceiling. The main level of the building features a door (pictured on the right side of the image) that leads into a main corridor to the other rooms. The stairs on the bottom left lead down to the basement. The two lines on either end of the reactor are intended to be inflow and outflow pipes for the biosolids. The inflow pipe would be connected to the biosolid tank just outside the building which would transport the sludge to the AD reactor. The outflow pipe would transport the sludge into a storage tank. All of the interior walls are made of 8-inch thick load-bearing masonry block as this material will support the weight of the ceiling above and is also inexpensive. Both ceilings in the basement and 1st floor are made of concrete. The doors were all made of single wood panel, as this material is inexpensive, and stable.

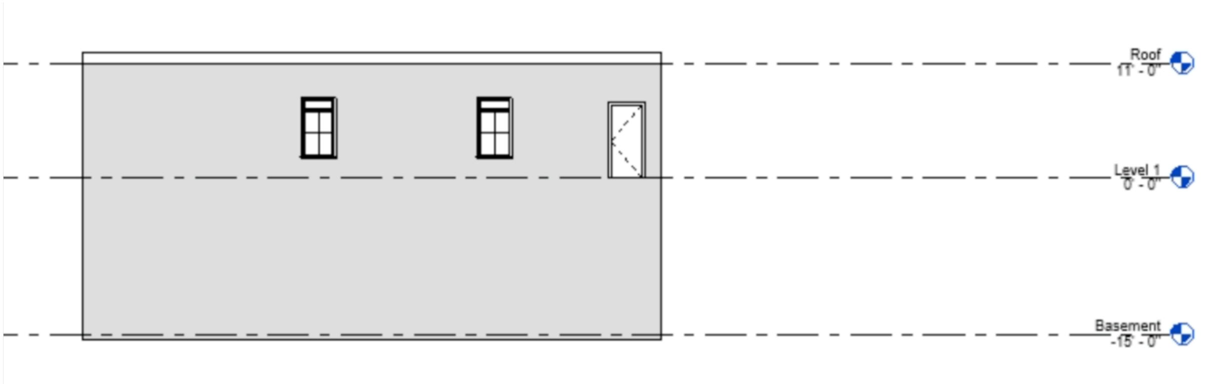

Figure 12. Elevation View

Figure 12 depicts an elevation view of the building from the front side. The basement is 15 feet below grade while the first floor extends 11 feet above grade and connects to the roof, which is made of stainless steel. This material was chosen because mainly because of its durability, which would make the high up-front cost worth it in the long term. The windows were fixed transom windows made of tempered glass. Tempered glass was chosen because it is strong and durable.

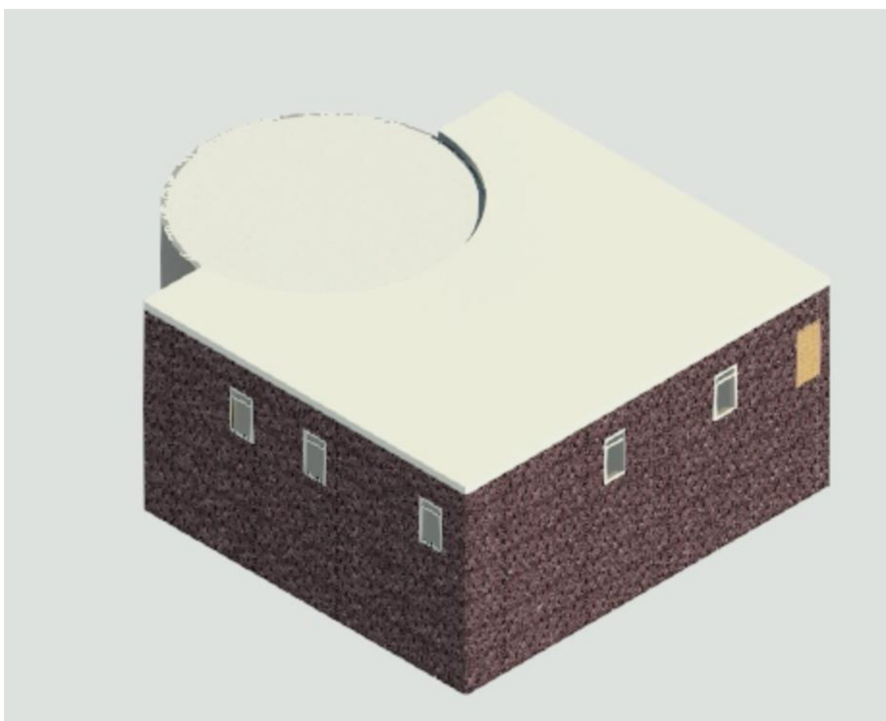

Figure 13. Front Isometric Render

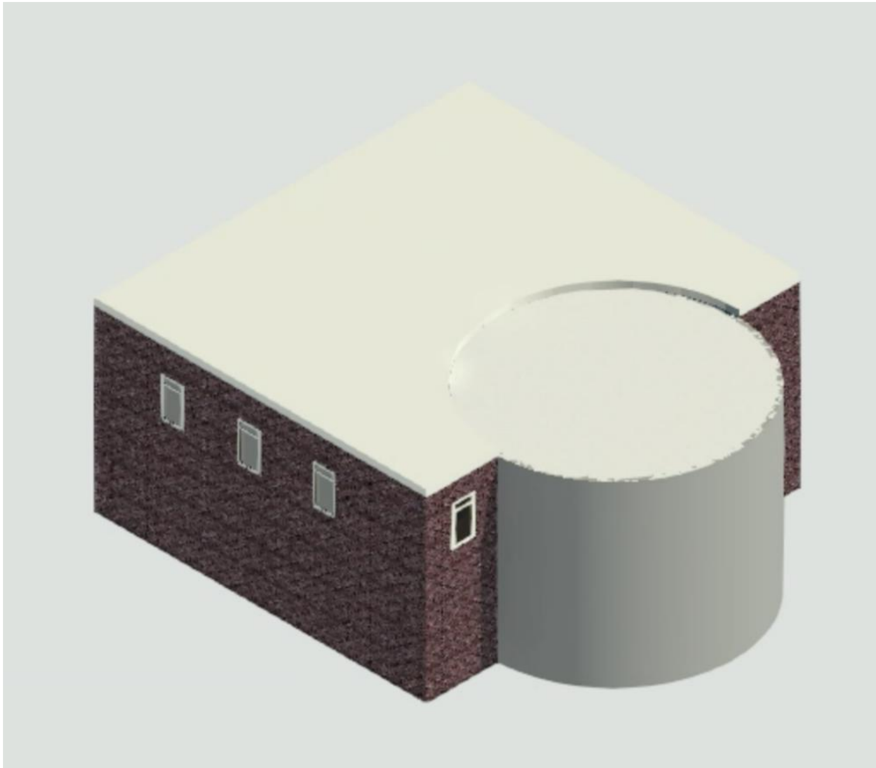

Figure 14. Back Isometric Render

Figures 13 and 14 are 3D renderings of the building from the front and back side showing the exterior materials used such as the load-bearing brick, concrete exterior of the AD reactor, single wood panel door, fixed transom windows, and stainless-steel roof.

4.2 Objective 2: Calculate the Byproducts

4.2.1 Calculate Methane Output

To calculate a range of methane production rates from the AD reactor, Equations 5 and 6 were used. These values were dependent on the influent sludge flow rates as well as the percent of BOD removal. BOD removal may vary depending on the composition of the sludge. Multiple sources provided different ranges for potential BOD removal ranges, but in general, the BOD removal rate from a municipal wastewater AD reactor ranged between 70-90% (Berg, 2015; Utami, 2016; Chou, 2019). In order to determine the actual BOD removal rate possible from AD of the Bridgewater WWTP sludge, a small-scale pilot study could be conducted; however, this was not possible for our team due to limited time and resources. The range of values for methane production from the AD reactor is provided in Table 5.

Table 5. Methane Produced [ft^3/day] at Different BOD Removal Rates [%] and Sludge Flow Rates [gpd].

Sludge Flow Rates	BOD Removal 70%	BOD Removal 80%	BOD Removal 90%
Average Flow Rate (8,143 gpd)	102.0	116.6	131.5
Minimum Flow Rate (1,786 gpd)	22.3	25.6	27.9
Maximum Flow Rate (12,626 gpd)	158.2	180.8	203.9

Based on average methane content in typical biogas composition and Table 5, our team estimated the amount of biogas produced in total with average flow rate and 80% BOD Removal to be between 233.2 ft^3/day and 155.5 ft^3/day (50 to 75% methane content) (Inoplex, 2018).

4.2.2 Calculate Digestate Output

Table 6 gives the calculated values for effluent sludge from the AD reactor in tons per day. These values are only theoretical because the actual sludge removal rate depends heavily on the bio-chemical characteristics of the specific sludge.

Table 6. Theoretical Effluent Sludge Values for Different Percent VS Removal

Percent VS Removal	Total Effluent Sludge (tons/day)	Total Effluent Sludge (tons/year)
40%	0.74	270
50%	0.67	245
60%	0.60	220

Based on the values in Table 6 as well as the value of sludge tonnage removed from the facility each year (350 tons), the AD process reduces the percent of total solids between 23% and 37%.

4.2.3 Model Biogas and Digestate Production

GPS-X was used to model the upgraded WWTP with and without the addition of an AD. The model of the upgraded WWTP was provided by Stantec employees who had previously created these models. When the AD was added to the entire process, the model could not converge and therefore no values were used from this specific model. By not converging, that means that when the model was run, it could not reach 100% completion because it got stuck in a loop or could not calculate values without error. However, a visual representation of how the entire process with an AD could be modeled can be seen in Figure 15.

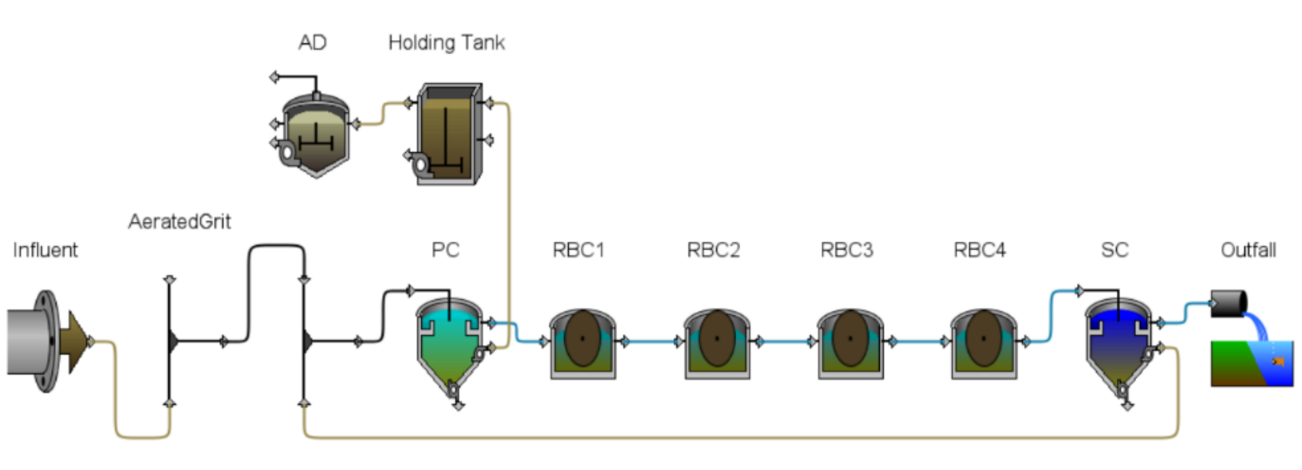

Figure 15. Complete WWTP System in GPS-X

To simulate the AD reactor and allow the model to converge, we created a simplified model which used the output of the Primary Clarifier from the original model as the input or “influent sludge. From this model, we found that given the composition of sludge entering the AD, the biogas would be composed of 63.27% methane. Additionally, the estimated HRT was 21 days, which was comparable to our estimate of 20 days. If the 63.27% methane composition is used to find the amount of total biogas produced, the flow rate of biogas produced would be approximately 1,380 gpd.

4.3 Objective 3: Assess the Energy

4.3.1 Determine Energy Input Required

Table 7 gives the calculated values for the energy required to heat the sludge to 100˚F in the AD reactor throughout the year. Since Bridgewater is in New England, the energy requirements vary seasonally as the initial sludge temperature varies greatly between the winter and summer months. The values used for the initial sludge temperature are from data from the Bridgewater WWTP for minimum (48˚F), maximum (75˚F), and average (62˚F) sludge temperatures throughout the year (Bridgewater WWTP, 2020).

Table 7. Energy Required to Heat Sludge

Initial Sludge Temperature	**Energy Needed (kWh/day)**
48˚F (9˚C)	993
62˚F (16˚C)	726
75˚F (24˚C)	477

4.3.2 Assess Options for Biogas Usage

Table 8 compares different options for biogas utilization. The methods chosen for comparison were those that initially made the most sense given the features of the WWTP. Flaring the biogas was not considered because this is typically done in batch reactor style AD, and the decision to use a CMFR was already made (BiogasWorld, 2021). Additionally, CHP with a gas turbine was not considered because this option is typically used at a larger scale (Riley et al, 2020). Instead, a micro-gas turbine was considered. Finally, selling biogas back to the grid was not considered because of the small amount of biogas produced by the AD system. To sell biogas to the grid it must first be upgraded significantly to meet renewable natural gas standards. The relative capital costs for biogas upgrading technologies increases drastically as system size decreases. Despite this, our team still sought to find information regarding costs for a small upgrading system. The lowest cost range found was for systems processing 100m^3 of biogas per hour; our system would only produce 0.2360m^3 of biogas per hour, making this an unrealistic option (Sun et al, 2015).

Table 8. Comparison of Biogas Utilization Methods

Method	**Biogas Boiler**	**CHP with Reciprocating Engine**	**CHP with Stirling Engine**	**CHP with Micro-Gas Turbine**	**CHP with Fuel Cell**
Heat Produced (kWh/yr)	9,000	5,500	9,500	5,000	2,500
Electricity Produced (kWh/yr)	N/A	4,000	2,000	3,000	5,500
Tolerance to Biogas Impurities	high	medium	low	high	very low
Installed Cost (USD)	*	$56,000 - $203,000	$70,000 - $700,000	$77,000 - $224,000	$210,000 - $700,000
O&M Cost (USD/yr)	*	$76 - $237.50	$115	$64 - $160	$80 - $360
Estimated Savings (USD/yr)	*	$410 - $570	$400	$350 - $450	$400 - $670
Payback Time (years)	*	130 - 350	175 - 1,750	220 - 500	525 - 1,050

*An estimated cost for this item was not available and our team did not receive a response from vendors on a quoted price.

As shown in Table 8, options for converting biogas into heat and electricity are very expensive. Therefore, AD systems with CHP are not typically installed at small facilities where the minimal amount of biogas produced does not make the system cost effective. Since the Bridgewater WWTP has a relatively small daily flow rate, the amount of methane produced from AD does not make it worthwhile to install an expensive CHP system. Instead, we are proposing to use the biogas produced from AD to power a boiler. Since AD requires an extensive amount of heat input, a boiler will be necessary to heat the system, regardless of whether biogas is reused. This means that using biogas to fuel a boiler will not result in any additional costs for biogas usage technology. Additionally, many boilers can combust both biogas and natural gas, which is very beneficial in the case of the Bridgewater WWTP since the amount of biogas produced is not enough to power the AD reactor (Viswanathan, 2018). By fueling the boiler with both biogas and natural gas, the WWTP will be able to purchase less natural gas to run the AD system, lowering the overall costs of the system.

4.3.3 Quantify Biogas Energy Production

Based on the estimated amount of methane produced, the amount of energy obtained from methane, and the thermal efficiency of a typical boiler, it was determined that the biogas produced from AD at the Bridgewater WWTP could produce 9,000 kWh per year of thermal energy. A more accurate value for the energy produced from biogas could be obtained through the implementation of a small-scale pilot study of the AD process with the Bridgewater WWTP sludge. Our team was limited on time and resources and therefore was not able to conduct such a study.

4.4 Objective 4: Perform an Economic Analysis

4.4.1 Determine Installation Costs

Building Costs

Table 9 gives a breakdown of the costs for each aspect of the building.

Table 9. Tabulated Material Costs (Homeadvisor, 2021)

Material	**Unit**	**Total Units**	**Cost per Unit**	**Total Cost**
Load-bearing brick	Square feet	3000	$45	$135,000
Concrete foundation	Square feet	3000	$4.3	$13,000
Polyurethane flooring	Square feet	6000 (2 floors)	$3.3	$20,000
Concrete ceiling	Square feet	6000 (2 floors)	$1.6	$10,000
Stainless steel roof	Square feet	3000	$2.81	$8,450
Masonry Block	Linear foot	118	$240	$28,320
Windows w/ tempered glass	1 window	8	$600	$4,800
Single wood panel door	1 door	5	$750	$3,750
Metal Stairs	1 stairwell	1	$5,000	$5,000
Demolition	-	-	-	$20,000
			Total	**$248, 320**

Our team considered this the “base building cost,” as it does not include any electrical, plumbing, HVAC, excavation, grading, or insulation costs. Additionally, the cost of the SCADA equipment and office space was already included in the Preliminary Design Report (PDR) produced by

Stantec for Bridgewater. Upgrades to the laboratory space were also included in the PDR and therefore were not factored into the final cost for the new building in this report.

Reactor Costs

The cost for constructing the AD reactor and the building were based on quotes from vendors and research of previously constructed AD reactors. The water treatment technology company provided us with a quote for the sludge mixer, the fixed cover, and the gasholder. These are the primary components that make up the AD reactor, other than the tank itself. The estimated quote for these components was $780,000. For the tank itself, we reached out to a concrete environmental services vendor and received a quote for $270,000. Our team contacted multiple vendors for a quote on the boiler system but did not receive information on a cost estimate for a boiler system. For this reason, the cost of the reactor was based on the tank and the large equipment that makes up the digester.

Other components that our team did not receive quotes for but should be considered as an additional cost include electrical wiring and equipment, piping and supports, valves, fittings, pipe lubricating greases, any pumping systems, painting, and welding costs. Due to the large amount of items that were not quoted, we referred to our estimate as the "base reactor cost."

To estimate the cost of the contractor and engineering services, we used service cost percentages from the PDR. Table 10 includes the total estimated cost of contractor and engineering services based on the estimated cost of installation for the building and reactor.

Table 10. Base Installation Costs and Installation Service Costs

Construction Factors	**Cost (USD)**
Base Building Costs	248,320
Base Reactor Costs	1,050,000
Contractor: 15% Profit	197,250
Contractor: 3% Bonds/Insurance	39,450
Engineer: 10% Engineering-design services	131,500
Engineer: 12% Construction-design services	15,7800
Engineer: 30% Contingency	394,500
Base Total for Installation Costs	2,218,820

Based on Table 10, the estimated base installation costs for the AD reactor and adjoining building were $2,218,820.

4.4.2 Determine Disposal Costs

The sludge treatment and disposal options considered by Stantec include upgrading the compost facility, or sending dewatered sludge to a landfill, reuse facility, or incinerator (Graham, 2020). This cost breakdown can be found in Table 13. The conclusion of Stantec's report recommended disposing of the sludge in a landfill with 3-9% inflation costs added into the calculation for this disposal and transportation cost. The report also recommends moving away from the compost facility due to the increase to taxpayers to upgrade the facility and the labor needs. Given this information, our team recommends that when accounting for the changes being made to the Bridgewater WWTP, the remaining sludge from the AD would be sent to a landfill for disposal. With this assumption in mind, we assessed and compared the estimated costs for landfill disposal of sludge with and without the use of an AD.

The cost of disposal in a landfill without AD was reported to be between \$73,000 and \$126,000 for approximately 350 tons of sludge produced annually. With the AD, our team calculated in Table 6 that 245 tons of sludge would be produced annually. This would mean that the cost of disposal would be between \$51,000 and \$88,000 with AD. This would lead to a decrease in disposal costs by about \$30,000 annually.

The cost of transportation without AD was also calculated to be between \$62,400 and \$206,700. If a disposal truck holds 16 tons of wet solids per trip, our team calculated that the cost of transportation for sludge after AD would be between \$43,600 and \$144,400. This is a decrease in transportation costs annually by \$18,800 to \$62,300. With the addition of AD, the cost of landfill disposal and transportation is decreased by about 30%.

4.4.3 Determine Operation and Maintenance Costs

Operation and maintenance (O&M) costs for the AD were approximated based on the following activities:

- Maintaining temperature, pH, and alkalinity
- Minimizing tank foaming and odor
- Tank cleaning
- Ensuring a consistent inflow and outflow of sludge
- Boiler maintenance (frequency dependent on H_2S gas content) (Coyne, 2017)

With the addition of the SCADA system, which could help maintain many of the chemical and physical components of the AD, our team has approximated that labor requirements would likely be part time and maintenance may be more occasional, depending on the longevity of the AD and the boiler system. Table 11 illustrates the cost of the estimated O&M.

Table 11. Total O&M Costs

Service	**Annual Hours**	**Hourly Rate**	**Annual Cost (USD)**
Operator	480	55.00	26,400
Mechanic	120	55.00	6,600
Total O&M	520	-	33,000

Another key operational cost is the electricity needed to heat the boiler system. The boiler must be maintained at a constant temperature of 86 F to 100 F. Given the size of the AD and influent temperature of the sludge, we calculated the amount of natural gas needed to heat the AD which can be found in Table 7. Given these values, we calculated the average annual natural gas costs based on the assumption that natural gas costs in 2021 are approximately $0.0284/kWh (*Cost of Gas*, 2021). Table 12 shows the hourly cost to heat the sludge at different initial sludge temperatures, as well as the average annual cost.

Table 12. Hourly and Annual Costs to Heat Sludge

Initial Sludge Temperature	Daily Cost (USD)	Average Annual Cost (USD)
48˚F (9˚C)	28.20	7,520
62˚F (16˚C)	20.61	
75˚F (24˚C)	13.56	

To help supplement a small percentage of this cost, if the methane were added to the boiler at 25 kWh per day, this average annual cost would be decreased by approximately $260. This would result in a new average annual heating cost of $7,260.

4.4.4 Calculate 20 Year Cost and Payback Times

Table 13 displays the cost breakdown for the primary economic costs of each disposal method and waste handling process considered for the WWTP.

Table 13. Complete Comparison of Economic Factors (Graham, 2020)

Costs (USD)	**Compost Upgrades**	**Landfill**	**Incineration**	**Reuse Facility**	**AD & Landfill**[20]
Installation	3,499,000	-	-	-	2,218,800
Maintenance (annual)	217,000	-	-	-	40,300
Transportation (annual)	*	62,400-206,700	31,200-72,540	124,020-186,420	43,600-144,400
Disposal (annual)	*	73,000-126,000	175,000	126,000	51,000-88,000
Total Annual Cost	425,200	207,660-322,600	206,200-247,500	250,000-312,400	230,00-367,800
Total 20-Year Cost (+ Inflation)	6,750,000	4,153,200-12,000,300	4,124,000-10,902,200	5,000,400-11,455,40	4,973,300-7,984,400

*These costs were not calculated by Stantec or were presumed to be negligible (Graham, 2020). However, based on our teams site visit in which we discussed transportation and disposal costs of compost with operators and Stantec employees, these activities do have substantial associated

[20] These calculations included data from (Graham, 2020) as well as most sources in the previous Results sections.

costs particularly during the wintertime. This is because the compost is often purchased for local land use, but when land applications are halted during the winter, the facility must pay to transport and dispose of their compost.

To compare the 20-year cost of landfilling alone and with the addition of an AD, we found the mean 20-year cost of both options. The mean 20-year cost for the landfilling with an AD was $6,478,850. The mean 20-year cost of landfilling alone was $8,076,750. The difference between these two mean values was approximately $1,600,000.

5.0 Discussion & Conclusion

After completing our analysis of an alternative option for sludge disposal at the Bridgewater Municipal Wastewater Treatment Plant (WWTP), our team made a final evaluation of the system in terms of technical and non-technical aspects such as feasibility, practicality, and overall impact.

5.1 Environmental & Social Impacts

Sludge from wastewater treatment can be disposed of by landfill disposal, incineration, or compost. Stantec performed a cost-benefit analysis of various sludge disposal options for Bridgewater based on the criteria of financial analysis, energy usage, WWTP operations, and site layout compatibility. According to this analysis, Stantec has recommended that Bridgewater Municipal Wastewater Treatment Plant (WWTP) discontinue on-site composting and instead dispose of sludge in a landfill (Graham, 2020).

Landfills present many problems. First, high concentrations of toxic waste leak into nearby land, communities, and water bodies, contaminating natural habitats, homes, and drinking water sources (EPA, 2021). These leaked toxins can be in the form of liquid and gaseous chemicals, which can be linked to serious health problems. When waste is buried without access to oxygen or naturally forming microbes in the environment, the breakdown of this waste is very slow (Paolini, 2018). Waste can last for decades, causing concern for future generations. Additionally, when sludge is disposed of in a landfill, methane is produced through unregulated anaerobic digestion (AD). This methane is not typically captured or used, and therefore is released into the atmosphere, exacerbating the effects of climate change. Methane is 25 times more potent at trapping heat in the atmosphere than carbon dioxide (Paolini, 2018). Due to these concerns landfills across the country are closing, and those that continue to stay open are filling to capacity. Massachusetts, in particular, has few locations left to dispose of trash, so it is then diverted to neighboring states such as New Hampshire, New York, or Maine. The transportation costs and out-of-state waste disposal taxes are much more economically challenging and can be more than double the cost (Hand, 2019).

Incinerators offer another option for disposal, but many are currently closed. Massachusetts has long issued on-and-off moratoriums on incinerators that do not meet air pollution standards, and there is little predictability in when the seven existing incinerators in Massachusetts might be open. Even when incinerators are open, they present other serious environmental and health concerns from chemicals that cause problems such as air pollution, acid rain, carcinogenic waste, birth defects (EPA, 2021).

Compared to the traditional waste system composed of landfills and incinerators that have many concerns associated with them, AD offers hope to the organic waste disposal community. When

AD is implemented, it effectively converts organic waste into renewable energy and reduces the amount of overall solid waste (EPA, 2021).

The sustainability of AD falls in line with Massachusetts' goals for the state's sustainability plans produced and supported by the Massachusetts Department of Environmental Protection (MassDEP, 2021). To incentivize AD, there are programs that allow for financial and technical assistance. The State Revolving Fund Clean Water (SRFCW) Program provides 2% interest loans to assist municipalities in the planning and construction of AD systems at WWTPs (EPA, 2021). Other programs provide tax-exempt financing, as well as grants dedicated to AD projects. While the cost of building an AD is high, these programs can make it more feasible for facilities to install these systems. Additionally, there is money that can be made from the cost savings of no longer delivering sludge to a landfill as well as the potential to produce energy on site (MassDEP, 2021).

5.2 Feasibility and Practicality

Throughout the course of this project, our group has continuously assessed the feasibility and practicality for the implementation of an AD at Bridgewater WWTP. With all aspects of our design in mind, our determination is that it is technically feasible to implement an AD, but practicality depends on the Town of Bridgewater's assessment.

With respect to the physical aspects of the design, an AD saves significant space in the facility. Due to a solid content of the effluent sludge at about 30% total solids, the dewatering building can be decommissioned and stripped. This building can be either used for additional treatment processes or demolished for other purposes as needed by the facility. The administration building proposed in this project is designed to reduce the footprint of the current administration building, which is successful if built around the AD reactor. Therefore, in terms of space constraints, AD is feasible and practical for this facility.

In consideration of the chemical components of the reactor, there is some biogas produced and overall solids waste is reduced. A small amount of biogas is produced: 183 ft^3 per day. The second chemical component of the AD is digestate. Based on calculations, there will be 245 tons of digestate per year, which is about a 30% reduction of overall sludge solids to be disposed of. The final amount of sludge is an average of 0.67 tons per day with 30% total solids, as opposed to 2.3 tons per day of solids with 23% total solids from dewatering. Therefore, in terms of the chemical components of the system, AD is feasible and practical as the system produces energy and reduces sludge.

With consideration to the energy requirements of the system, there is not enough biogas energy produced to power the AD reactor. To heat the amount of incoming sludge takes 700 kWh per day, and the reactor produces about 25 kWh per day, or only 3.5% percent of the thermal energy required. This heat energy alone cannot be powered by the biogas produced during AD.

Therefore, it is feasible to use the biogas to help power the AD reactor, but not practical due to the need for more energy from an external source.

Finally, the economic analysis provides that without AD, it cost about $8 million over a 20-year period to dispose of sludge to a landfill. However, with all AD cost including installation, maintenance, and sludge disposal, the total cost is $6.5 million over a 20-year period. Although the cost is less overall to implement AD, the up-front installation cost is about $2 million. This is a substantial amount of money to add to a $30 million project and may not be possible with Bridgewater's WWTP project budget. Although the cost is feasible and practical in the long-term solution, the practicality of an up-front cost depends on Town factors outside of our knowledge or control.

In conclusion, these considerations give the result that although AD is feasible at the Bridgewater WWTP, but practicality is ultimately dependent on the amount of money Bridgewater is willing and able to spend up-front on an AD system.

5.3 Limitations

Through the course of this seven-week project, many of Stantec's and WPI's resources were utilized by the team to produce a comprehensive report. Overall, our most impactful limitation was the seven-week timeframe to complete our project. Despite our best efforts to incorporate as many aspects of the design as possible, there were multiple limitations that we aim to recognize.

In terms of the chemical modeling of the system, our team used the GPS-X modeling software. Although a smaller and simplified version of the AD process worked when run in the model, the model of the entire WWTP with AD could not compute, due to the many components of the system.

Additionally, none of the sludge from the Bridgewater WWTP was assessed in a lab by our team to determine the exact chemical components. This analysis would have allowed our team to more accurately estimate the amount of biogas and digestate produced from AD of the sludge, as well as the concentration of methane in the biogas.

Finally, in the design, our team only focused on some of the chemical, physical, and electrical aspects of the system. Aspects not incorporated in design and cost include but are not limited to piping, electrical wiring, and contracting fees.

5.4 Recommendations

If AD were to be implemented, a pilot study should be performed in a lab to determine specific chemical components of byproducts. Additionally, financial grants and loans should be researched by the Town to further aid the initial installation costs. If residents and local stakeholders are interested in the possibility of AD, a committee should be formed to research and apply for funding available by local, state, and national government.

If Bridgewater ultimately decides not to include an AD in the new upgrade, we recommend the town finds alternative methods for sludge disposal after dewatering other than a landfill or incinerator. Further research should be done to find an option for sludge to be reused, such as in composting, or transported to a larger AD facility nearby.

5.5 Conclusion

After completing our analysis of an alternative option for sludge disposal at the Bridgewater WWTP, we have determined that while it is technically feasible to install an AD system at this location, the practicality needs to be further assessed. Based on our analysis of the byproducts of the AD process, the amount of biogas produced is not sufficient to provide energy to heat the reactor significantly, resulting in minimal cost savings. Early on in this project we knew that the amount of biogas produced would not be enough to provide significant cost savings, given the large amount of energy needed to heat the reactor. However, we hoped that the AD process would reduce the amount of sludge needed to be sent to a landfill. Our calculations showed that the reactions occurring in the AD reactor reduced the amount of solid waste from the facility by about 30%. This is the largest benefit of installing an AD system at this facility. The reduction in solid waste results in cost savings from sending less sludge to a landfill as well as environmental benefits associated with diverting sludge from landfills. Despite these advantages, installing an AD system has significant upfront costs that may make it impractical for the Town of Bridgewater. However, if the Town is enthusiastic about the environmental benefits of AD and options for grant funding are evaluated, AD could be a viable option.

Although AD did not turn out to be as effective as we had hoped, our team enjoyed a valuable learning experience while working on this project. This project allowed us to learn about the planning and design aspects of environmental and civil engineering projects that we could not have learned in the classroom. By working with Stantec, we were able to see firsthand how a real engineering project is executed and the steps necessary to making a final decision. Additionally, this project allowed us all to learn about topics outside of the typical realm of our environmental and civil engineering education. For example, energy played a major role in this project, which was something that our group had minimal knowledge on. To understand the energy aspects of AD, this was a topic that had to be heavily researched to obtain a solid background level of knowledge. Also, our group chose to use the modeling software GPS-X to model the AD process and determine the amounts of byproducts formed. This software was new to our group, but after reviewing user guides and speaking with professors as well as Stantec employees, we were able to gain a basic level of understanding of the program. While our proposal did not prove to be as practical as we had intended, we are grateful for the educational opportunities that this project provided us.

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Appendices

Appendix A: Project Proposal

Anaerobic Digestion Reactor Design
for Bridgewater Wastewater Treatment Plant

A Major Qualifying Project Proposal Submitted to the Faculty of Worcester Polytechnic Institute
In Partial Fulfillment of the requirements for the Bachelor of Science Degree

Maia Gifford, Evelyn Mortimer, Marshall Watts, Rachael Zmich

October 11, 2021

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Capstone Design

The Civil and Environmental Engineering Departments at Worcester Polytechnic Institute are ABET accredited programs. Part of the requirements for ABET accreditation of a university program is a capstone project with a design component (ABET, 2021). Worcester Polytechnic Institute has chosen to fulfill this requirement by having students in these programs complete a Major Qualifying Project (MQP) during their final academic year.

The Bridgewater Wastewater Treatment Facility is seeking to upgrade and add multiple processes to their current treatment train and overall site. These upgrades are essential for the longevity and wellbeing of the facility and the community it serves. Stantec was hired to design this system upgrade and has more than 90% of the design plan completed. Our MQP team will be working with Stantec, a consulting and design firm, to consider alternative design options for the Bridgewater Wastewater Treatment Facility. We have chosen to focus on researching and exploring an alternative option for the compost building which would involve creating an anaerobic digestion (AD) system to reuse the compost (primarily sludge) and to partially power the facility itself. We have considered the impacts of this project and have outlined them in this section.

Economic

AD is a common process utilized in wastewater treatment facilities, as it both reuses a major byproduct of wastewater treatment, sludge, and has the potential to create energy that can power the facility. In Massachusetts, there are programs that allow for financial and technical assistance for AD projects. The State Revolving Fund Clean Water (SRFCW) Program provides 2% interest loans to assist municipalities in the planning and construction of AD systems at wastewater treatment plants (EPA, 2021). Other programs provide tax-exempt financing, as well as other grants dedicated to AD projects. While the cost of building an anaerobic digester is high, there is money that can be made from the cost savings of no longer delivering sludge to a landfill as well as the potential to produce energy on site.

Environmental

The primary focus of this project is to assess alternative design options for the Bridgewater Wastewater Treatment Facility and part of the reason for this is to see if any part of this project could be more environmentally sustainable. AD systems can significantly increase the sustainability of a site. If there is enough inflow to reach on-site energy and heating needs, then the WWTP has the potential to become energy-independent, and off-grid. If the site remains on the electric grid, then any excess energy produced can be added to the local grid for nearby residents. This locally sourced renewable energy can reduce greenhouse gas emissions that contribute to climate change, which disproportionately affects vulnerable populations. AD is potentially more environmentally sustainable than sending sludge to a landfill because this system would be reusing the sludge for an alternate purpose, as well as decreasing the use of natural gas for power at the facility.

Ethical

Our team will follow the guidelines of the American Society of Civil Engineers Code of Ethics and, to the best of our ability, provide an unbiased analysis of this alternative design option. We will consider the resources and equity impacts of an AD with the nearby community in mind.

Social & Political

When instituted in a community WWTP, AD has social and political implications. Controlling odors is one of the most difficult aspects of designing a WWTP. Although smells are not physically harmful, smells are physiologically disturbing. Foul smells can waft into nearby neighborhoods and businesses, which causes objections between residents and their idea of the plant. For local residents and businesses, AD can help reduce unpleasant odors. AD reactors provide immediate disposal of wastewater sludge, whereas unprocessed and transported sludge in large quantities can cause odor and nearby water pollution.

Health & Safety

During this project, we will consider the public health risks of having AD in close proximity to neighboring communities. In addition, we will assess this alternative in comparison to the public health risks of sludge being brought to a landfill. Our team will also work to ensure the structural components of the AD system are as safe as possible and up to building code.

Key Terms and Abbreviations

AD - anaerobic digestion/digester

BOD - Biological Oxygen Demand

BSU - Bridgewater State University

CWMP - Comprehensive Wastewater Management Plan

GPD - gallons per day

MGD - million gallons per day

MQP - Major Qualifying Project

NPDES - National Permit Discharge

RBD - rotating biological contactors

WWTP/WWTF - Wastewater treatment plant/facility

VFA - volatile fatty acids

1.0 Introduction

The town of Bridgewater, Massachusetts has had a municipal wastewater treatment facility since the 1960s (Graham, 2020). This system has had upgrades since this time, most recently in 1987, but the town is now looking to build new systems and repair various processes within the facility. Stantec, a consulting and design firm with an office in Burlington, Massachusetts, was hired to develop the designs for this renovation. Part of the renovation includes the removal of the compost building on site which served to repurpose the sludge produced by the facility to residents in the area. Our team will be researching and exploring an alternative option for the compost building which would involve creating an anaerobic digestion (AD) system to reuse the compost and to partially power the facility itself. Our team will be working with employees from Stantec and professors from the Civil, Environmental, and Architectural Engineering Department at WPI to produce a proposal for this sludge and compost-based anaerobic digester.

Our goal for this project is to assess the technical feasibility and practicality of implementing an AD system in the Bridgewater municipal wastewater treatment facility. In order to reach this goal, we will complete the following three objectives.

1. Design an AD process which suits the facility
2. Design the layout and basic structure of an AD on this site given the current site layout
3. Perform an economic analysis for implementing an AD at the Bridgewater WWTF

Once these objectives have been reached, we will be able to determine if it is feasible and practical to build an AD system at the Bridgewater WWTF.

2.0 Background

2.1 Stantec

Stantec is an international design firm with over 22,000 employees and 400 locations around the world. In Massachusetts alone, there are six (6) different offices which provide their own variety of services, including but not limited to, community development, landscape architecture, and geotechnical engineering (Stantec, n.d.). For this project, our team will be working with a team from the Stantec Burlington office.

2.2 The Town of Bridgewater

Geography

The town of Bridgewater is located in Plymouth County, Massachusetts, in the Brockton metropolitan area approximately 27 miles south of Boston. The town is located at the intersection of Interstate 495 and Mass. Route 24, two major roads in the area. There are multiple water bodies in the area, most notably the Taunton River as well as several local lakes and ponds, and multiple wetland areas. There is also a state forest, town forest, and several conservation areas such as the Hockomock Swamp Wildlife Management Area. (The Town of Bridgewater, 2021)

Government

The Town of Bridgewater is one of fourteen Massachusetts municipalities that have applied for and received a city form of government but have voted to retain "The town of" in all official titles. Due to this, Bridgewater has a ‘city’ form of government, led by nine City Councilors: seven Precinct Councilors, two "at-large councilors," as well as an appointed Town Manager, Assessor, and Tax Collector. Due to this system of government, it is required that the town council must vote ⅔ of full council on all planning and financial decisions made about the WWTP. These votes are based on the opinions and ideas from the residents in the seven precincts, as well as the budget decided by the town manager and assessor. (The Town of Bridgewater, 2021)

Demographics and Land Use

The town is predominantly developed residential. To support the growing population of homeowners in the area, residential use is continuously growing. This has halted commercial and industrial development in comparison to other nearby towns. The most increasing population is college-age students, in connection with the nearby Bridgewater State University (BSU). BSU is a major public university enrolling nearly 11,000 students and contributes to the largest amount of sewer inflow in comparison to other nearby institutions such as the Bridgewater Correctional

Complex, an institution owned and operated by the Commonwealth's Department of Corrections, or Bridgewater State Hospital (United States Census, 2020).

Master Plan

The town of Bridgewater is currently in the process of drafting a new Master Plan to be released in 2022. There are six sections to this plan, four that are relevant to the Bridgewater WWTP and AD project (The Town of Bridgewater, 2021).

The first objective is land use. The town aims to provide clear, concise, and transparent zoning regulations to guide regulatory boards and landowners as well as balance land use and development with environmental stewardship and social equity concerns. The next objective is to improve transportation. The goals behind transportation are to minimize vehicular congestion downtown, increase access to parking, and improve safety and accessibility for all, and reduce single-occupancy vehicle trips. In the category of natural resources and open space, the town aims to protect natural resources while providing and promoting open space access. For public facilities and services, the town plans to provide efficient, reliable, high-quality services and well-maintained facilities that residents consider town assets rather than unnecessary tax burdens as well as reduce municipal energy use and water consumption. The final two objectives are in the categories of housing and economic development, which do not seem to directly relate to the WWTP. (The Town of Bridgewater, 2021)

2.3 Bridgewater WWTP Project

In December 2019, the Town of Bridgewater allocated money and resources to a Comprehensive Wastewater Management Plan (CWMP) performed by a private engineering consulting company, Weston & Sampson. This report analyzed how to improve the wastewater, drinking water, and stormwater treatment processes (Weston & Sampson, 2019).

In terms of infrastructure, the town has a well-developed water supply, storage, and distribution system. There is a centralized sewer system, which provides wastewater collection, treatment, and disposal for approximately 30% of the developed parcels in town (Weston & Sampson, 2019). Of these developed parcels, nearly all receive municipal water service from the Bridgewater Water Department. Stormwater is managed with localized drainage collection systems that recharge the groundwater or flow to existing surface water via an outfall to the Taunton River. This report has determined that in order to improve the town's water system, it is most important to focus on wastewater issues with less emphasis on drinking water and stormwater issues (Weston & Sampson, 2019).

The main goal for the CWMP was to find the best solutions to Bridgewater's wastewater management challenges. This includes the following objectives:

8. Add extensions to the existing municipal sewer system.

9. Improve nutrient removal to comply with the required federal (NPDES) discharge permit.
10. Continued on-site system use and management
11. Re-rate plant for a nominal increase in flow with a commensurate increase in permitted flow.
12. Regulate future sewer extensions and connections to serve the identified needs areas and to allocate the remaining limited system capacity to a targeted development.
13. As the town's major sewer user, BSU plans and sewer capacity needs should be agreed upon together with financial commitments for system capital improvements
14. Continue ongoing efforts to remove extraneous wastewater treatment plant flows through its Infiltration/Inflow identification and reduction program (Stantec, 2021).

2.4 Current Wastewater Treatment Train

The Bridgewater Wastewater Treatment Facility (WWTF or WWTP) is designed to treat 1.44 MGD of municipal wastewater and 20,000 GPD of sewage from Bridgewater residents (Graham, 2020). The treatment process removes nutrients and bacteria from the raw wastewater in accordance with the town's NPDES permit. When raw wastewater initially enters the plant it flows through a headworks system consisting of a comminutor and aerated grit removal system. These steps cut up larger material in the influent to less than 5/16 inch pieces and remove large debris to avoid damaging equipment along the treatment train. The influent is then combined with secondary sludge and ferric chloride (for phosphorus removal) before entering one of two primary clarifiers. Here settleable solids are removed from the base of the tanks, and scum is scraped off the surface of the water. Effluent from the primary clarifiers moves through four stages of biological treatment consisting of 14 rotating biological contactors (RBC) to remove biological oxygen demand (BOD) and to nitrify ammonia. Then, the water moves through one of two secondary clarifiers to settle out biological solids. This effluent then enters a chlorine contact tank for disinfection and is treated with sulfur dioxide for dechlorination prior to discharge to the Town River. (Graham, 2020)

Sludge from these processes is mixed in a below-grade sludge storage tank and dewatered in a two-belt system. Any residual water removed from this process is returned to the start of the treatment train and dewatered sludge is moved to an onsite composting area. The sludge is aerated and then reused for land fertilization. In Stantec's Preliminary Design Report, it is proposed to remove the on-site composting area and transition to trucking sludge off-site for treatment. (Graham, 2020)

2.5 Anaerobic Digestion and Biogas Recovery

Our proposed method with regards to the Bridgewater WWTF is to implement an AD system to process sludge and produce biogas to fuel the facility. In AD, bacteria is added to organic matter to break it down in the absence of oxygen. An overview of this process is shown in Figure 1.

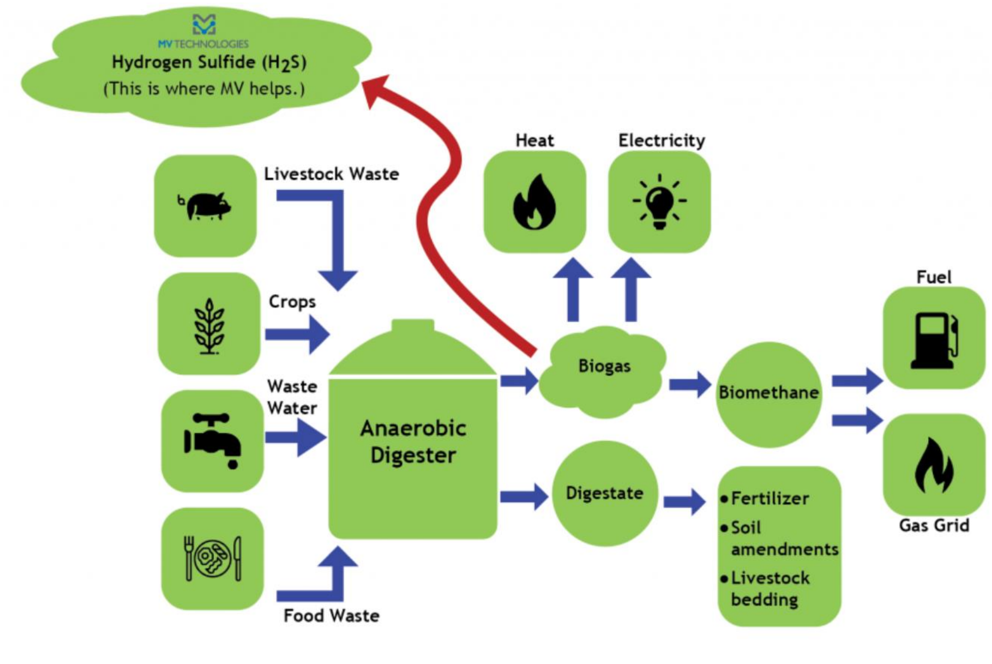

Figure 1: Basic schematic of AD (Ag Biogas, 2020)

The organic matter used in AD can vary from animal manure to food waste to waste from restaurant grease traps (EPA, n.d.). In the case of the Bridgewater WWTF, wastewater sludge will be used as the input. Sludge is a byproduct of wastewater treatment and is typically either reused, for agricultural or other purposes, or disposed of in a landfill. In order to use sludge as an input for anaerobic digestion it is important to understand the specific makeup of the sludge. The biochemical content of sludge depends greatly on the properties of the influent wastewater to the facility, but it generally "consists of large-sized solids such as grit or sand, organic and inorganic substances, and pathogenic microorganisms, heavy metals, and toxic or nontoxic contaminants" (Grobelak, Czerwińska, & Murtas, 2019). When looking at the characteristics of sludge there are three main categories to focus on: physical, chemical, and biological. The physical properties of sludge determine how the sludge can be treated. The chemical properties determine what nutrients are present, and the biological properties determine the microbes and organic material in the sludge (Grobelak, Czerwińska, & Murtas, 2019). For AD and biogas recovery, the nutrients and organic matter are important to determine the amount of biogas that can be produced from the sludge.

According to EPA estimates, the amount of biogas fuel that would be produced from 100 gallons of wastewater is approximately 1 cubic foot. If AD were used to treat the total daily inflow of the plant, 14,400 cubic feet of biogas fuel could be produced per day. This is based on the average design flow of 1.44 MGD of municipal wastewater that the facility is permitted to treat (Graham, 2020). This would be equivalent to about 814 kWh of usable electricity produced per day. To put this number into context, 814 kWh of electricity would be able to power an average household for a month (EIA, 2020).

The basic steps of the AD process are hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Hydrolysis breaks down the sludge input into smaller pieces that can be used in the subsequent steps. Depending on the characteristics of the sludge, this step can sometimes be the rate-determining step in the AD process. Because of this, hydrolysis is sometimes done in a separate reactor prior to the rest of the AD process. In the next step, acidogenesis, acidogenic microorganisms produce volatile fatty acids (VFAs) from the broken down sludge. In protein rich wastewater sludge, amino acids typically dominate the production of VFAs. The process in which amino acids are broken into VFAs can also produce ammonia which can be detrimental to the AD process, so this is a crucial step to monitor. During the next step, acetogenesis, the previously produced VFAs are converted into acetates, which can then be used by acetolactic methanogens in the methanogenesis step to produce methane. Methanogenic microorganisms are the most sensitive of the microorganisms involved in AD. These microorganisms cannot be exposed to oxygen, and have a slow regeneration time of 5 to 16 days. Typically, these four steps are carried out in a single, sealed, batch reactor. (Meegoda et al., 2018)

Typically, an industrial scale AD is shaped as an enclosed, cylindrical tank. The structure of the tank also normally includes some form of mechanical circulation method, often in the form of a mixer vertically running through the tank, spinning close to the bottom of the substrate. The size and shape of the tank is dependent on many different factors, including the average amount of material inflow and the piping which connects the AD to the rest of the system. (Penn State Extension, 2021)

3.0 Methodology

3.1 Scope

The goal of this project is to assess the technical feasibility and practicality of implementing an AD system in the Bridgewater municipal wastewater treatment facility. We have determined a set of three objectives to guide our project and accomplish our goal.

> **Objective 1:** Design an AD process inside of the structure which would be suited well for the facility and known parameters.
>
> **Objective 2:** Design the layout and structure of an AD for this facility given the current site layout.
>
> **Objective 3:** Perform a cost-benefit analysis for implementing an AD at the Bridgewater Wastewater Treatment Facility in terms of short term and long term economic, environmental, and social impacts.

For each objective we have outlined a set of tasks that we will complete to reach the objective. These tasks are detailed in the following subsections.

Objective 1

Design an AD process which will be suited well for the facility and known parameters.

For our first objective we will be designing the AD process in accordance with the physical building design and the chemical makeup of the sludge. In this objective we will also determine how biogas produced from the AD process can be used to power the WWTP or added to the grid. Initially, we will analyze potential software programs to use to complete this objective. We will also have to familiarize ourselves with our chosen software before proceeding to the next step in this objective. Once a software has been chosen, we will design a functional reaction process for AD at this WWTF using our knowledge of the chemical and biological makeup of the sludge and the typical steps in an AD process. We will then design a layout for the process that will fit in the building designed in the next objective. This layout will include design for how sludge moves through the process as well as what is done with the byproducts.

Objective 2

Design the layout and structure of an AD for this facility given the current site layout.

Our next objective is to design the layout of an AD at the Bridgewater WWTF. To meet this objective we will first use GIS to layout the current site design and then develop a potential alternative layout for the site including an AD facility. In doing this we will be sure to limit the introduction of additional impervious surfaces, as the site is located near a wetland and stormwater infiltration is a concern. Once we have determined a location for the on-site AD facility we will use Revit to develop a preliminary structural design of the facility, keeping in mind the process of AD and the design of the preexisting composting building.

Objective 3

Perform a cost-benefit analysis for implementing an AD at the Bridgewater WWTF in terms of short term and long term economic, environmental, and social impacts.

For our final objective we will be analyzing the costs and benefits of implementing an AD at the Bridgewater WWTF. In order to do this we must first analyze cases of past AD implementation projects at WWTPs. When reviewing case studies we will be sure to note successes and failures of past projects, whether energy from the AD process was used to power the WWTF, how much energy was able to be produced through the AD process, what sludge nutrient ratios provided the maximum amounts of energy, and how much labor was required to oversee the process. While performing our case study analysis we will also be researching the economic, environmental, and social costs and benefits of the alternative of trucking wastewater sludge to a landfill facility and powering the WWTP with natural gas. We would like to directly compare these cost findings of the WWTP with the AD system to the cost of the WWTP with the current proposed changes. These costs will include constructing the building and other structural aspects of the AD process. Once we have completed this research we will quantify the information we have gathered and use a spreadsheet to directly compare the costs and benefits of AD and this alternative.

3.2 Deliverables

At the conclusion of this project we will have produced a written report of our proposed designs, a summary of the cost-benefit analysis, a presentation for the employees at Stantec working on the Bridgewater WWTP project, and a poster for Project Presentation Day at WPI in April. We will also produce an informational brochure or infographic outlining the potential options and benefits of building an AD system at a WWTP. This brochure could be given to the decision makers in the Town of Bridgewater or other wastewater treatment plants who may be considering this alternative in the future.

3.3 Project Timeline

We have developed a Gantt chart for the steps we will take to reach our goal in the next term. This chart is shown in Figure 2.

Project Timeline								
Week	1	2	3	4	5	6	7	8
Task	Oct 25 - 29	Nov 1 - 5	Nov 8 - 12	Nov 15 - 19	Nov 22-23	Nov 29 - Dec 3	Dec 6 - 10	Dec 13 - 16
Refine Goals & Objectives								
Site Visit								
Literature Review								
AD Reactor Process Model								
GIS Site Design Model								
Revit Structural Model								
Cost Analysis								
Alternative Cost-Benefit Analysis								
First Draft Report								
Second Draft Report								
Final Report								
Final Presentation								

Figure 2: Project Timeline

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Appendix B: Site Visit Report

Cited As:
(David Graham, Personal Communication, November 4, 2021)

Sources:
David Graham - Stantec Engineer
Brian Shea - Stantec Engineer
Robert Correia - Assistant Superintendent

Site Visit Overview

One of our Stantec contacts, David Graham, facilitated the tour of the site. He first started off by taking our group to the part of the plant that aerates the water and filters primary pollutants. The physical and chemical processes that took place in this part of the plant were explained in depth such as aeration, screening, and comminution. Graham then took our group to the headworks building where it was explained how the sludge, sewage, septic and grit removal pumps function. He mentioned how all of the pumps will be upgraded in the upcoming site renovation. The tour then transitioned to the primary clarifiers before our group was shown the dewatering and disinfection building. In this part of the plant it was explained how the biosolids are extracted from the water and transported using a conveyor belt, until eventually being trucked out to local landfill. Graham explained to our group that the current method of disinfecting the water involves the use of chlorine gas, but that method will eventually shift to the use of UV. Graham then took our group to the secondary clarifiers before showing us the rotating biological contractors (RBCs), where it was further explained how the water is cleaned aerobically. Lastly, Graham took our group to the composting area where all the biosolids were stored before being trucked to a local landfill. It was explained that the composting area will be removed in the coming upgrades. In its place will be more parking spaces, a men's and women's locker room building, as well as more storage rooms. Some of the key pieces of information that our group found helpful with regards to our project is the fact that the Bridgewater plant runs on a significant amount of renewable energy, signifying that the energy required to run the WWTP is not of concern. In addition it was explained that the sludge in the sludge holding tank has an average solids composition of about 3-4%.