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Abstract

The aim of this study was to evaluate the techno-economic feasibility of integrating an energy recovery technology for biogas produced through sewage sludge anaerobic digestion in a real municipal wastewater treatment plant (WWTP). Using available literature and monthly effluent reports from the WWTP, the methane production rate was calculated and evaluated energetically for the anaerobic digester and for the WWTP. A cost analysis was conducted for six scenarios of biogas use: installing a boiler to produce heat, installing a gas engine or a microturbine, or a fuel cell to produce heat and electricity, bottling and compressing biomethane, or injecting biomethane into the natural gas grid. It was recommended that the WWTP install a gas engine to produce heat and electricity due to its capability of reducing electricity demands in the WWTP, its wide use in other WWTPs, a low annual capital cost, and high revenue.

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1. Introduction

Municipal wastewater treatment plants (WWTPs) consist of various advanced biological and physicochemical treatments (Demir and Yapicioglu, 2019). Because of these treatments, WWTPs produce different greenhouse gases (GHGs), such as $CO_{2(g)}$, $CH_{4(g)}$, and $N_2O_{(g)}$ (IPCC *et al.*, 2014). Methane and nitrous oxide emissions from WWTPs have increased consistently in the last decades with emission levels reaching 667 and 108 $MtCO_{2(eq)}$ in 2010(IPCC *et al.*, 2014). Physical and chemical characteristics of wastewater (WW) have a significant impact on the total GHG emissions of a single plant (Bani Shahabadi, Yerushalmi and Haghighat, 2009), although some processes produce more GHG than others. Within the WWTP, the biological removal of nitrogen have the highest contributions to GHG emissions. Nitrous oxides are emitted primarily during biological nitrogen removal, commonly done through the combination of aerobic and anoxic processes (Law *et al.*, 2012). Methane emissions are primarily released in aerobic digestion tanks; but methane can also be produced from sewer transfer (Masuda *et al.*, 2018). Moreover, off-site emissions are mainly due to raw material use, with anaerobic and hybrid treatments representing the highest raw material use and emissions (IPCC *et al.*, 2014).

Various innovative changes can be made in WWTPs to reduce GHG emissions. For instance, including primary and secondary aerobic tanks in the wastewater treatment line can reduce methane emissions (IPCC *et al.*, 2014). Improved plant design and operational strategies (e.g., modifying the chemical oxygen demand to nitrogen ratio (COD/N)) can reduce emissions of nitrous oxides (Kampschreur *et al.*, 2009). Sewage sludge anaerobic digestion is a promising cost-effective microbial process to produce methane, reduce its fugitive emissions and increase energy production in WWTPs (Karakurt, Aydin and Aydiner, 2012; Khawer *et al.*, 2022). Therefore, this study aims to evaluate the techno-economic feasibility of integrating an energy recovery technology for biogas produced through sewage sludge anaerobic digester in a real municipal wastewater treatment plant (WWTP). This study will calculate theoretical values of biogas and biomethane production in a WWTP by analyzing the chemical and physical characteristics of sludge produced. A comparison of available biogas upgrading technologies and their costs will be conducted.

1.1. Sewage sludge anaerobic digestion

Physical, chemical, and biological processes within the WWTP generate sewage sludge waste mainly composed of dewatered microbial biomass containing different concentrations of metals, hazardous materials, and pathogens (Appels *et al.*, 2008; Di Capua *et al.*, 2020). The chemical and physical characteristics of the sludge produced, depend on the source as well as the operation conditions of the WWTP (Khawer *et al.*, 2022).

Primary sludge, containing between 97% and 99% water and highly putrescible organic matter, is produced through a physical primary treatment generally done through sedimentation tanks. This process removes about 50–60% of the suspended solids and 30–40% of the biological oxygen demand (BOD) from the wastewater (Appels *et al.*, 2008; Metcalf and Eddy, 2014; Liew *et al.*, 2021). Secondary sludge, or activated sludge, containing between 98% and 99% water and high levels of active microbes, is produced through a secondary biological treatment where aerobic microorganisms remove BOD, suspended solids and nitrogen and phosphorous (Metcalf and Eddy, 2014; Liew *et al.*, 2021). This secondary sludge is recirculated to maintain the concentration of microorganisms in the tanks (Appels *et al.*, 2008). Primary and secondary sludge are combined to undergo further treatment (Appels *et al.*, 2008).

Further treatment can include thickening (T), anaerobic digestion (AD), road transport (R), mechanical dewatering (MD), indirect drying (ID), and incineration (I) depending upon the intended use of the treated sludge. The varying sludge disposal routes are presented in Table 1. T is needed for all the intended uses of the treated sludge and AD can be applied to nearly all the intended uses. Therefore, AD of sewage sludge should become an essential process in advanced WWTPs (Di Capua et al., 2020).

Table 1. Sludge disposal routes. Adapted from: Appels et al. (2008)

Intended Use	Treatment
Agriculture	T + (MD or AD or AD + MD) + R
Landfill	T + (MD or AD + MD) + R
Solid fuel	T + MD + ID + R
Solid fuel (WWTP USE)	T + AD + MD + ID
Ash	T + (MD or AD + MD) + ID + I

AD is defined as a biological process conducted by microorganisms in the absence of air that is used to stabilize and breakdown organic matter (Linyi *et al.*, 2020). This process produces a stabilized digestate and biogas mainly composed of carbon dioxide and methane (~ 20-40% CO_2 and 50-70% CH_4) as well as trace amounts of H_2S and NH_3 depending on the organic matter composition described by the Bushwell (1952) formula seen in Equation 1 (Appels *et al.*, 2008; Metcalf and Eddy, 2014; Vidal-Barrero *et al.*, 2022).

$$C_vH_wO_xN_yS_z + \left(v - \frac{w}{4} - \frac{x}{2} + \frac{3y}{4} + \frac{z}{2}\right)H_2O \rightarrow \left(\frac{v}{2} + \frac{w}{8} - \frac{x}{4} - \frac{3y}{8} - \frac{z}{4}\right)CH_4 + \left(\frac{v}{2} - \frac{w}{8} + \frac{x}{4} + \frac{3y}{8} + \frac{z}{4}\right)CO_2 + yNH_3 + zH_2S \quad (1)$$

AD consists of four main stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis as seen in Figure 1 (Wardani *et al.*, 2020). In the hydrolysis stage, hydrolytic bacteria convert complex organic matter composed of carbohydrates, fats, and proteins into simple organic matter composed of sugar, fat acids and amino acids. Due to the presence of large complex macromolecules, this stage is rate-limiting influencing the volume of methane produced and the anaerobic digester design (Linyi *et al.*, 2020; Khawer *et al.*, 2022). In the acidogenesis stage, acidogenic bacteria convert the products of the hydrolysis stage to volatile organic acids, alcohols, and ketones. In the acetogenic stage, acetogenic bacteria convert the chemicals in the previous stage to acetate, hydrogen gas, and carbon dioxide. The final stage is the methanogenesis stage where acetate and hydrogen gas are transformed to methane and carbon dioxide through methanogenic bacteria. The sulfidogenic stage is shown as a dotted line in Figure 1 because oxidized sulfur concentrations, including sulfate, sulfite, and thiosulfate, vary greatly depending upon the source of organic matter (Metcalf and Eddy, 2014).

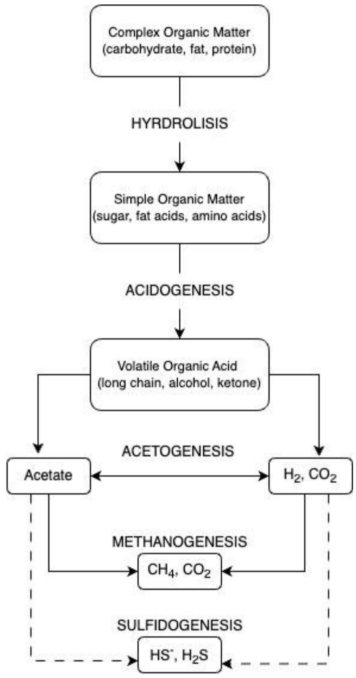

Figure 1. Anaerobic digestion staged process scheme. Source: Wardani et al. (2020)

The specific generation of methane in a conventional AD digestor with sewage sludge ranges from 0.19-0.24 NM^3/kg volatile solids (Di Capua *et al.*, 2020). The biogas production from sewage sludge in 2006 represented 18% of Europe's total biogas production (Mottet *et al.*, 2010). However, the methane yields depend on various factors, including solid retention time (SRT), pH, macronutrient and micronutrient concentration, temperature, and hydraulic retention time (HRT) (Di Capua *et al.*, 2020; Wardani *et al.*, 2020).

1.2. Factors influencing Anaerobic Digestion

Important factors that influence AD include solids retention time, hydraulic retention time, temperature, alkalinity, pH, inhibitory substances, and the bioavailability of nutrients and trace metals (Metcalf and Eddy, 2014). Methanogenic bacteria are particularly sensitive to environmental factors and any changes in the organic feedstock (McCarty, 1964). This makes the AD process sensitive to changes in their environment including changes in pH, organic load rate, and temperature (Wardani *et al.*, 2020). A good pH for AD is between 6.6 and 7.6, although the optimal range is from 7.0-7.2 (McCarty, 1964). The feedstock should also be free of high concentrations of metals due to their capacity to inhibit methanogenic bacteria growth and cause an increase of volatile acids in the reactor (McCarty, 1964). Typical inhibitory concentrations are displayed in Table 2.

Table 2. Concentrations of inhibitory organic compounds to methanogenic bacteria. Source: Metcalf and Eddy (2014)

Substance	Moderately inhibitory concentration (mg/L)	Strongly inhibitory concentration, mg/L
Na^+	3,500-5,500	8,000
K^+	2,500-4,500	12,000
Ca^{2+}	2,500-4,500	8,000
Mg^{2+}	1,000-1,500	3,000
Ammonia-nitrogen	1,500-3,000	3,000
Sulfide, S^{2-}	200	200
Cu(II)	–	0.5 (soluble), 50-70 (total)
Cr (IV)	–	3.0 (soluble), 200-250 (total)
Cr (II)	–	2.0 (soluble), 180-420 (total)
Ni(II)	–	30 (total)
Zn(II)	–	1 (soluble)

The factors described in this section are controlled through the operation of the anaerobic digestor. Furthermore, the factors decided during process selection are solids retention time (SRT), hydraulic retention time (HRT), and temperature. The configuration and type of reactor chosen affects these three parameters.

1.2.1. Temperature

The two main temperature ranges of operation for the stabilization of sewage sludge are: mesophilic, ranging from 35ºC to 40 ºC, and thermophilic, ranging from 55ºC to 70ºC (Lin *et al.*, 2018). Growth rate of methanogens decrease as the temperature decreases as seen in Figure 2. Therefore, psychrophilic temperature range is not commonly used to stabilize WWTP sludge.

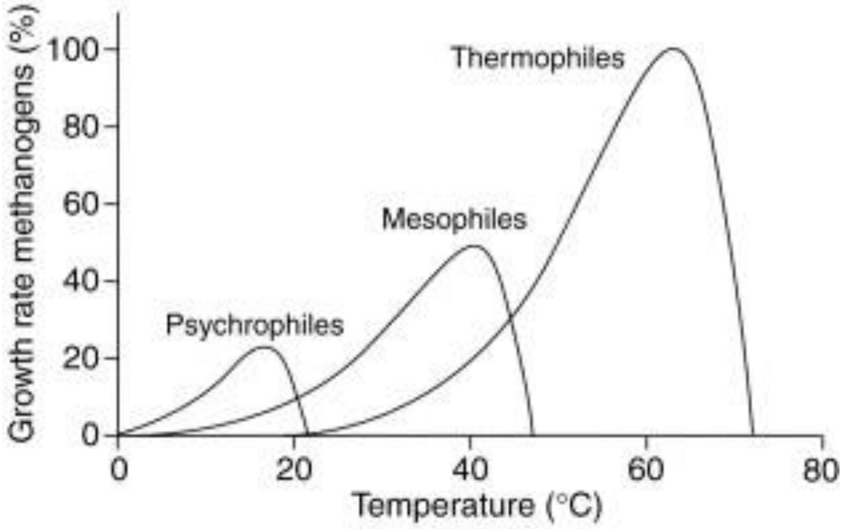

Figure 2. Relative growth rates of psychrophilic, mesophilic, and thermophilic methanogens. Source: Lettinga (2001)

Kinetic velocity and organic matter degradation rates under thermophilic temperatures are faster than those in mesophilic temperatures due to the positive impact of temperature on biochemical reaction rate (Gebreeyessus and Jenicek, 2016; Wardani *et al.*, 2020). Under same HRT conditions, higher rate of biogas production and higher COD removal typically occur in thermophilic conditions (Wardani *et al.*, 2020). In fact, the methane production increased from 35.8% to 48.2% in thermophilic temperatures when compared to mesophilic conditions (Kardos, 2011). However, an increase in ammonia inhibition can sometimes be seen in thermophilic conditions due to the chemical equilibrium shifting towards the production of ammonia (Sung and Liu, 2003). Biomethane production is not the only criteria when it comes to designing an anaerobic digestor. Energy demand is also an important factor to be considered, as well as quality and quantity of sludge post treatment required. Table 3 presents advantages and disadvantages of mesophilic and thermophilic AD systems.

Table 3. Advantages and disadvantages of mesophilic and thermophilic temperature ranges. Source: Gebreeyessus and Jenicek (2016)

	Mesophilic System	Thermophilic System
Advantages	During the biogas production organic material is stabilizing, fermented sludge can be applied as dung	Increased gas output due to the faster reaction; higher methane gas content and reduction of hydrogen sulfide content in the biogas
		Lower HRT/SRT needed
		Smaller reactor volume demand
	Sludge's quantity reducing	More pathogen destruction
	Sludge's fertilization ability reducing	Sludge's dehydration getting better
	Sludge's water down take capacity getting better	Reduced foam formation in the reactor
Disadvantages	Higher investment costs because it needs a larger reactor volume because HRT is higher	Higher heating energy demand
		Process is more sensitive to temperature fluctuation

Disadvantages in thermophilic AD include the higher energy demand and higher instability, which has led to mesophilic AD being the predominant temperature range used globally (Gebreeyessus and Jenicek, 2016). Conversely, thermophilic AD requires a lower retention time for stabilization which is preferred when smaller reaction tanks are preferred (Gebreeyessus and Jenicek, 2016). HRT and SRT vary depending upon temperature range of operation and are decisive design parameters to consider when sizing the reactor.

1.2.2. Solids retention time

Solids retention time (SRT) is defined as the average time that solids remain in the AD digestor, and it is a critical design and operating parameter (AgSTAR Program, 2020). Digestors should be designed with an appropriate SRT to maintain a continuous growth of methanogenic bacteria and an appropriate reaction time (Press, 2010). An appropriate SRT will have bacterial mass that tolerates variations in the operating conditions of the digestors (Metcalf and Eddy, 2014). When the designed SRT is low, the loss rate of methanogenic bacteria is higher than their growth rate and volatile fatty acids (VFAs) increase in the reactor, leading to further inhibition in methanogenic bacteria growth (AgSTAR Program, 2020).

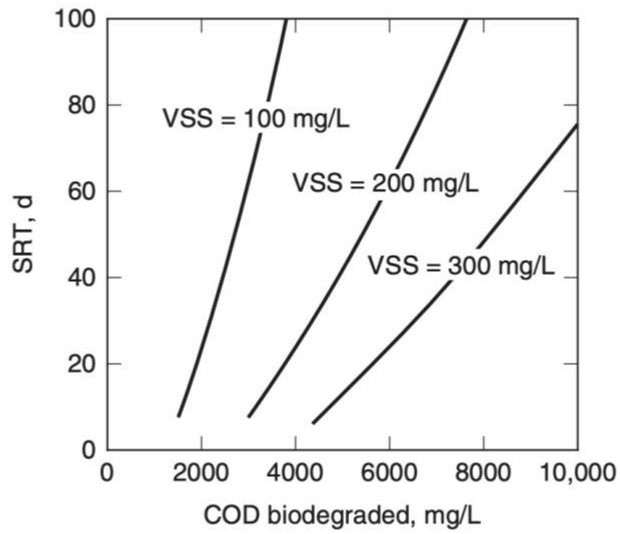

Figure 3. Estimate of SRT as a function of the amount of COD biodegraded and effluent VSS. Source: Metcalf and Eddy (2014)

The desired SRT depends upon the selection of the type of digestors described in Section 1.2.4. COD biodegradation increases as the SRT increases, as seen in Figure 3, where the amount of volatile suspended solids (VSS) to leave the reactor are shown in three different lines. The lower the concentration of VSS leaving the reactor, the longer SRT is needed (Metcalf and Eddy, 2014).

1.2.3. Hydraulic retention time

Hydraulic retention time (θ or HRT) is defined as the average time the liquid fraction of sewage sludge remains in the digestor. HRT depends on the volume (V) and flow of the digestor (Q) as seen in Equation 2.

θ = VQ (2)

HRT defines the inflow and the volume during the design of the digestor (Metcalf and Eddy, 2014). During the digestion of sewage sludge, commonly done on completely mixed reactors, HRT and SRT are the same. If the solids concentration entering the reactor is high, it is recommended to increase the HRT to ensure an efficient process. A shorter HRT translates to a smaller digestor which decreases the capital cost of the project but also decreases its efficiency (Meegoda et al., 2018). Generally, mesophilic digestion requires an HRT between 15-30 days, and thermophilic digestion requires an HRT between 10-20 days (Metcalf and Eddy, 2014). In fact, HRT depends on the configuration, temperature, and type of digestion chosen (Meegoda *et al.*, 2018).

1.2.4. Types of Anaerobic Technologies

The three main types of anaerobic digestors for sewage sludge are completely stirred tank reactors (CSTR), plug flow reactors, and mixed film reactors (Uddin and Wright, 2023). CSTRs require hydraulic or mechanical stirring which requires energy input, while all three types of reactors require pumping energy (Metcalf and Eddy, 2014). Depending on the temperature range of operation and the ambient temperature, the reactors would require heat energy and material of reactor affects the energy losses and can increase the energy demand of the system (Metcalf and Eddy, 2014). Table 4 shows the advantages and disadvantages for the types of anaerobic digestion.

Table 4. Advantages and disadvantages of anaerobic digestors Source: Uddin and Wright (2023)

Digester type	Total solid (%)	HRT (days)	Advantages	Disadvantages
CSTR	3–10	10–25	Suitable for different ambient conditions Can tolerate feedstock variations	Higher energy demand for mixing
Plug flow	10–15	10–25	Operating cost is low Can digest high solid feedstock	Solids can be settled on the bottom
Fixed film	1–5	>5	HRT is very low Digester size is smaller	Digester media can be plugged with solid content

1.2.5. Configuration

Common configuration for AD is one- and two-stage reactor (Leite *et al.*, 2016; Micolucci *et al.*, 2018). In the one-stage reactor, the four main stages of AD shown in Figure 1 occur in the same reactor (Lanko et al., 2020).To overcome the rate limiting stage of hydrolysis (Linyi *et al.*, 2020), AD can be done in a two-stage reactor where hydrolysis and acidogenesis occur in the first stage, while acetogenesis and methanogenic occur in the second stage (Srisowmeya, Chakravarthy and Nandhini Devi, 2020). The two stage reactors can be done in a combination of temperature ranges, either increasing or decreasing through the stages, or with the same temperature ranges as seen in Figure 4.

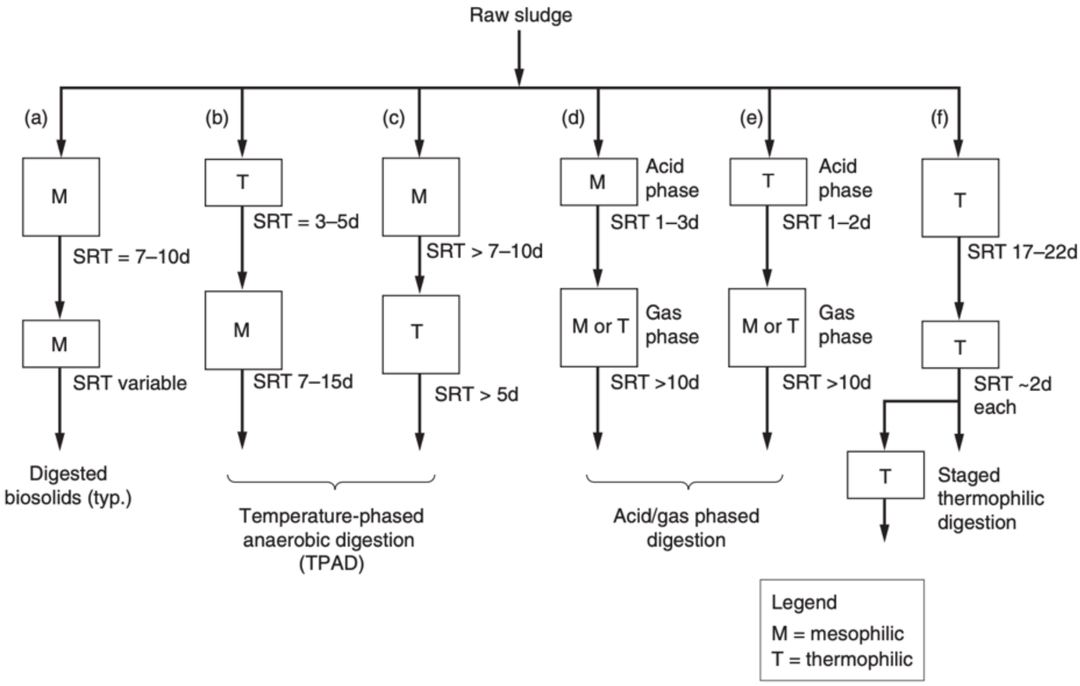

Figure 4. Two stage AD temperature ranges Source: Metcalf and Eddy (2014)

Table 5 shows the experimental results when comparing a one-phase and two-phase AD in a thermophilic (55ºC) temperature range with the same OLR, HRT, and sewage sludge (Leite *et al.*, 2016). Total volatile solids (TVS) removal increased from 34 to 38% in a two-phase digester when compared with a single-phase digester, yielding a global specific biogas production increase from 0.21 $m^3/kgTVS_{fed}\cdot d$ to 0.31 $m^3/kgTVS_{fed}\cdot d$. Overall, a 2-phase process produced 15% more energy than the one-phase process, even when accounting for energy losses being 14% greater than those in the one-phase process (Leite *et al.*, 2016).

Table 5. Experimental yields for one-phase and two-phase AD. Source: Leite et al. (2016)

Parameter	Single phase	2-phase fermenter	2-phase digestor	Units
Biogas production	0.07 ± 0.01	0.13 ± 0.02	0.13 ± 0.01	m^3/d
Biogas production rate	0.50 ± 0.1	0.87 ± 0.13	0.55 ± 0.05	$m^3/ m^3 \cdot d$
Biogas productivity	0.21 ± 0.04	0.05 ± 0.01	0.25 ± 0.03	m^3/TVS_{fed}
TVS reduction	34 ± 3.5	22 ± 4.6	38 ± 2.7	%
CH_4 content	62 ± 5	35 ± 3	69 ± 2	%

The most common configuration used is a mesophilic one-stage digestion due to its simpler and stable operation although the tendency seems to be changing towards a thermophilic one-stage digestor or a temperature phased two-stage digestor because of its metabolically and pathogen removal efficiency (Lanko *et al.*, 2020). Pretreatment can also influence the amount of biogas produced. For sewage sludge, pretreatment technologies include sonification, high pressure Lysing centrifuge, focused pulsed technology, steam explosion, and hydrothermal (Carrere *et al.*, 2016).

1.3. Use of biogas

Biogas can be applied in three main ways: electricity production through cogeneration, injection into the natural gas grid, and converted to compressed natural gas (CNG) to be distributed beyond the WWTP. In the three cases, biogas is recovered and used as a biofuel. The main difference between these options is the end costumer; for cogeneration, its usage is within the plant as electricity, for injection, its usage is by costumers of the natural gas grid, and for CNG, its usage is by consumers of cylindric gas. Table 6 shows generally what impurities need to be removed depending on the use of biogas.

Table 6. General impurities removal per biogas application. Source: Ullah Khan et al. (2017); Khan et al. (2021)

Application	H_2S(g)	CO_2 (g)	H_2O (v)	Siloxanes
Cogeneration	< 250 ppm_v	No removal required (25-30%)	To avoid condensation (<3%)	Removal required (9–44 ppm_v)
Injection to Natural gas grid	Removal required (5 mg/m^3)	Recommended (<4%)[1]	Removal required (<3%)	Removal required [2]
Compressed natural gas (CNG)	Removal required (2-15 mg/m^3)	Removal required (≤3%)[1]	Removal required (1-8%)	No removal required

1 Percentage of CO_2(g) removal varies depending on local regulations.
2 Removal of siloxanes varies depending on local regulations.

1.3.1. Electricity production through cogeneration

Cogeneration refers to the production of heat and power using either: internal combustion engines, microturbine, fuel cells, gas turbine, steam turbine, or combined cycle (Jiang *et al.*, 2009). The main advantage of cogeneration is that it does not require removal of CO_2, although high CO_2 concentrations reduce the efficiency of energy generation by lowering the calorific heat value (Sun *et al.*, 2015). The main disadvantage is its low electrical efficiency, but these depend upon the technology used as seen in Table 7. Among the available cogeneration technologies, fuel cells offer the highest electrical and heat recovery efficiency and the lowest pollutant emissions but the highest equipment cost (Trendewicz and Braun, 2013).

Table 7. Combined heat power (CHP) facilities at WWTPs in the US, their efficiency, and cost. Source: Trendewicz & Braun(2013)

Technology	Number of CHP in WWTPs in US	$\eta_{electrical}$ (%)	$\eta_{heat\ recovery}$ (%)	Equipment Cost ($/kW)
Internal combustion engine	54	37–42	35-43	465-1600
Microturbine	29	26–30	30-37	800-1,600
Fuel cell	13	40-45	30-40	3,800-5,280
Gas turbine	5	19–34	30-37	1,100-2,000

It is preferred to remove water vapor to avoid condensation in gas lines (Ullah Khan *et al.*, 2017). To avoid corrosion of the engine used, a desulfurization technique should be used to have H_2S(g) concentration levels below 375 mg/m^3 (Ullah Khan *et al.*, 2017).

1.3.2. Injection into natural gas grids

Biogas needs to be purified into biomethane before a proper injection into the natural gas grid, where it is physically mixed and diluted with natural gas and transported across the grid directly to consumers (Chandra *et al.*, 2011). The purification needed, often referred as biogas upgrading, should be done to have a similar quality than natural gas (> 95%) in the existing pipeline grid, but regulation varies depending on the location and quality of the existing pipeline as seen in Table 8.

Table 8. Biomethane requirements in various countries for injection to the natural grid. Source: (Foss, 2004; Svensson, 2014)

Component	USA [1]	Sweden	France	Switzerland	Germany	Netherlands	Spain
CH_4 (% vol)	–	≥97	≥97[2]	≥96	≥96	≥95	≥95
CO_2 (% vol)	<2	≤3	≤2.5	≤4	≤6	≤3	≤2.5
O_2 (% vol)	<0.2	≤1	≤0.01	≤0.5	≤0.001	≤0.5	≤0.3
H_2 (% vol)	<0.25 (grain per 100 ft3)	≤2	≤6	≤4	≤2	≤0.5	≤5
CO (% vol)	–	–	≤2	–	–	≤2900 mg/m3	<2
H_2S (mg/Nm^3)	< 5.72	≤10	≤5	≤5	≤5	≤5	≤15
Total sulphur (mg/Nm^3)	<20	≤23	≤30	≤30	≤30	≤15.5	<50
NH_3 (mg/Nm^3)	–	≤20	≤3	≤20	–	≤3	–
H_2O (mg/Nm3)	–	≤3	–	–	–	≤80	–
Water dew point (°C)	>-10, < 55 Bar	≤−8	<–5	–	–	–	≤2
Metals (mg/Nm^3)	–	–	≤1	≤5	≤5	–	–
Siloxanes (mg/Nm^3)	–	–	–	–	–	≤5	–
Halogens (mg/Nm^3)	–	–	≤1 (Cl) ≤10 (F)	≤1	0	≤50/25 (Cl/F)	–
Mercaptans (mg/Nm^3)	–	–	≤6	≤5	≤15	≤6	–

[1] When biogas is injected into pipeline in the US, it must be cleaned to “pipeline quality” defined in Pathways II rule, 79 Fed. Reg. 42128, 42138 (July 18, 2014) and 40 CFR §80.1401. However, the US EPA has not previously explained the interpretation of the term “pipeline quality” (US EPA, 2016) and the most stringent natural gas quality values throughout all supply companies in Annex A (PG. 16 Foss, 2004) are presented in this table. These values depend upon the quality of the gas in the pipeline injected.
[2] de Ladoucette (2013)

Anyone registering to inject biomethane into a commercial pipeline in the US will need to (US EPA, 2016):

1. Describe technologies being used to treat biogas to pipeline quality.
2. Present a summary table with the results from the certificates of analysis (COA). The COAs should demonstrate technologies are successful. They

should be from an independent lab for a representative sample, and should contain the following information:

   a. Sample of the raw biogas produced at the digester
   b. Sample of the “cleaned up” biogas after treatment.
   c. Sample of the biogas after blending with non-renewable gas (if biogas is blended with non-renewable gas prior to injection)
   d. Specifications for the commercial distribution pipeline into which pipeline quality biogas will be injected

3. Documentation of any waiver provided by the commercial distribution pipeline for any parameter of the biogas that does not meet the pipeline specifications, if applicable.

The COAs must report major and minor gas components regulated by the pipeline, including methane, carbon dioxide, nitrogen, oxygen, heating value, relative density, moisture, hydrogen sulfide, total sulfur, total organic silicon/siloxanes, moisture, and any additional parameters for which the pipeline being used has specifications (US EPA, 2016).

1.3.3. Bottled compressed natural gas

Compressed natural gas (CNG) produced with biogas, referred as bio-CNG, can be made after reaching ≥ 97% CH_4 and with a pressure of 20-25 MPa (2900-3600 psi); with the purposed of reducing storage volume and facilitate transportation (Molino *et al.*, 2013). The compression process is expensive due to high pressures needed, but it is justified due to the high heating value and value of bio-CNG for transportation (Krich *et al.*, 2005)

Bio-CNG, when used for transportation, has similar engine performance, gas consumption, and efficiency when compared to CNG, with a fuel economy of 24.11 km/kg for bio-CNG and 24.38 km/kg for CNG (Olsson and Eriksson, 2007; Subramanian *et al.*, 2013). When it comes to emissions, these vary slightly depending upon the contaminant as seen in Figure 5. NO_x, HC, and CO emissions are higher for bio-CNG when compared to CNG used as vehicular fuel. The differences in emissions are partly due to ethane and propane found in CNG having activation energies lower than methane, resulting in a better combustion (Ullah Khan *et al.*, 2017). Hydrocarbons (HC) are released during incomplete combustion due to poor oxidation at low temperatures when the vehicle is heating up (Ullah Khan *et al.*, 2017) Bio-CNG contains a higher concentration of N impurities which is released during combustion as NO_x (Ullah Khan *et al.*, 2017).

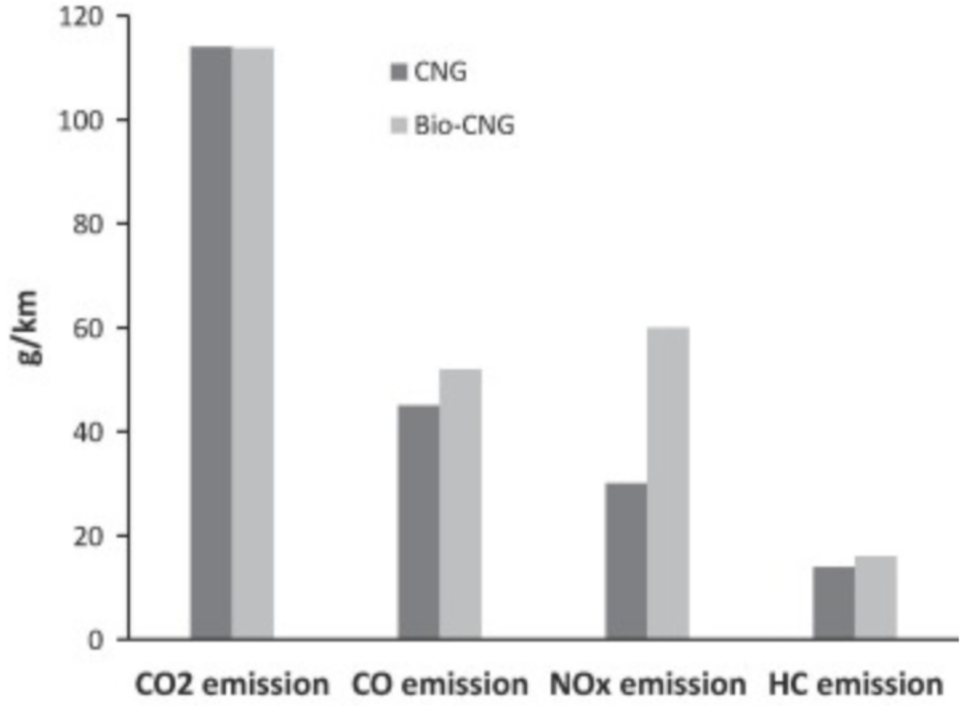

Figure 5. Combustion emissions of CNG and bio-CNG when used as vehicle fuel. Data source: Subramanian et al. (2013) and summarized in Ullah Khan et al. (2017)

1.4. Biogas upgrading

Biogas needs to be upgraded to remove water, H_2S, CO_2, siloxanes, hydrocarbons, NH_3, and Table 9 illustrates the potential negative impact of these compounds. Corrosion is a major issue that needs to be controlled prior to usage of biogas. This section will present available technologies to remove these impurities from biogas and upgrade it to biomethane.

Table 9. Biogas impurities and their consequences. Source: Ryckebosch et al. (2011) and Sun et al. (2015)

Impurity	Concentration in biogas	Possible Impact
CO_2	30–40%	Low calorific value
Water	1–5%	Corrosion in compressors, gas storage tanks and engines due to reaction with H_2S, NH_3 and CO_2 to form acids Accumulation of water in pipes Condensation and/or freezing due to high pressure Dust Clogging due to deposition in compressors, gas storage tanks
H_2S	0–4000 ppm	Corrosion in compressors, gas storage tanks and engines Toxic concentrations of H_2S (> 5 cm^3/m^3) remain in the biogas SO_2 and SO_3 are formed due to combustion, which are more toxic than H_2S and cause corrosion with water
Siloxanes	–	Formation of SiO_2 and microcrystalline quartz due to combustion; deposition at spark plugs, valves and cylinder heads abrading the surface
NH_3	100ppm	Corrosion when dissolved in water O_2/air Explosive mixtures due to high concentrations of O_2 in biogas

1.4.1. CO_2 removal

The main technologies available for the purification of biogas are water scrubbers, chemical scrubbers, membrane technology, pressure swing adsorption (PSA), and organic physical scrubbers (Khan *et al.*, 2021). Figure 6 shows that water scrubber is the most widely used technology for CO_2 removal from biogas in Europe.

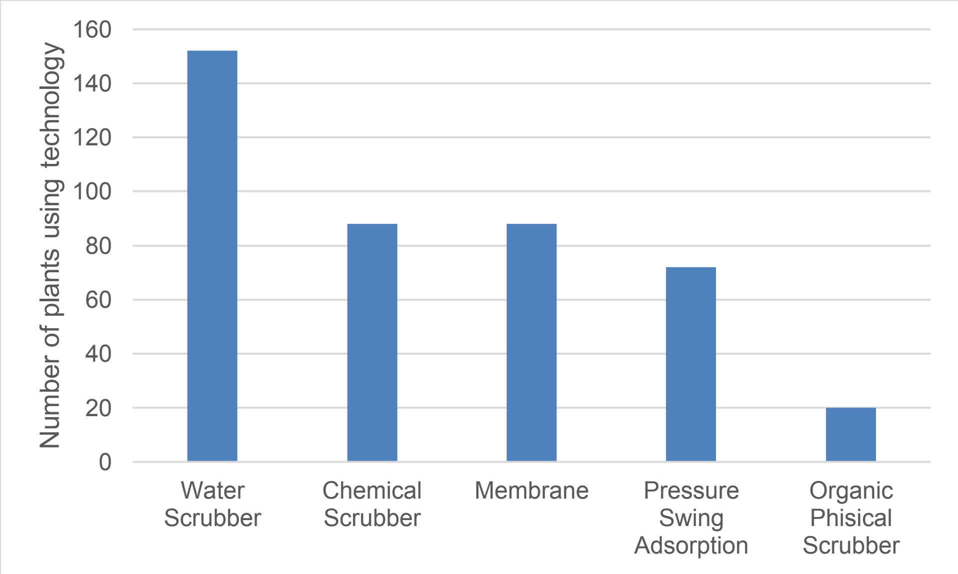

Figure 6. Number of biomethane plants with upgrading technology in Europe. Source: Khan et al. (2021).

Some of these technologies require heat, pressure, and/or energy input or might require pretreatment of biogas. A comparison summary of the conventional biogas upgrading technologies is presented in Table 10. Membrane technology requires the lowest investment and operating cost as well as the lowest energy demand per m^3 of biogas (Khan *et al.*, 2021). These technologies will be further described in the following subsections with the purpose of determining an appropriate technology for CO_2 removal, if required for the application described in Section 1.3.

Table 10. Comparison of different conventional CO2 removal technologies. Source: Khan et al. (2021)

Requirement	Membrane	Pressure Swing Adsorption	Water Scrubber	Chemical Scrubber
Off-gas treatment recommended	Yes	Yes	Yes	No
Desulfurization Requirement	Yes	Yes	No	Yes
Water Demand	No	No	Yes	Yes
N_2 and O_2 removal	Partial	Possible	No	No
Chemical Requirement	No	No	No	Yes
Operation Pressure (bar)	6–8	4–10	4–10	Atmospheric
Outlet Pressure (bar)	4–6	4–5	7–10	4–5
Heat Demand	None	None	None	100–180 °C
Energy Demand (kWh/m^3 biomethane)	0.25–0.43	0.46	0.46	0.27
Running Cost (€)	81,750	187,250	110,000	134,500
Investment Cost (€)	233,000	680,000	265,000	353,000
Maintenance cost (€/year)	25000	56000	15000	59000
Methane Losses (%)	<1.5	<2	<2	<0.1
Maximum recovery (%)	96–98	>96	>97	99.5
Technical Availability	98	94	96	91

1.4.1.1. Water scrubber

Water scrubbing works by absorbing CO_2 in the absorption column at high pressure due to the solubility of CH_4 in water being much lower than CO_2 (Bauer *et al.*, 2013; Sun *et al.*, 2015). CO_2 is released from the water added in the desorption column using a stripper medium at atmospheric temperature (Bauer *et al.*, 2013). After the processes, CH_4 concentration in the resulting biomethane ranges around 80-99% depending on the initial content of N_2 and O_2 in the biogas and CH_4 losses due to dissolution in water (~ 3-5%) (Sun *et al.*, 2015).

Energy is used primarily for the recirculation of water and compression of gas prior to entering the system (Sun *et al.*, 2015). Some water scrubbers in application do not have recirculation of water but this addition lowers water demand and stabilizes the operation(Bauer *et al.*, 2013). H_2S can be removed through a water scrubber, however, it can cause corrosion and it is recommended to be removed before entering the scrubber (Sun *et al.*, 2015).

1.4.1.2. Chemical scrubber

Chemical scrubbing works similarly to water scrubbing for CO2 removal, but uses chemical solvents, like methanol, N-methyl-pyrrolidone (NMP) or polyethylene glycol ethers (PEG),which has a higher solubility in the chemical solvent when compared with water as a solvent (Bauer *et al.*, 2013; Sun *et al.*, 2015). The Genosorb process is the most used in biogas upgrading, which uses a combination of dimethyl ethers and polyethylene glycol as solvents (Bauer *et al.*, 2013). It is recommended to use chemical scrubbing compared to water scrubbing when CO_2 concentrations are low (Sun *et al.*, 2015). CH_4 losses are low because the chemical solvent reacts selectively with CO_2, but this technology requires regeneration of chemical solvents at 40ºC which increases the energy demand (Bauer *et al.*, 2013; Sun *et al.*, 2015).

1.4.1.3. Membrane technology

Biogas is upgraded through molecular sized membranes where CO_2 and H_2S pass through the permeate side while CH_4 remains in the inlet side (Wellinger and Lindberg, 2000). Other compounds such as water vapor and hydrogen are also removed in this process (Bauer *et al.*, 2013). Membranes made of polyimide or cellulose-acetate are commercial options suitable for upgrading biogas (Sun *et al.*, 2015). CH_4 losses are mainly due to CH_4 passing through the membrane (Sun *et al.*, 2015).

Besides having low energy demand as well as low operational and investment costs, an advantage to this technology is that it requires no water or chemical demands and because of its modular capabilities, it can scale down or up without efficiency losses (Bauer *et al.*, 2013).

1.4.1.4. Pressure swing adsorption

Pressure swing adsorption (PSA) separates N_2, O_2 and CO_2 from CH_4 based on physical properties of biogas where these are adsorbed to solid surfaces based on molecular size (Bauer *et al.*, 2013; Sun *et al.*, 2015). Adsorption materials can be activated carbon, natural and synthetic zeolites, titanosilicates, silica gels, and carbon molecular sieves (Bauer *et al.*, 2013). H_2S is toxic to PSA because it adsorbs into the material irreversibly causing damage (Sun *et al.*, 2015) and, therefore, should be removed prior to the PSA column. CH_4 losses are approximately 2-4% present in the effluent gas of the PSA (Sun *et al.*, 2015).

1.4.2. Water removal

Biogas is always saturated with water after leaving the digestor (Awe *et al.*, 2017). Its water content is temperature dependent; water content increases as the temperature increases and it is approximately 5% at 35 °C (Ryckebosch, Drouillon and Vervaeren, 2011). Water removal techniques include physical drying methods and chemical drying methods, and these are presented in Table 11 with their advantages and disadvantages.

Table 11. Advantages and disadvantages of water removal techniques. Source: Ryckebosch, Drouillon and Vervaeren (2011)

Method	Advantages	Disadvantages
Condensation method	Higher HC's dust and oil are removed Simple techniques Often used as pretreatment before other techniques	Atmospheric pressure: dew point minimum 1 °C Gas at higher pressure to reach lower dew point (minimal −18 °C) but freezing can occur
Adsorption dryer **Silica** **Aluminum**	High removal: dew point −10 till −20 °C Low operational cost Regeneration possible	More expensive investment: pressure 6–10 bar Dust and oil need to be removed in advance
Absorption with glycol	High removal: dew point −5 till −15 °C Higher HC's and dust are removed Not toxic or dangerous	More expensive investment: high pressure and 200 °C for regeneration Higher gas volumes (>500 m^3/h) to be economical
Absorption with hygroscopic salts	High removal efficiency Not toxic or dangerous	No regeneration done

1.4.3. H_2S removal

As seen in Table 6, H_2S needs to be removed to use in cogeneration, CNG, and injection to the grid due to its corrosive properties and potential damage in piping and motors (Sun *et al.*, 2015). Desulfurization can be done during digestion or after digestion and it is recommended to do during digestion considering that the CO_2

removal techniques presented in Table 10 require the removal of H_2S (Khan *et al.*, 2021). Table 12 shows the existing commercially available technologies and their advantages and disadvantages.

Table 12. Advantages and disadvantages of commercially available H_2S removal technologies. Source: Ryckebosch, Drouillon and Vervaeren (2011)

Method	Advantages	Disadvantages
Biological with O_2/air (in filter/scrubber/digester)	Low investment and exploitation: low electricity and heat requirements, no extra chemicals or equipment required Simple operation and maintenance	Concentration H_2S still high (100–300 $cm^3\ m^{-3}$) Excess O_2/N_2 in biogas implies difficult upgrading or additional cleaning Overdosing air results in explosive mixture
$FeCl_3$/$FeCl_2$/$FeSO_4$ (in digester)	Low investment: storage tank and dosing pump Low electricity and heat requirements Simple operation and maintenance Compact technique H_2S not in biogas wire No air in biogas	Low efficiency (100-150 $cm^3\ m^{-3}$) Expensive operation (iron salt) Changes in pH/temp not beneficial for the digestion process Correct dosing is difficult
Fe_2O_3/$Fe(OH)_3$-bed	High removal efficiency: >99 %	Sensitive for water
Rust steel wool impregnated wood chips or pellets	Mercaptanes are also captured Cheap investment Simple	Expensive operation costs, Regeneration is exothermic: risk of ignition of chips Reaction surface reduced each cycle Released dust can be toxic
Absorption in water	H_2S <15 $cm^3\ m^{-3}$ Low cost when water is available (not regenerative) CO_2 is also removed	Expensive operation: high pressure, low temperature Difficult technique Clogging of the absorption column possible
Chemical absorption **NaOH** **$FeCl_3$**	Low electricity requirement Smaller volume, less pumping, smaller vessels (compared to absorption in H_2O) Low CH_4 losses	Expensive investment & operation More difficult technique Not regenerative
Chemical absorption **$Fe(OH)_3$** **Fe-EDTA** **Cooab™**	High removal efficiency: 95-100 % Low operation cost Small volume required	Difficult technique Regeneration through oxygenation $CO_2 \rightarrow H_2CO_3$ (using EDTA) leads to precipitation

Method	Advantages	Disadvantages
	Regenerative Low CH_4losses	Buildup of thiosulfates from chelates + H_2S (using EDTA)
Membranes	Removal of >98 % is possible CO_2 is also removed	Expensive operation and maintenance Complex
Biological filter	High removal possible: >97 % Low operational cost	Extra H_2S-treatment to reach pipeline quality O_2/N_2 in biogas implies difficult and additional upgrading steps
Adsorption on activated carbon (Impregnated with KI 1-5 %)	High efficiency (H_2S <3 cm^{-3} m^3) High purification rate Low operation temperature Compact technique High loading capacity	Expensive investment and operation CH_4 losses H_2O and O_2 needed to remove H_2S H_2O can occupy the binding places of H_2S Regeneration at 450 °C Residue present till 850 °C

1.4.4. Siloxanes removal

Siloxanes are used in cosmetics, pharmaceuticals, and anti-foam products in detergents and are continuously increasing in municipal wastewater with concentrations ranging from 1-400 mg/m^3 (Ryckebosch, Drouillon and Vervaeren, 2011) These organic silicon compounds are oxidized to silicon oxide during the combustion of biogas and abrade the surface of plugs, valves, and cylinder heads causing severe damage on engines (Wellinger and Lindberg, 2000). For this reason, different siloxane removal technologies have been developed before combustion of the produced biogas. Commercially available techniques with their advantages and disadvantages are presented in Table 13.

Table 13. Advantages and disadvantages of siloxane removal technologies. Source: Ryckebosch, Drouillon and Vervaeren (2011)

Method	Advantages	Disadvantages
Absorption with organic solvents	High removal efficiency (97%)	Complete removal not possible
Absorption in strong acid	High removal efficiency (<95%)	Corrosion Environmental issues Hazardous chemicals
Adsorption on silicagel	High removal efficiency (<95%) Higher removal capacity vs activated carbon (50% extra) Regeneration possible (95% desorption at 250 °C)	High pressure needed Moisture decreases efficiency
Adsorption on activated carbon	High removal efficiency (95%) Regeneration possible (desorption < desorption with silicagel at 250 °C)	High pressure needed (higher adsorption capacity) Moisture decreases removal efficiency
Cryogenic separation	High removal efficiency (99.3% at −70 °C) Removal of several impurities	Expensive investment and operation (high pressure and low temperature)

1.5. Biosolids management

Biosolids produced by WWTPs contain different quantities of organic matter, macronutrients, and micronutrients including K, Na, Ca, and need to be routed into agriculture, landfill, solid fuel, or ash as seen in Table 1 (Appels *et al.*, 2008; Wang and Lee, 2021). Biosolids from sewage sludge can contain carbon content greater than 50% (Weidemann *et al.*, 2018), N content between 1-5% (Mayer *et al.*, 2016; Wang and Lee, 2021), and P content around 5% (Mayer *et al.*, 2016). Nitrogen and phosphorus are essential macronutrients for plants to grow. Therefore, biosolids from sewage sludge have the potential to be used for agricultural applications (Mayer *et al.*, 2016; Manasa *et al.*, 2020).

In the US, the management and disposal of sewage sludge used to land, incinerators, or landfills, is regulated by the Clean Water Act, 40 CFR Part 503 (40 CFR Part 503, 1993). All biosolids must be measured for microbial standards including salmonella sp., fecal coliforms, enteric viruses, and viable helminth ova and are divided into Class A or Class B depending on the treatments applied to the biosolids (Table 14).

Table 14. Alterative treatment process for Class A and Class B biosolids. Source: Boczek (2019)

Class A	**Class B**
Thermally treated biosolids: Subjected to 1 of 4 time and temperature regimes.	Monitoring of indicator organisms: fecal coliform densities must be less than 2 million MPN or CFU/g total solids at time of disposal
High pH – High temperature: Meet specific criteria with respect to pH, temperature, and air-drying.	
Treated in other processes: must show the ability of reducing enteric viruses, viable Helminth ove, along with maintenance conditions.	Treated in one of the following processes to significantly reduce pathogens (PSRP): aerobic digestion, air drying, non-thermophilic aerobic digestion, composting, and lime stabilization.
Treated with unknown processes: must be tested for all pathogen and meet fecal coliform, salmonella requirement at time of use and disposal.	
Treated in one of processes to further reduce pathogens (PFRP): composting, dry heat, heat treatment, thermophilic anaerobic digestion, beta ray, gamma ray irradiation, and pasteurization.	Treated to process equivalent to PSRP: as deemed by the permitting authority
Treated in process equivalent to a PFRP: determined by the permitting authority	

To meet Class A biosolids microbial standards, they must have a fecal coliform of less than 1000 MPN/g total dry solids and salmonella sp. of less than 3 MPN/4 g total dry solids (3 MPN/4 g TS) (Boczek, 2019). Class B biosolids have fecal coliform limits of less than 2.0×10^6 MPN/g TS or less than 2.0×10^6 CFU/g TS (Boczek, 2019). Biosolids that do not meet the minimum of Class B cannot be land applied. The other difference between Class A and Class B biosolids are where land application can be done. Class B have site restrictions and usage for crop harvest, animal grazing and public access as presented in Table 15. In addition, Class B materials cannot be sold or given away in bags or other containers.

Table 15. Class B biosolids restrictions. Source: Boczek (2019)

Land use	Restriction of use after land application
Food crops where harvest touches biosolid	14 months
Food crop with harvest below land surface	20 months, if biosolids remain for ≥4 months 38 months, if biosolids incorporate in soil
Food crops that do not touch biosolid	30 days
Animal grazing	30 days
Turf growing	1 year
Public access	1 year, for high potential use sites 30 days, for low potential use sites

The application of biosolids in agricultural land features concerns regarding long-term accumulation of toxic elements or health risks due to emerging contaminants in wastewater, including pharmaceuticals, polycyclic aromatic hydrocarbons (PAH), perfluorinated alkyl substance (PFAS), cosmetics, and microplastics (Gianico *et al.*, 2021) and, therefore need regulation on maximum contaminant concentrations. In the EU, these concentrations are regulated through “EU Sewage Sludge Directive (86/278)” and in the US by the Clean Water Act, 40 CFR Part 503. Concentration levels are presented in Table 16.

Table 16. Limits of metals and non metals for sludge use in agriculture. Source: 40 CFR Part 503, 1993; Boczek, 2019; Gianico et al., 2021

	US (Clean Water Act, 40 CFR Part 503)			**EU (Directive 86/278/EEC)**[1]	
Pollutant	**Sludge – Class B**	**Sludge – Class A**	**Soil – Class A**	**Sludge**	**Sludge treated soil (6< pH$_{soil}$<7)**
Arsenic	75	41	2	–	–
Cadmium	85	39	1.9	20-40	1-3
Chromium	3,000	3,000	150	–	–
Copper	4,300	1,500	75	1,000-1,750	50-140
Lead	840	300	15	750-1,200	30-300
Mercury	57	17	0.85	16-25	1-1.5
Molybdenum	75	75	–	–	–
Nickel	420	420	21	300-400	30-75
Selenium	100	36	5	–	–
Zinc	7,500	2,800	140	2,500-4,000	150-300

1 Directive has been consolidated in 01/01/2022.

The US has more metals regulated as well as stricter concentrations that need to be met for nearly all contaminants when considering Class A biosolids. In addition, the US regulates microbials and then classifies the biosolids, while in the EU these are not yet regulated.

2. Methodology

2.1. Description of case study

The WWTP studied includes unit processes, such as primary sedimentation, biological aerobic treatment, denitrification, filtering, and UV disinfection. It provides the service for approximately 227,000 customers (US Environmental Protection Agency, 2023). About a third of the territory is combined sewer system (CSS), that handles sewage and wet weather event flows within the same system, and two thirds is a municipal separate storm sewer system (MS4), which has two separate systems for sewage and storm water. The WWTP has a capacity of 1.97 m^3/s (45 MGD, approx. 250,000 PE) for dry weather flow and 3.29 m^3/s (75 MGD) for wet weather flow. A diagram representing the sludge, wastewater, and recirculation flows of the existing WWTP can be seen in Figure 7.

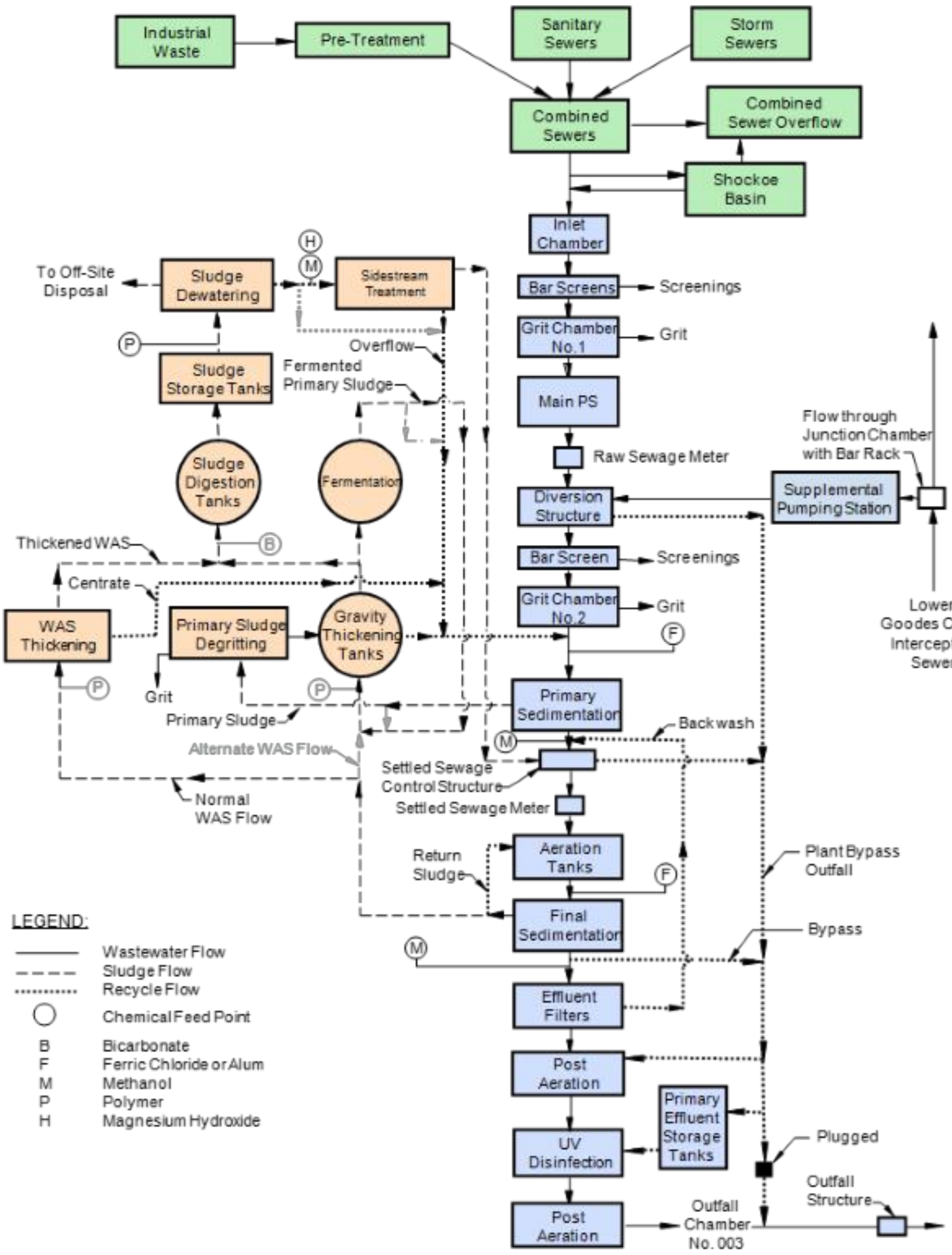

Figure 7. Complete WWTP flow diagram for wastewater flow, in a solid line, sludge flow in a dashed line, and recycle flow in a dotted line. Pretreatment processes are shown in green; wastewater processes are shown in blue and sludge processes are shown in orange.

Pretreatment is displayed in green, sludge in orange, and wastewater in blue. Wastewater flow is represented with a solid line, sludge flow with a dashed line, and recycled flow is represented with a dotted line. The following sections will describe the sludge treatment facilities, pumping units, and gas equipment.

2.1.1. Sludge treatment facilities

The sludge treatment facilities include thickening, storage, anaerobic digestion, and dewatering. The two main flows into the sludge treatment facilities come from primary sedimentation and from the secondary sedimentation after the aerobic tanks.

The WWTP is designed to offer flexibility in operation and offers alternative routes for wastewater and sludge treatment during special scenarios. The facilities related to anaerobic digestion are five tanks where digestion occurs, one storage tank, where uncontrolled fermentation likely takes place, two sludge control buildings and one operational waste gas burner. Currently, 100% of the biogas produced during digestion is burned in the waste gas burner. The size parameters for the digestion tanks are shown in Table 17.

Table 17. Fixed cover sludge digestion tank information.

Parameter	Value
Diameter of Tanks (m)	Varies to 29.3
Side Water Depth (m)	8.5
Hopper Depth (m)	3.2 to 3.5
Volume per tank (m^3)	6,626 to 6,711
Total Volume of 5 tanks (m^3)	33,414
Gas Pressure	0 Bar

In basic operation, the five digestors operate in parallel, as individual units, fed continuously one at a time. Sludge is pumped into the digestors from the Sludge Thickening Building where it is mixed with the thickened WAS, thickened primary sludge, and hot recirculating sludge. There are sludge heat exchangers located in the basement of the sludge control facilities. Mixed sludge is heated in the exchangers prior to entering the digestor. The digestor is continuously mixed by circulation of sludge using pumps. Gas from all digestors is collected in a common digestor gas system. The plant has three boiler centers, where biogas can be burned to produce energy and reduce dependency on natural gas.

Currently, all digested gas is burned in the waste gas installation located in sludge control building #2. The Digestors are heated using purchased natural gas. In addition, the sludge can be fermented prior digestion when it is stored continuously for a period. During this operation, Digestor No. 5 or Digestor No. 6 serve as fermentation tanks. These can also serve as unheated secondary digestion tanks for additional sludge stabilization, gravity thickening, and off-gassing biogas.

2.1.2. Pumping facilities

Sludge pumping equipment is located in the Sludge Control Buildings. The pumping equipment are comprised of:

- 9 Circulation Pumps – Displayed in Table 18
- 2 Sludge Booster Pumps
- 2 Sludge Feed Pumps

The power required for the circulation pumps was calculated using Equation 3.

$$P = \frac{Q \times \Delta h \times \rho \times g}{3.6 \times 10^6 \times \eta} \qquad (3)$$

Where: (i) P= power required for pumping (kW), (ii) Q = rated flow (m^3/h), (iii) Δh= total displacement head (TDH, m), (iv) ρ= sludge density (1000 kg/m3), (v) g= gravity (9.81 m/s^2), (vi) η= pump efficiency (%), and (vii) 3.6 x 10^6 = conversion factor. Source: Vogelesang (2008)

Table 18. Sludge circulation tanks.

Pump	Rated Capacity		Drive	Serve	Assumed efficiency[1]	Power (kW)
	Flow (m^3/h)	TDH (m)				
P1	91	11	Constant Speed	Tank #2	0.6	4.4
P2	182	18	Variable Speed	Tank #2	0.6	15.1
P3	182	18	Variable Speed	Tank #1	0.6	15.1
P4	91	11	Constant Speed	Tank #1	0.6	4.4
P5	227	8	Variable Speed	Dewatering	0.6	8.5
P6	182	18	Variable Speed	Tank #3	0.6	15.1
P7	91	11	Constant Speed	Tank #3	0.6	4.4
P8	182	18	Constant Speed	Tank #4	0.6	15.1
P9	182	18	Constant Speed	Tank #4	0.6	15.1

1. Source: Budzianowski, Wylock and Marciniak (2017)

2.1.3. Sludge heating

Sludge is heated to maintain the sludge at a constant 35 ºC through heat exchangers. The heat exchangers consist of:

- Supplement Heat Exchangers
- Sludge Heating Water Circulation Pumps
- Secondary Heating Pumps
- Steam Converters
- Expansion Tanks

The heating system contains one hot water loop, shown in blue on Figure 8, which consists of a supply and return flow. In addition, the sludge being heated is shown in brown, interacting with the blue how water loop. Red indicates a pump or valve is in operation. While green indicates a pump or valve is closed.

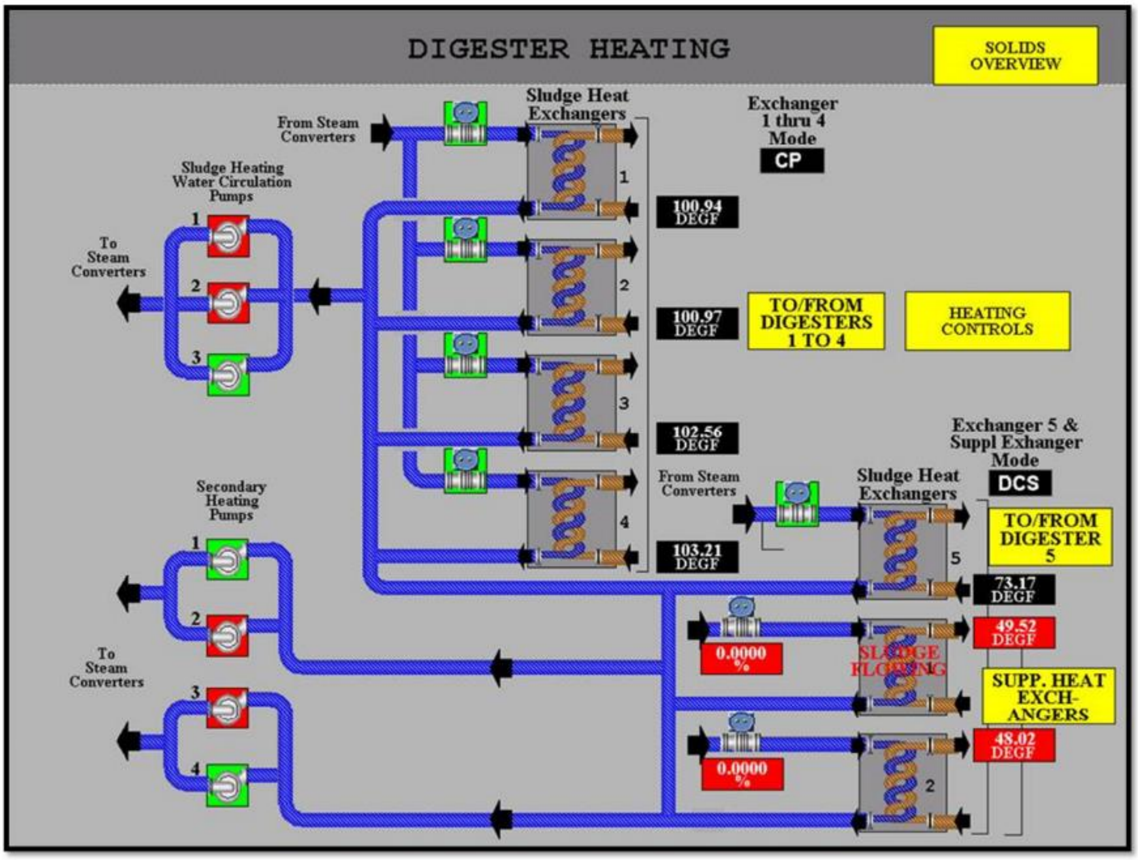

Figure 8. Digester Heating Plant DCS Graphic Screen.

2.1.4. Sludge gas equipment

Sludge gas produced during AD can be used for the boilers in three different boiler centers located in the Sludge Dewatering Building, the Administration Building, and the Blower Building as shown in Figure 9. Digester gas produced is shown in blue, and the natural gas bought from out of the WWTP is shown in green.

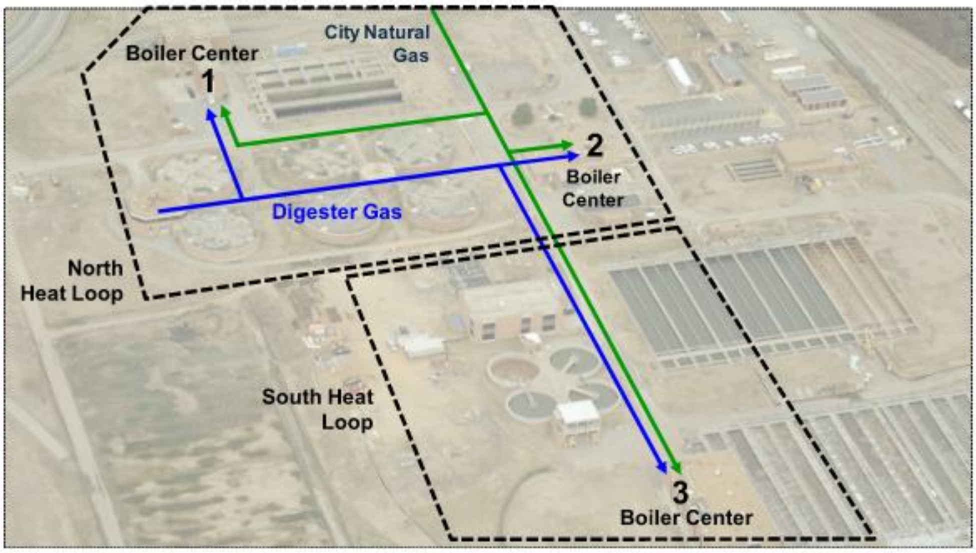

Figure 9. Existing system sludge gas connections in WWTP.

Information on the boiler centers is presented in Table 19.

Table 19. Existing boiler centers information.

Location	Installation Year	Boiler Rating (BHP) [1]	Installed Fuel Efficiency (%)	Heat Output (MMBtu/hr) [2]
Sludge Dewatering Building	1972	200	80	6.6
Sludge Dewatering Building	1988	250	80	8.4
Administration Building	1956	150	80	5.0
Administration Building	1970	150	80	5.0
Blower Building [3]	1972	125	80	4.1
Blower Building [3]	1989	70	80	2.3

1. 1 BHP (Boiler Horsepower) = 33,479 Btu/hr (13.15 times larger than a standard horsepower)
2. MMBtu/hr = million British thermal units per hour
3. Blower building boilers feed into south heat loop and do not contribute to digester heating.

Main sludge gas equipment included under the heading of Sludge Digestion is as follows:

- Sludge Gas Condensate Tank
- Accumulators and Sediment Trap

- Waste Gas Burners
- Flame Trap and Pressure Relief Valve Assembly
- Flame Traps and Flame Traps with Thermal Shut-Off Valve
- Assemblies
- Sludge Gas Compressors

2.1.5. Data collection

The WWTP is required under their NPDES permit to monitor discharges and internal operations and report analytical results to verify compliance status (US Environmental Protection Agency, 2010). The WWTP studied creates Monthly Effluent Report (MER) with data required under their NPDES permit. Data was extracted from the reports dating from January 2019 to January 2021. After January 2021, the WWTP stopped including any information on the anaerobic digestors in their MERs. Therefore, data was limited to two years.

This data was used to determine (i) the total solids (TS) destroyed in the anaerobic digestors (%); (Equation 4), (ii) the total solids loading to digestors (lb/d); (Equation 5), and (iii) volatile solids concentration entering the digestors (%VS W/W (% Volatile Solids weight/weight)).

$$TS_{destroyed} = \frac{TS_{dewatering} - TS_{thickeners}}{TS_{thickeners}} \quad (4)$$

$$Solid\ loading\ to\ digestors = Q\ x\ \rho_{sludge} \quad (5)$$

The MERs were also used to determine the alkalinity, pH, HRT, and temperature used in the anaerobic digestors.

2.1.6. Ambient temperature

The average monthly temperature, displayed in Figure 10, were used for the energy balance portion of the study. Given that the average ambient temperature ranges from a high value of 26.6 ºC to a low value of 3.8ºC, the energy to heat the sludge and the digestor varies significantly and therefore was calculated on a monthly basis.

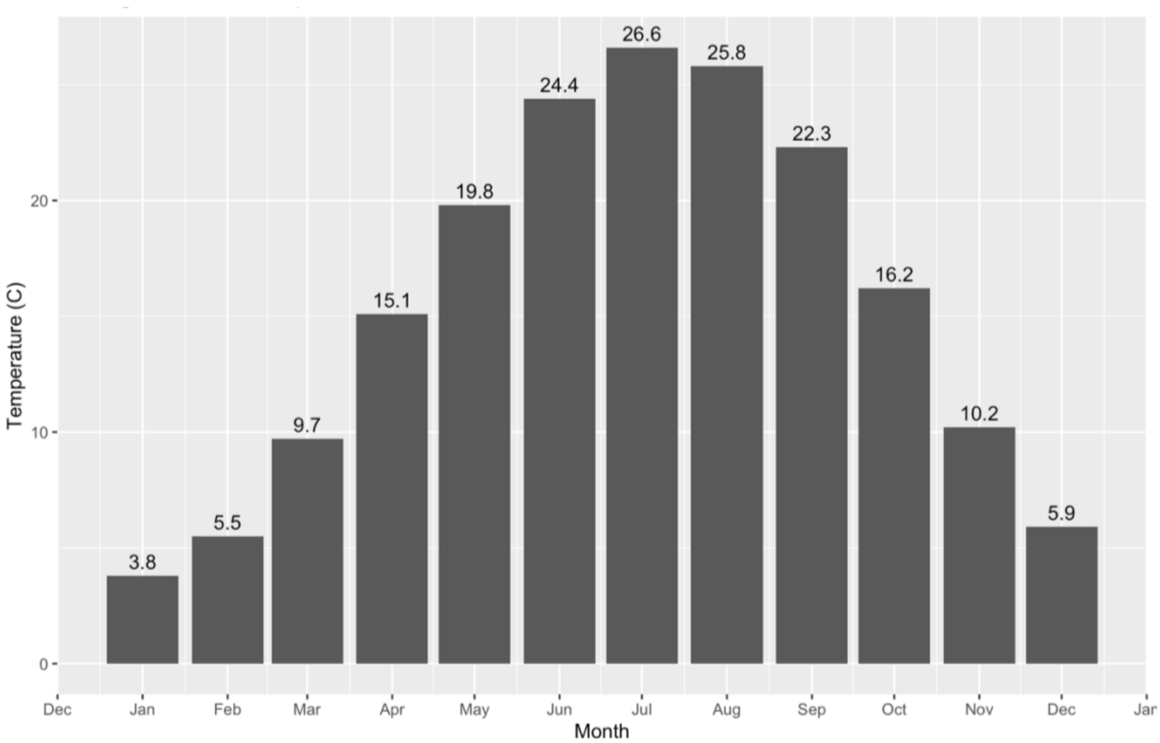

Figure 10. Average monthly ambient temperatures. Source: NOAA (2024)

The average monthly ambient temperature was considered to be constant throughout the day and the month and was used as T_{amb} in the equations presented in Section 2.2.3.

2.2. Data analysis

Data extracted from the MER's explained in Section 2.1.5 was then analyzed using: (i) stoichiometry, (ii) mass balance, (iii) energy balance and (iv) financial balance.

This section will further describe the methodology used to analyze the data and present the results.

2.2.1. Calculation of the theoretical yields of biogas and biomethane

Stoichiometry was used to calculate the theoretical yields of biogas and biomethane using the average of two sludge samples with elemental composition presented in Table 20.

Table 20. Elementary composition of biodegradable volatile solids in sewage sludge samples (SS). Source: Moscoviz and Jimenez (2021)

	C	H	O	N
SS 1	1	1.58	0.28	0.11
SS 2	1	1.72	0.21	0.05
Average=	1	1.65	0.25	0.08

Equation 1 represents a complete degradation in organic matter. A partial degradation of organic matter was also considered by using Equation 6.

$$CH_hO_oN_n(s) + a\ H_2O(l) \rightarrow b\ CH_4(g) + c\ CO_2(g) + dNH_4^+(l) + dHCO_3^-(l) + e\ CH_{1.8}O_{0.5}N_{0.2}\ (s) \quad (6)$$

Where:

$$\boldsymbol{a} = 1 - 0.25 \times h - 0.5 \times o + 1.75 \times n - (\frac{Y_{X/S}}{4.2}) \times (2.6 + 0.65 \times h - 1.3 \times o - 1.95 \times n)$$

$$\boldsymbol{b} = (1 - Y_{X/S}) \times (0.5 + 0.125 \times h - 0.25 \times o - 0.375 \times n$$

$$\boldsymbol{c} = 0.5 - 0.125 \times h + 0.25 \times o - 0.625 \times n - (\frac{Y_{X/S}}{4.2}) \times (1.1 + 0.275 \times h - 0.55 \times o - 0.825 \times n)$$

$$\boldsymbol{d} = n - (\frac{Y_{X/S}}{4.2}) \times (0.8 + 0.2 \times h - 0.4 \times o - 0.6 \times n)$$

$$\boldsymbol{e} = (\frac{Y_{X/S}}{4.2}) \times (4 + h - 2 \times o - 3 \times n)$$

$Y_{X/S}$ represents the overall biomass yield during AD in $gCOD_x\ (gCOD_{consumed})^{-1}$ (Moscoviz and Jimenez, 2021). The typical order of magnitude ranges from 0.10-0.15 $gCOD_x/gCOD_{consumed}$ (Batstone *et al.*, 2002). Furthermore, the percentage of CH_4 was calculated using Equation 7 where b equals the coefficient before CH_4 in the chemical equation and c equals the coefficient before CO_2 (Moscoviz and Jimenez, 2021).

$$\%CH_4 = \frac{100 \times b}{b + c} \quad (7)$$

Subsequently, stoichiometry was used to determine the ultimate methane yield($B_{0,max}$), calculated based on 1 kg of chemical oxygen demand (COD). The chemical equation is displayed in Equation 8.

$$CH_4(\mathrm{g}) + 2O_2(\mathrm{g}) \leftrightarrow CO_2(\mathrm{g}) + 2H_2O(v) \quad (8)$$

$B_{0,\,max}$ was calculated to be 0.35 Nm^3 CH_4 per kilogram of COD destroyed as shown by Equation 9.

$$B_{0,max} = 1\ kg\ O_2 \times \frac{1\ kmol\ O_2}{32\ kg\ O_2} \times \frac{1\ kmol\ CH_4}{1 kmol\ O_2} \times \frac{22.4\ Nm^3 CH_4}{1 kmol\ CH_4} = 0.35 \frac{Nm^3 CH_4}{kg\ COD_{destroyed}} \quad (9)$$

All calculations were done assuming normal conditions of temperature 273.15 K and pressure 101.325 kPa (NPT).

2.2.2. Mass balance calculation for anaerobic digestor and dewatering

Biogas production occurs in a continuously stirred tank reactor (CSTR). The chemical degradation of VS over time follows first order kinetics. It was assumed that the sludge entering the digestor was composed in equal parts of primary and secondary sludge. The kinetic constants (k) and biodegradability factors (f_i) presented in Vinardell et al. (2021) were used to calculate the average k and f_i factor for a sludge sample similar to the one entering the WWTP studied. These factors are shown in blue in Table 21.

Table 21. Chemical parameters used to calculate mass balance within the anaerobic digestor. Source: Vinardell et al. (2021)

Primary Sludge						
	PS_1	PS_2	PS_3	PS_4	PS_5	Average
k (1/d)[1]	0.23	0.23	0.31	0.29	0.25	0.26
f_i[2]	0.61	0.58	0.63	0.60	0.60	0.60
Secondary Sludge						
	SS_1	SS_2	SS_3	SS_4	SS_5	Average
k (1/d)[1]	0.22	0.18	0.16	0.20	0.24	0.20
f_i[2]	0.36	0.29	0.40	0.33	0.48	0.37
50% Primary sludge and 50% secondary sludge[3]						
k (1/d)[1]	0.23	0.21	0.24	0.25	0.25	0.23
f_i[2]	0.49	0.44	0.52	0.47	0.54	0.49

1.First order kinetics constant.
2.Substrate biodegradability. Calculated as: fi=B0/B0, max.
3. Assumed.

The schematic shown in Figure 11 was used to calculate the mass balance within the anaerobic digestor and the dewatering tank.

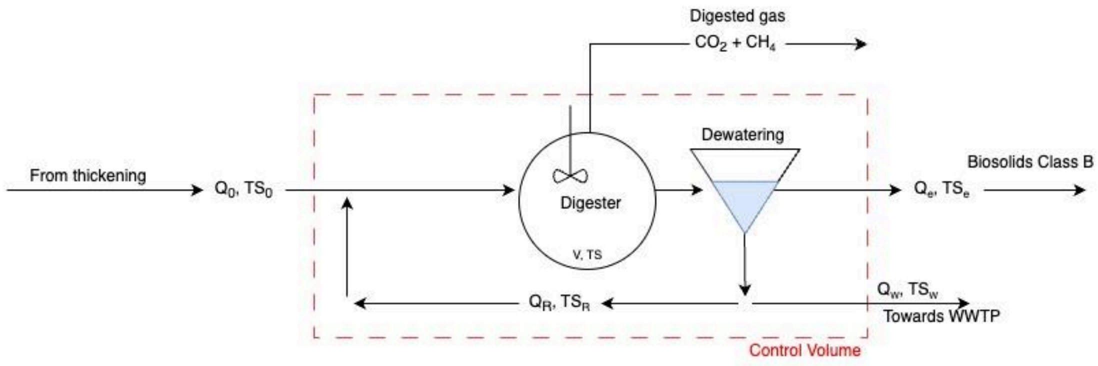

Figure 11. Mass balance schematic for anaerobic digestor and dewatering tank. Control volume is marked in red using dashed line.

The control volume is shown in red in Figure 11. Using the control volume from Figure 11, Equation 10 was derived applying mass balance principles.

$$V\frac{dTS}{dt} = Q_0TS_0 - (Q_eTS_e + Q_wTS_w) - \mathrm{k} \times \mathrm{TS} \times \mathrm{V} \quad (10)$$

Calculations were done using TS in % W/W. The mass balance assumed a control value composed of the 5 reactors operating in the plant. The outflows of the equation include the liquid (Q_W) and solid portion (Q_e) after dewatering. A closed system in steady state was assumed to calculate methane yield. Equation 11 is the result of these assumptions. Equation 11 only considers the AD process.

$$B = B_0 \times \frac{k\theta}{1 + k\theta} \qquad (11)$$

Where: (i) B_0= substrate ultimate methane yield (m^3 CH_4/ kg VS) = f_i x $B_{0,\,max}$, (ii) B = methane yield (m^3 CH_4/ kg VS), (iii) k= first-order kinetic constant (1/d), and θ= hydraulic retention time (days). Source: Vinardell et al. (2021)

The total solids (TS) concentration was calculated through Equation 12 by using a mass balance in TS considering a degradation of VS following first order kinetics. Equation 12 only considers the AD process.

$$TS = TS_0 \times \frac{1}{1 + k\theta} \qquad (12)$$

Where: (i) TS = concentration TS in the AD reactor (%), (ii) TS_0= concentration TS in the AD influent (%), (iii) k= first-order kinetic constant (1/d), and θ= hydraulic retention time (days). Source: Vinardell et al. (2021)

Assuming that the digested gas flow contains no water, Equation 13 was used to calculate the water leaving the digestor going back to the WWTP. This equation also assumed constant volume within the digestor and dewatering tank.

$Q_0 – Q_e – Q_W = 0$ (13)

Assuming that the system enters steady state during AD, Equation 14 was used to calculate the TS% in the biosolids Class B.

$$TS_0 Q_0 - Q_e TS_e - Q_w TS_w - \mathrm{k} \times \mathrm{TS} \ \times \mathrm{V} = 0 \quad (14)$$

Where, solving for TS_e:

$$TS_e = (TS_0 Q_0 - Q_w TS_w - \mathrm{k} \times \mathrm{TS} \ \times \mathrm{V}) \frac{1}{Q_e} \quad (14B)$$

Although a substantial amount of information to solve the mass balance was available through the MER, many other parameters were taken from available literature. The values used in the mass balance equation are summarized in Table 22. The values sourced through the MERs have been calculated by taking the average of the values while excluding any NULL and values equal to 0. The values sourced through calculations, were done using the equations described, assumed values, and literature sourced values.

Table 22. Calculated parameters for mass balance for anaerobic digestor and dewatering tank.

Name	Symbol	Value	Unit	Source
Water Flow Rate, In	Q_0	162.15	gpm	MER
Water Flow rate, In	Q_0	883.87	m^3/day	MER
Total Solids in liquid, out	TS_w	1.82	%	MER
Total Solids, in	TS_0	6.73	%	MER
Total digestor volume	V	1,180,000	ft^3	MER
Total digestor volume	V	33,400	m^3	MER
Solid flow rate, out	Q_e	88.5	Wet Ton/day	MER
Solid flow rate, out	Q_e	88.5	m^3/day	MER
Hydraulic retention time	Θ	35.9	days	MER
Density of sludge	ρ	1,000	kg/m^3	Metcalf and Eddy (2014)
Useful digestor volume	–	70	%	Assumed
%VS/%TS	–	60	%	Henze and Comeau (2008)
VS in Q_0	--	4.04	%	Calculated
VSC (VS Consumed)	--	43	%	Calculated
Organic loading rate	--	35,691	kg VS/d	Calculated
Water flow rate, out	Q_w	795.39	m^3/day	Calculated
Total solid in solid, out	S_e	24	%	Calculated
Total solids in reactor	TS	0.72	%	Calculated
Methane production rate	Q_{CH4}	5,440	Nm^3/d	Calculated

The mass balance diagram for the anaerobic digestor and dewatering tank was calculated to be the one presented in Figure 12.

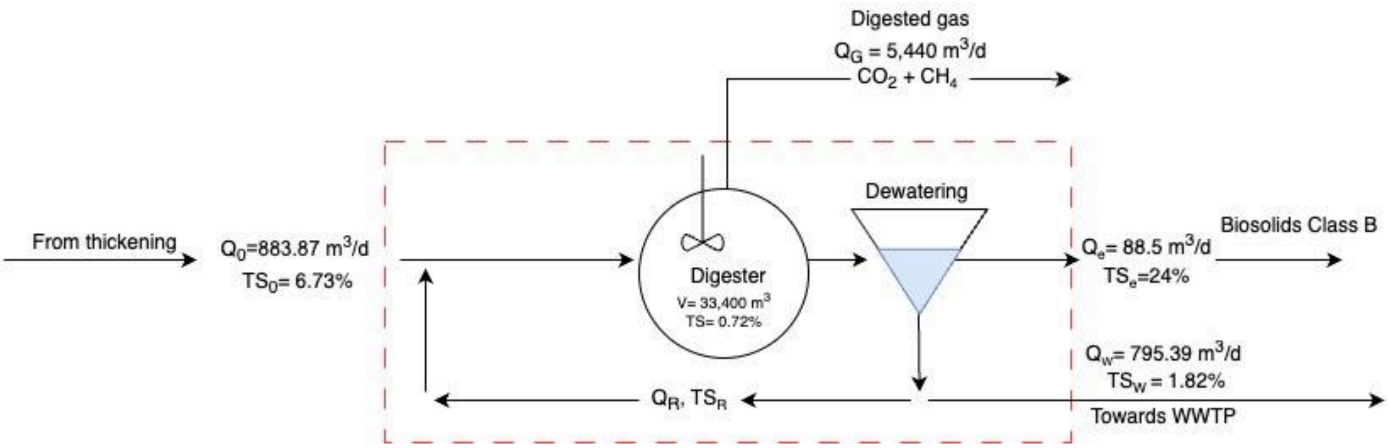

Figure 12. Calculated mass balance diagram for anaerobic digestor and dewatering tank. Control volume is marked in red using dashed line.

The calculations resulting from mass balance were subsequently used to calculate the energy balance.

2.2.3. Energy balance of anaerobic digestor

Values presented in Table 23 were extracted to estimate the typical energy consumption of the processes involved in the WWTP. These were then multiplied by the WWTP inflow, which was calculated to be equal to 235,008 m^3/d to determine the daily energy consumption of the WWTP.

Table 23. Typical energy consumption of various treatment processes on WWTP. Source: Metcalf and Eddy (2014)

Technology	Energy Consumption (kWh/m³)	
	Min	Max
Wastewater influent pumping	0.032	0.045
Screens	0.0003	0.0005
Grit removal	0.003	0.013
Trickling Filters	0.061	0.093
Return sludge pumping	0.008	0.013
Activated sludge	0.23	
Secondary settling	0.003	0.013
UV disinfection	0.01	0.05
Gravity thickening	0.0003	0.0016

Six scenarios were considered for biogas use presented in Figure 13. These scenarios include a) using a boiler to produce heat for digestor and sludge heating, b) using a microturbine unit as a combined heat power (CHP) device, c) using a molten carbonate fuel cell (MCFC) as a CHP device, d) a conventional CHP unit, e) biogas upgrading for injection to natural gas grid, and f) biogas upgrading for being transported as compressed biomethane.

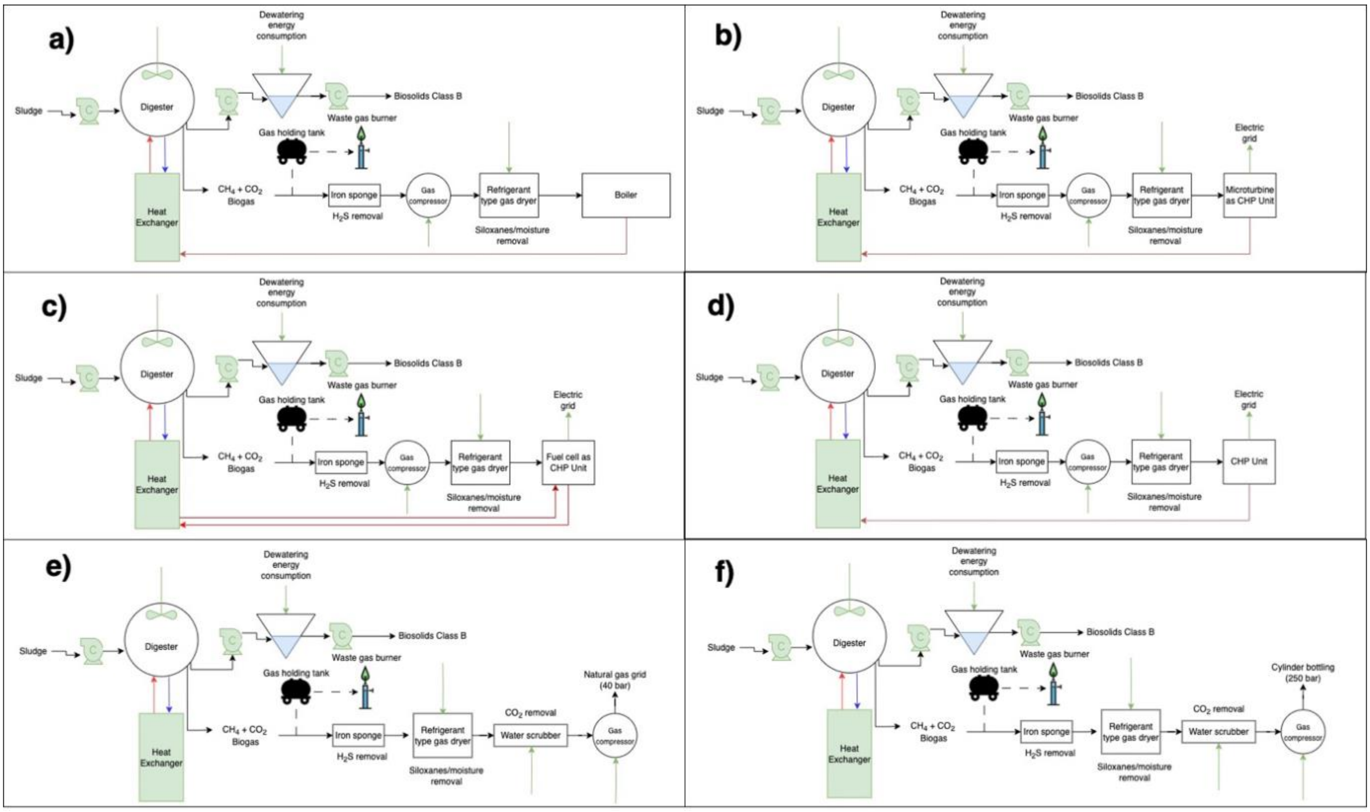

Figure 13. Scenarios for biogas use. Source: Gaikwad and Katti (2014) and Metcalf and Eddy (2014).

The parameters used for the energy balance include the energy input, consumed by the process, and the energy output, produced by the process. The energy input is the sum of the energy used for stirring, pumping, and heating the sludge. While the energy output is the sum of the energy produced, either through electricity and/or heat or through energy vectors, in the scenarios analyzed.

The following equations were used to calculate the energy input.

1. Energy required for heating the sludge ($E_{H,1}$)

$$E_{H,1} = Q \times C_P \times (T_{AD} - T_{sludge}) \times (1 - \eta_H) \quad (15)$$

Where: (i)Q = flow rate of sludge (m^3/d), (ii) C_P= specific heat of sludge (4.2 kJ/m^3 °C)[1] (iii) T_{AD}= temperature in digestor (ºC) (iv)T_{sludge}= sludge temperature (ºC)[2] (v) η_H= heat recovered from effluent sludge (85%)[3] Source: Pilli et al. (2015)
[1]Source: Metcalf and Eddy (2014)
[2]Assumed to be the same as the ambient temperature. See Figure 10.
[3] Assumed.

2. Energy required for heating the digestor ($E_{H,2}$)

$$E_{H,2} = \Sigma(k \times A) \times (T_{AD} - T_{amb}) \times 86.4 \times \eta_H \quad (16)$$

Where: (i) k = heat transfer coefficient (W/(m^2 °C)), (ii) A= surface area of digestor (m^2), (iii) T_{AD}= temperature in digestor (ºC), (iv) T_{amb}= ambient temperature (ºC)[1], (v)η_H= heat recovered from effluent sludge (85%)[2], and (vi) 86.4 = conversion coefficient of W into kJ/d.
[1] Varies monthly. See Figure 10.
[2] Assumed.

The heat transfer coefficient varies depending on the surface area of the reactor. The k values were extracted from Metcalf and Eddy (2014) and are displayed in Table 24.

Table 24. Heat transfer coefficients used with surface area.

	k (W/(m^2 °C))[1]	A (m^2)	Heat Loss (W/°C)
Inner concrete wall	5.1	778	3,965
Top Cover	1.9	605	1,149
Floor	1.7	605	1,028
		$\Sigma(k \times A) =$	6,142

1.Source: Metcalf and Eddy (2014)

3. Electric energy required for pumping sludge ($E_{E,1}$)

$$E_{E,1} = Q \times \theta \qquad (17)$$

Where: (i) Q = flow rate of sludge (m^3/d) and (ii) Θ = electricity consumption for pumping (kWh/m^3_{sludge})

The electricity consumption for pumping was calculated by converting the power in Table 18 to energy. The values were then summed based on the assumption that all pumps would run under normal WWTP conditions. Energy consumption values are displayed in Table 25.

Table 25. Energy consumption of pumps 1-9 in WWTP. Source: Table 18.

Pump	Energy consumed (kWh/m^3)
P1	0.0008
P2	0.0028
P3	0.0028
P4	0.0008
P5	0.0016
P6	0.0028
P7	0.0008
P8	0.0028
P9	0.0028
θ =	0.0179

4. Electric energy required for digestor mixing ($E_{E,2}$)

$$E_{E,2} = V \times \omega \times 24 \qquad (18)$$

Where: (i) V = volume of reactor (m^3), (ii) ω = electricity consumption for stirring (0.008 kW/$m^3_{digestor}$), and (iii) 24 = conversion factor from kW to kWh. Source: Metcalf and Eddy (2014)

5. Electric energy required for biogas compressing ($E_{E,3}$)

The power needed to compress the gas was calculated assuming it was an isentropic compression, without friction, internal leakage, and perfectly insulated.

$$E_{E,3} = \frac{k \times Z \times R \times T_1}{k-1} \times [\left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} - 1] \times Q_m \times \eta \qquad (19)$$

Where: (i) k=Gas isentropic coefficient (1.3067 for 33% CO_2 and 67% CH_4), (ii) Z = gas compressibility factor; assummed to be 1, (iii) R= gas constant (kJ/ kg K), (iv) T_1=Temperature into compressor (K) (assumed to be the same as temperature digestor, 35ºC = 308K) (v) P_1 = Pressure inlet compressor (14.8 kPa), (vi) P_2 = Pressure outlet compressor (kPa), (vii) Q_m=Compressor throughput (kg/s), and (viii) η = compressor efficiency (%); assumed to be 55%[1]. Source: Green (2007). [1] Source: Budzianowski, Wylock and Marciniak (2017)

The energy requirements for scenarios explored in this study are presented in Table 26.

Table 26. Energy requirements for compressing biogas.

Compressing energy for bottling (250 bar)	0.057	kWh/m^3
Compressing energy for combustion (1 bar)	0.004	kWh/m^3
Compressing energy for grid injection (14 bar)	0.018	kWh/m^3

Equations 20 and 21 were used to calculate the energy output.

1. Electric energy produced ($E_{E,4}$)

$$E_{E,4} = P_{CH_4} \times \eta_x \times \delta \qquad (20)$$

Where: (i) PCH_4 = methane production rate (Nm^3 CH_4/d), (Iii) η_x = efficiency of electric system[1], and (iii) δ= lower heating value of methane (35,800 kJ/m^3 CH_4).[2]
[1]Varies depending on the system. See Table 27.

Table 27. Efficiencies of electric system

Technology	**Efficiency – η_x (%)**	**Source**
Gas engine	33	Monteith et al. (2005)
Microturbine as CHP Unit	30	Metcalf and Eddy (2014)[1]
Fuel Cell	45	Metcalf and Eddy (2014)[1]

1Higher range of efficiencies taken from Metcalf and Eddy (2014) assuming new installation would have highest possible efficiency.

2. Energy as heat produced ($E_{H,3}$)

$$E_{H,3} = P_{CH_4} \times \psi_x \times \delta \qquad (21)$$

Where: (i) P_{CH4} = methane production rate (Nm^3 CH_4/d), (ii) ψ_x = efficiency of heat system[1], and (iii) δ= lower heating value of methane (35,800 kJ/m^3 CH_4).[2]
[1]Varies depending on the system. See Table 28.
[2] Source: Metcalf and Eddy (2014)

Table 28. Efficiencies of heat systems.

Technology	Efficiency – ψ_x (%)	Source
Gas Engine	40	Monteith et al. (2005)
Microturbine as CHP Unit	37	Metcalf and Eddy (2014)
Boiler	80	Table 19
Fuel Cell	40	Metcalf and Eddy (2014)

Assuming no accumulation of energy within the control volume, the electric balance and the heat balance are Equations 22 to 25 according to Cheng et al. (2021):

For electric balance:

$E_{E,Net} = E_{E,4} – E_{E,3} – E_{E,2} – E_{E,1}$ (22)

For heat balance:

$E_{H,Net} = E_{H,3} – E_{H,2} – E_{H,1}$ (23)

The total net energy is the following:

$E_{Net} = E_{E,4} – E_{E,3} – E_{E,2} – E_{E,1} + E_{H,3} – E_{H,2} – E_{H,1}$ (24)

The energy ratio equation is the following:

$$ER = \frac{Energy\ input}{Energy\ output} = \frac{E_{H,1}+E_{H,2}+E_{E,1}+E_{E,2}}{E_{H,3}+E_{E,3}} \qquad (25)$$

2.2.4. Economic evaluation

The economic evaluation was calculated subsequently from the mass and energy balance. The purpose was to determine the economic feasibility of the scenarios studied. The majority of the parameters used to calculate the capital expenditures (CAPEX), operating expenditures (OPEX), and revenue (R) were taken from available literature. The compressor cost was estimated using Equation 26.

$$Compressor\ Cost\ (\$) = 5840\ (P)^{0.82} \quad (26)$$

Where: (i) 5840 and 0.82 = Correlation factors, and (ii) P= power for compression(kW). Function estimated through correlation. Source: Douglas (1988)

CAPEX was then annualized using Equation 27. The net cost was calculated using Equation 28.

$$Annualized\ CAPEX\ \left(\frac{\$}{y}\right) = \frac{i \times (1+i)^t}{(1+i)^t - 1} \times CAPEX \quad (27)$$

$$Net\ Cost\ \left(\frac{\$}{y}\right) = Annualized\ CAPEX + OPEX - R \quad (28)$$

where (i) CAPEX = capital expenditures ($), (ii) R = revenue ($/y), (iii) OPEX = operating expenditures ($/y), (iv) i = interest rate (5%) and (v) t = project lifetime (20 years). Source: Vinardell et al. (2021)

The main revenue comes from electricity produced through combustion of biogas (Scenarios a, b and c), through the selling of the biomethane (Scenarios d and e), and through the selling of compressed biogas (Scenario f). Table 29 provides the unit prices for these revenue streams considered in the various scenarios. This analysis does not account for any revenue generated from the sale of byproducts, as they are not relevant to the study. Additionally, no taxes are expected to be levied on the products produced through this process due to Virginia Code 58.1-2250, which exempts alternative fuels from taxation.

Table 29. Revenue unit price.

Item	Price	Source
Electricity produced	\$0.11/kWh	Virginia Department of Energy (2022)
Natural gas purchased	\$0.025/kWh	City Sourced
Biomethane injection sale	\$0.0085/kWh	City Sourced
CNG	\$0.698/Nm^3	US Department of Energy (2024)
Production Tax Credit for Electricity from Renewables[1]	\$0.015/kWh	H.R.5376 (2022)

1 Assumed to meet prevailing wage and registered apprenticeship requirements.

3. Results

3.1. Digestor parameters

The study period from January 2019 to January 2021 was defined and analyzed. The average HRT for all 5 reactors was 35.93 days. The flow entering digestor was 162.15 gpm. The average values for temperature, pH, and alkalinity are presented in Table 30.

Table 30. Average temperature, pH and alkalinity by digestor

Digestor Number	Temperature (°C)	pH	Alkalinity (mg/L $CaCO_3$)
#1	36.9	7.1	4,434
#2	37.5	7.1	3,491
#3	36.7	7.1	3,190
#4	36.3	7.1	2,884
#5	37.2	7.1	3,153
Average	36.9	7.1	3,430

3.1.1. Digestor pH

Optimal pH for digestion is from 7.0-7.2. The average digestor pH in the study period was 7.09 varying slightly by digestor. Digestor 3 had the lowest average pH at 7.05 and Digestor 1 has the highest average pH at 7.13. All averages are within the optimal pH range. Figure 14 shows the recorded pH over the study period with a best fit curve.

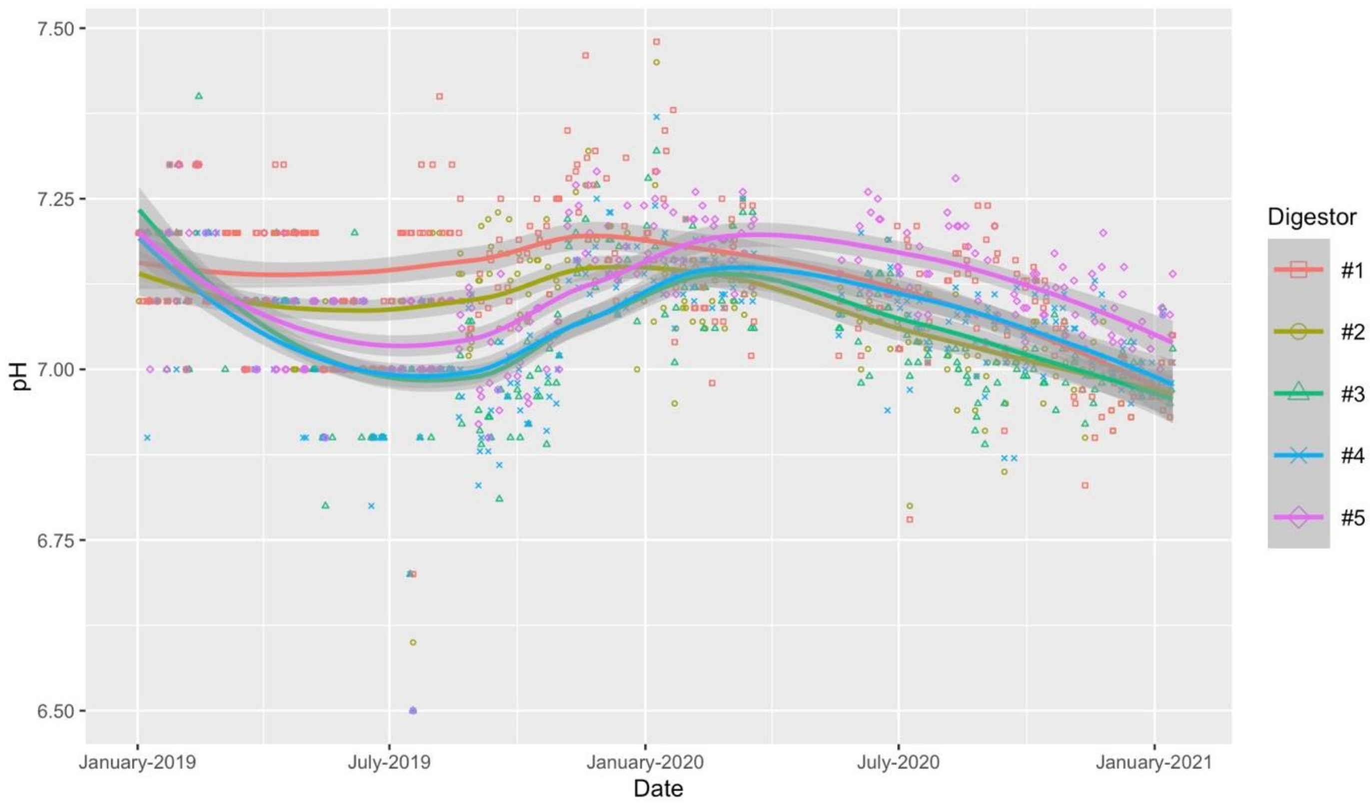

Figure 14. Digestors monitored pH from January 2019 to January 2021. Digestor #1 shown in red squares, Digestor #2 shown in olive green circles, Digestor #3 shown in green triangles, Digestor #4 shown in blue X, and Digestor #5 shown in purple diamonds. A best fit curve was calculated using R Studio.

3.1.2. Digestor alkalinity

A range from 2,000 to 4,000 mg/L as $CaCO_3$, is typically needed during anaerobic digestor to offset potential VFA accumulation and maintain the pH at or near neutral (Metcalf and Eddy, 2014). Figure 15 shows the alkalinity in the 5 digestors during the study period as well as a best fit curve representing the trends in the data.

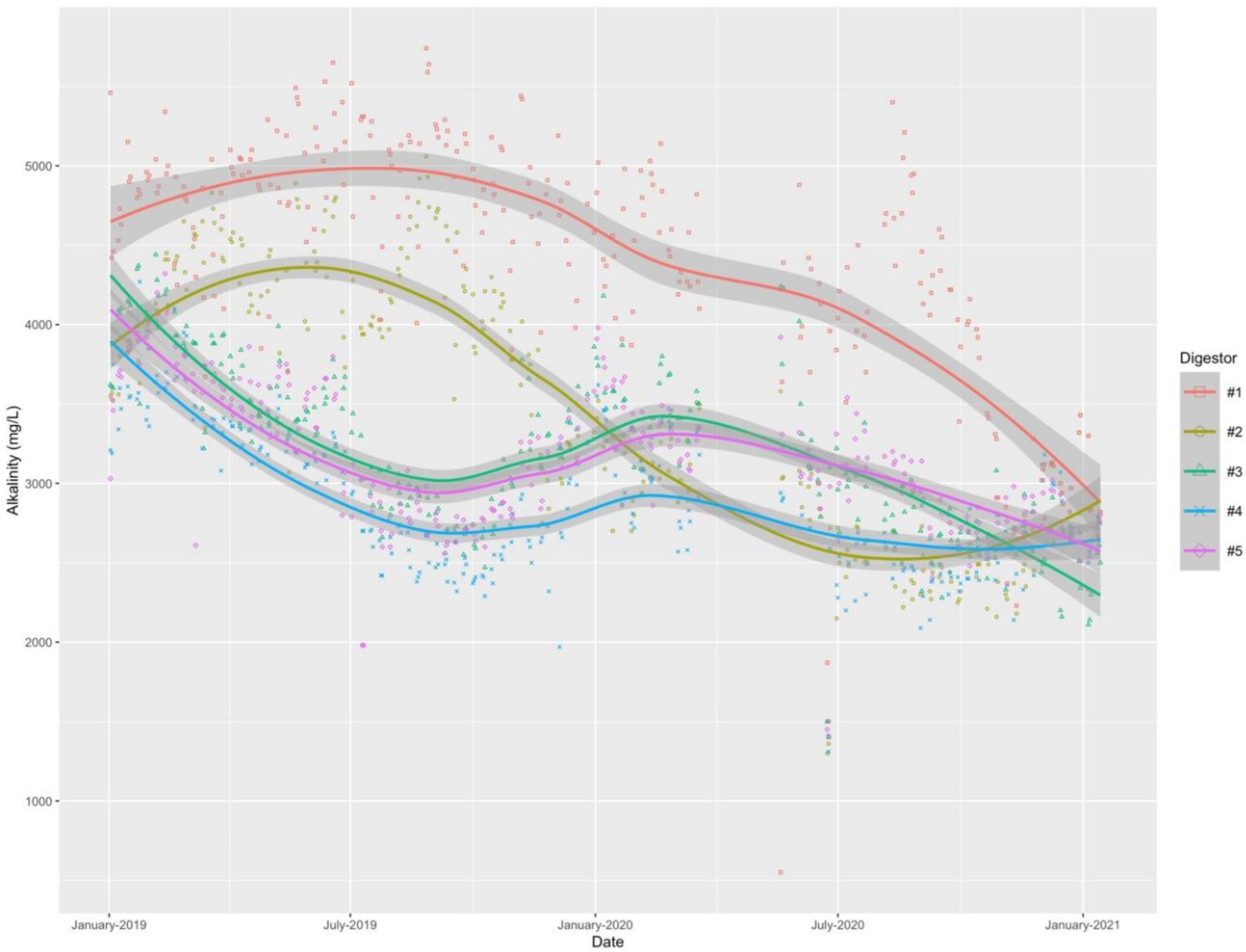

Figure 15. Digestor alkalinity (mg/L $CaCO_3$) from January 2019 to January 2021. Digestor #1 shown in red squares, Digestor #2 shown in olive green circles, Digestor #3 shown in green triangles, Digestor #4 shown in blue X, and Digestor #5 shown in purple diamonds. A best fit curve was calculated using R Studio.

Digestor 1 shows alkalinity values above 4,000 mg/L as $CaCO_3$ up to July 2020 when the values started to decrease. Digestor 2 shows alkalinity values higher than 4,000 mg/L as $CaCO_3$ during the first months of 2019 and alkalinity then decreased to the normal range. Digestors 3, 4, and 5 are within the normal range of alkalinity of anaerobic digestors.

3.1.3. Total solids reduction

An average of 72% of TS reduction was calculated during the study period considering the TS leaving the thickeners prior to construction and the TS entering the dewatering after digestion. This value is not a representation of the VS removal during anaerobic digestion but can be roughly related to the VS concentration. Figure 16 related the average pH of all digestors with the percentage of TS removed during digestion. No relationship between pH and TS removed can be concluded from the figure. pH of the digestors is maintained constant throughout the study period.

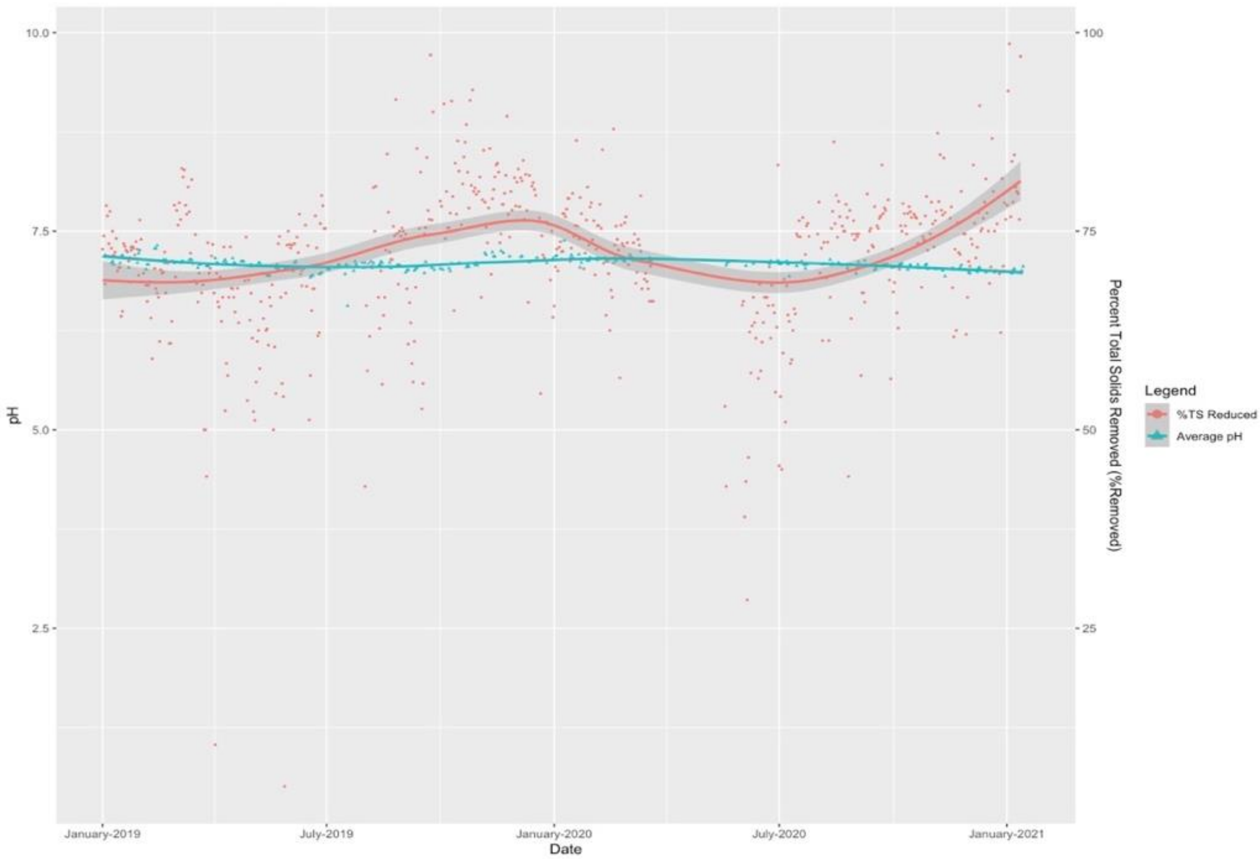

Figure 16. Average pH for 5 digestors (blue triangles) compared with %TS removed during digestion (red squares) from January 2019 to January 2021.

Figure 17 related the average alkalinity of all digestors with the percentage of TS removed during digestion. No relationship between the alkalinity and TS solids removed can be concluded from the figure. Average alkalinity decreased during the study period, although the pH could be kept constant in the system.

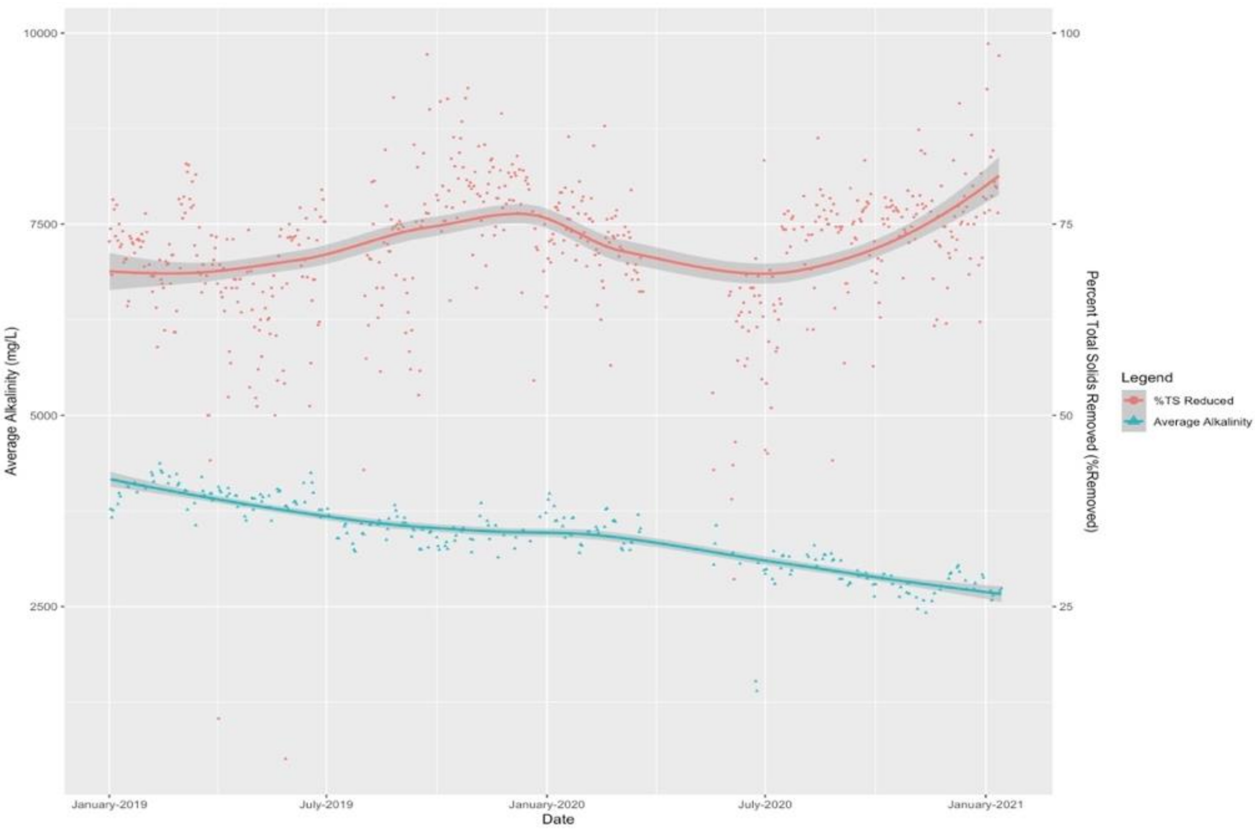

Figure 17. Average alkalinity (mg/L $CaCO_3$) for 5 digestors (blue triangles) compared with %TS removed during digestion (red squares) from January 2019 to January 2021.

3.2. Biogas theoretical yields

3.2.1. Stoichiometry

Using the values presented in Table 20, Equation 1 was converted to Equation 29.

$$CH_{1.65}O_{0.245}N_{0.08}(s) + 0.65H_2O\ (l) \rightarrow\ 0.82CH_4(\mathrm{g}) +\ 0.42CO_2(\mathrm{g}) +\ 0.08NH_3(l) \quad (29)$$

This equation gives a theoretical yield of 0.98 L CH_4/g $CH_{1.65}O_{0.245}N_{0.08}$ assuming a 100% TS consumption during the process.

Equation 6 contained the variable $Y_{X/S}$ that ranges from 0.10 to 0.15 g COD_X/g $COD_{consumed}$. The chemical equation was calculated using average of the entire range presented in Table 31.

Table 31. Calculations for values in Equation 6.

	$Y_{X/S}$= 0.1	$Y_{X/S}$= 0.11	$Y_{X/S}$= 0.12	$Y_{X/S}$= 0.13	$Y_{X/S}$= 0.14	$Y_{X/S}$= 0.15	Average
H_2O=	0.53	0.52	0.51	0.51	0.50	0.49	0.51
CH_4=	0.55	0.55	0.54	0.54	0.53	0.52	0.54
CO_2=	0.27	0.27	0.27	0.26	0.26	0.26	0.26
NH_4^+ and HCO_3^-=	0.06	0.05	0.05	0.05	0.05	0.04	0.05
$CH_{1.8}O_{0.5}N_{0.2}$=	0.12	0.13	0.14	0.15	0.16	0.18	0.15

The final chemical equation describing biogas production is displayed by Equation 30.

$$CH_{1.65}O_{0.245}N_{0.08}(s) + 0.51\, H_2O\ (l) \rightarrow\ 0.54\, CH_4(\mathrm{g}) +\ 0.26\, CO_2(\mathrm{g}) +\ 0.05NH_4^+(\mathrm{l}) + 0.05HCO_3^-(\mathrm{l}) + 0.15\, CH_{1.8}O_{0.5}N_{0.2}(s) \qquad (30)$$

Equation 30 gives a theoretical yield of 0.64 L CH_4/g $CH_{1.65}O_{0.245}N_{0.08}$ assuming a 100% consumption of organic matter fed to the bacteria. In addition, the methane theoretical production calculated using the methodology described in Section 2.2.2 are summarized in Table 32.

Table 32. Biogas theoretical production.

Equation	Nm^3 CH_4	Nm^3 CH_4/d	Nm^3 biogas/d	Nm^3 CO_2/d
Equation 29	240,300	9,080	13,660	4,590
Equation 30	157,500	5,950	8,870	2,930

3.2.2. Mass balance of anaerobic digestor and dewatering tank

The parameters in Table 33 were calculated using the methodology described in Section 2.2.2. The calculated methane production rate is 5,440 Nm^3/d. The TS leaving the centrifugal thickener (24% TS) is less than the standard 30% used in literature (Vinardell *et al.*, 2021).

Table 33. Mass balance calculation results.

Parameter	Symbol	Value	Units
VS in Q_0	--	4.04	%
VSC (VS Consumed)	--	43	%
Organic loading rate, in	--	35,691	kg VS/d
Water flow rate, out	Q_w	795.39	m^3/day
TS in solid, out	TS_e	24	%

Furthermore, digestor gas data was available from a 75-day monitoring period in 2012. Figure 18 shows the digestor gas production rate for the various methodologies considered. Average biogas rate during the total monitoring period equals 4,187 Nm^3/day. When considering the digestor's HRT equals 36 days, the calculated average for the HRT during the monitoring period equals 5,160 Nm^3/day. This is only 280 Nm^3/day less than what was calculated using the mass balance. The rate calculated using stoichiometry and assuming a full degradation of organic matter yielded the highest rate, but it was still 1,523 Nm^3/day less than the peak experienced in Day 4 of the monitoring period.

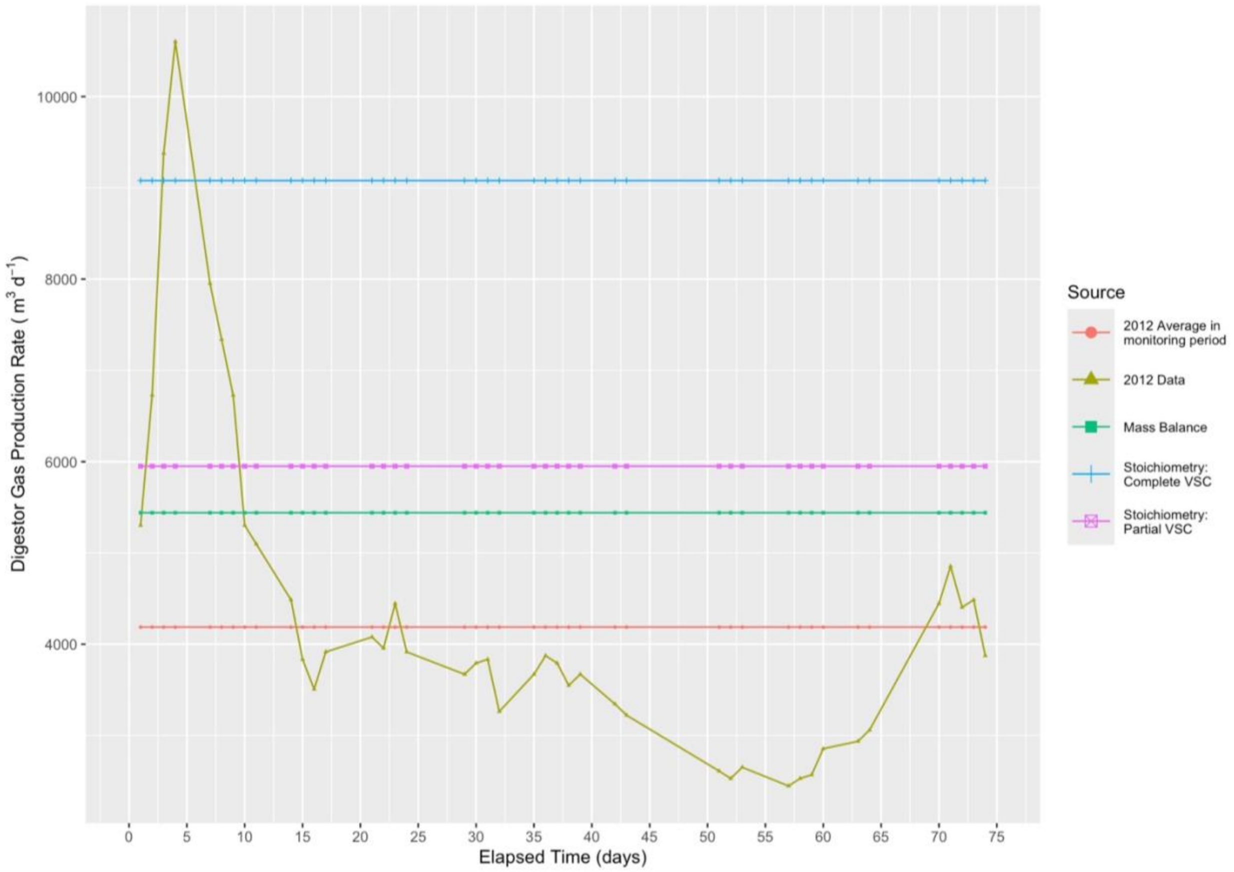

Figure 18. Calculated digestor gas production rate compared to monitored 2012 digestor gas production rate, in olive green triangles. Production rate calculated are shown in green squares when calculated using mass balance, in blue + when calculated assuming complete volatile solid consumptions (VSC) using Equation 1, and in purple squares when calculated assuming partial VSC using Equation 3.

The mass balance results are within the expected range when calculating theoretical values. The differences between the 2012 data and values calculated are presented in Table 34.

Table 34. Differences from 2012 monitoring data.

	Mass Balance	**Stoichiometry: Complete VSC**	**Stoichiometry: Partial VSC**
Difference from 2021 Data	23%	54%	30%

These differences can be due to various reasons further discussed in Section 5.

3.3. Energy balance of anaerobic digestor

The total energy consumption for the WWTP was estimated using the minimum and maximum ranges presented in Table 23. The resulting energy consumption is presented in Table 35. The table has a subtotal for the sludge related processes and a subtotal for the rest of the treatment processes in the plant. The activated sludge process was estimated to be the process that consumes the most energy in the plant. Other processes that consume significant amounts of energy include trickling filters, UV disinfection, and influent pumping. of energy include trickling filters, UV disinfection, and influent pumping.

Table 35. Estimate WWTP Energy Consumption.

Technology	Energy Consumption (kWh/d)	
	Min	Max
Wastewater influent pumping	7,520	10,575
Screens	71	118
Grit removal	705	3,055
Trickling Filters	14,335	21,856
Return sludge pumping	1,880	3,055
Activated sludge	54,052	
Secondary settling	705	3,055
UV disinfection	2,350	11,750
Gravity thickening	71	376
SUBTOTAL =	81,689	107,892
Pumping Sludge	79	79
Sludge Dewatering	11	11
Mixing	35	35
Compressing energy	20	308
PSA	0	1,714
SUBTOTAL =	146	2,148
TOTAL =	**81,834**	**110,040**

The values in Table 35 were assumed to be constant throughout the entire year. Furthermore, Table 36 presents values for the AD heat requirements that vary monthly based on the average ambient temperature shown in Figure 10. The heating requirements are as expected; increasing in colder temperatures and decreasing in warmer temperatures. The energy required to heat the digestor is insignificant during the month of July where ambient temperatures are nearly equal to operating temperatures under mesophilic conditions.

Table 36. Heating requirements varying monthly.

Month	Energy required for heating the sludge ($E_{H,1}$) (kWh/d)	Energy required for heating the digestor ($E_{H,2}$) (kWh/d)
January	24,922	24
February	23,637	23
March	20,462	20
April	16,394	16
May	12,910	12
June	9,449	9
July	7,790	7
August	8,354	8
September	11,024	11
October	15,591	15
November	20,100	19
December	23,330	22

The net energy for AD treatment calculated in kWh/d is displayed in Table 37. Scenario c produces the highest net energy while the boiler produces a net energy of 0 because it only produces energy as heat. Therefore, the excess heat produced during the combustion process, is lost. Gas engines and microturbines produce a comparable amount of energy when compared to the MCFC. Biogas bottling and injection to the grid only consumed energy and increased the total energy used by the WWTP. Biogas bottling consumed more energy than injecting to the grid due to a higher energy requirement to compress biogas into a cylinder bottle.

Table 37. Net energy for anaerobic digestion (AD) (kWh/d)

Month	Scenario a	Scenario b	Scenario c	Scenario d	Scenario e	Scenario f
January	0	10,173	19,639	13,329	-26,884	-27,093
February	0	11,459	20,925	14,615	-25,598	-25,808
March	0	14,638	24,103	17,793	-22,420	-22,629
April	0	18,710	28,176	21,865	-18,348	-18,557
May	0	22,197	31,663	25,352	-14,861	-15,070
June	0	25,661	35,127	28,817	-11,396	-11,605
July	0	27,321	36,787	30,477	-9,736	-9,946
August	0	26,757	36,223	29,912	-10,301	-10,510
September	0	24,085	33,551	27,240	-12,973	-13,182
October	0	19,513	28,979	22,668	-17,545	-17,754
November	0	15,000	24,466	18,155	-22,058	-22,267
December	0	11,767	21,233	14,922	-25,290	-25,500
AVERAGE=	**–**	**18,940**	**28,406**	**22,095**	**-18,117**	**-18,327**

The boiler produces a maximum of 42,070 kWh/d when burned completely. The digestor requires a maximum of 24,946 kWh/d to maintain mesophilic conditions as seen in Table 38. This means that the minimum amount of biogas that would still be burned is 41%, equivalent to 2,214 Nm^3/d, and the maximum amount of methane that would still be burned is 81%, equivalent to 4,432 Nm^3/d. This is a significant amount of methane that is currently not being valorized.

Table 38. Boiler balance for anaerobic digestor heating needs.

Month	Heat Required (kWh/d)	Methane required to heat digestor (Nm^3/d)	% Methane left	Excess Methane (Nm^3/d)
January	24,946	3,226	41%	2,214
February	23,660	3,060	44%	2,381
March	20,482	2,649	51%	2,792
April	16,409	2,122	61%	3,318
May	12,922	1,671	69%	3,769
June	9,458	1,223	78%	4,217
July	7,798	1,008	81%	4,432
August	8,362	1,081	80%	4,359
September	11,034	1,427	74%	4,014
October	15,606	2,018	63%	3,422
November	20,119	2,602	52%	2,839
December	23,352	3,020	44%	2,421

This raises a concern of using only a boiler to produce heat, when the opportunity of producing electricity exists.

The calculated energy ratio for AD treatment is displayed on Figure 19. No energy ratio for biogas bottling and injection into the grid could be calculated given that there was no heat or electricity output in the process. The energy output is biomethane which would be used outside WWTP and would not impact the energy input. MCFC produced 5.65 times more energy than required for AD at its peak. Meanwhile, the gas engine and microturbine produced 4.85 and 4.45 times more energy than necessary for the process.

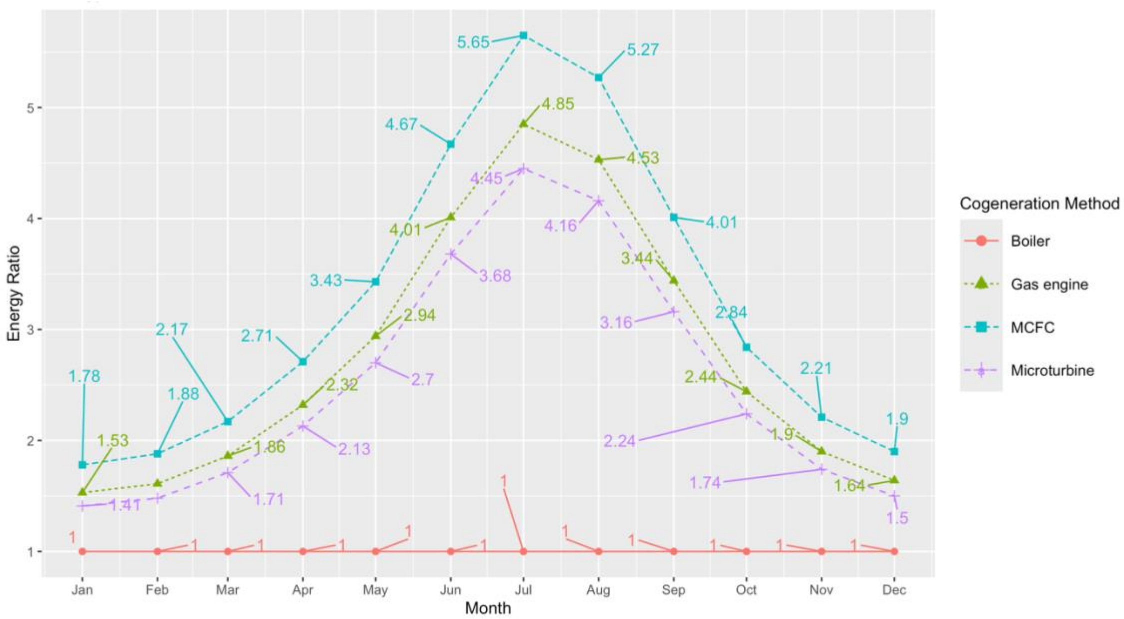

Figure 19. Yearly energy ratio, plotted monthly, for cogeneration methods considered. Boiler is shown in red circles, gas engine is shown in green triangles, molten carbonate fuel cell (MCFC) is shown in blue squares, and microturbines is shown in purple crosses.

The energy ratio is promising for all cogeneration methods except for the boiler, given that much of the heat produced by the boiler is lost. The net energy was then compared to the entire WWTP consumption to see the percent reduction of electric demand for the plant. Figure 20 shows the range considering the minimum and maximum values in Table 35 as well as considering the monthly variance of heat demand for AD process. MCFC yields reductions near 45% at its peak (minimum WWTP energy requirements, and July) while the boiler yields reductions higher than 40% if the heat produced is used in other processes of the plant. Gas engine averages at 23% energy reduction while microturbine has an average of 19% reduction. All of these are significant reductions to the energy demands of the WWTP.

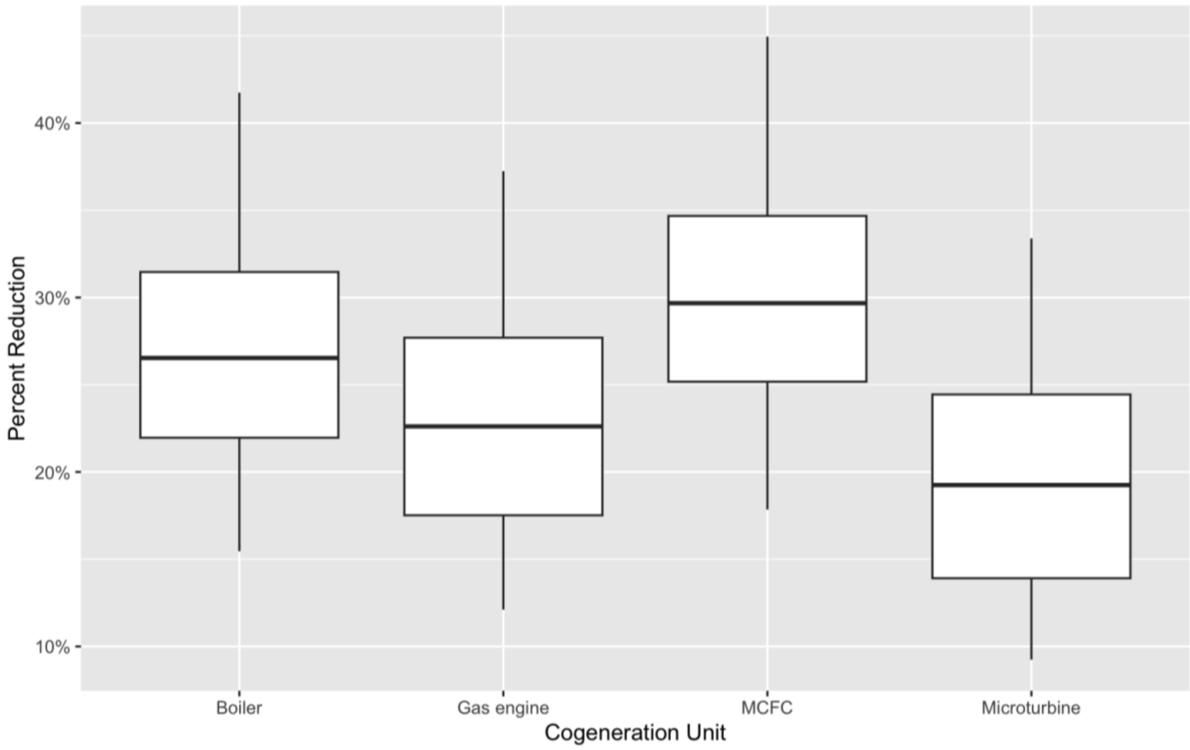

Figure 20. Energy demand percent reduction in the WWTP based on cogeneration methods from left to right: Boiler, gas engine, MCFC, and microturbine.

MCFC, followed by gas engine, and microturbine were the scenarios that produced the highest amount of energy. The boiler system has the possibility of reducing the WWTP energy consumption, only if there is more machinery available that requires heat. Biogas bottling and injection into the grid did not yield favorable results. An increase in the energy demand for the WWTP is not recommended. Although energy balance results for MCFC, gas engine, and microturbine are favorable, an economic evaluation was conducted to explore the feasibility of incorporating these cogeneration methods into the WWTP.

3.4. Economic evaluation

The financial balance conducted will be summarized in this section. Table 39 shows the annualized CAPEX for the scenarios considered in this study. MCFC had a total capital cost exceeding $21M, which is reduced to more than $14M with tax incentives. The unit equipment cost for MCFC was 55 times higher when compared to the cheapest unit cost which is the boiler. The annualized CAPEX for MCFC being higher than $1M makes this option unfeasible for the WWTP.

Table 39. CAPEX calculations for biogas use in boilers, gas engine, microturbine, MCFC, biogas bottling, and grid injection.

Parameter	Unit	Boiler	Gas Engine	Microturbine	MCFC	Biogas bottling[1]	Grid Injection[1]	Comments
Capacity	kW	1,040	730	660	990	230	230	Source: Mass and Energy Balance
Unit Capital Equipment Cost	$/kW	167	1,500	2,688	9,270			Source: Monteith et al. (2005)
Energy Equipment	$	173,680	1,095,000	1,774,080	9,177,300			
Biogas cleaning equipment	$	572,154	572,154	572,154	572,154	572,154	572,154	Source: Bauer et al. (2013) Assumed iron sponge, compressor, and refrigerant type dryer)
CO^2 Removal (PSA Unit)	$					1,246,766	1,246,766	Source: $5,500/(Nm3/h) from Ullah Khan et al. (2017)
Compressor Equipment	$					641,582	252,803	Source: Equation (26
Total Equipment Cost	$	745,834	1,667,154	2,346,234	9,749,454	2,460,502	2,071,723	
Installation	$	298,334	666,862	938,494	3,899,782	984,201	828,689	Assuming 40% Cost Factor
Building	$	600,000	600,000	600,000	600,000	600,000	600,000	Assuming $400/SF, for 1500 SF
Electrical	$	111,875	250,073	351,935	1,462,418	369,075	310,758	Estimated 15% equipment cost
I&C	$	74,583	166,715	234,623	974,945	246,050	207,172	Estimated 10% equipment cost
Contingency	$	149,167	333,431	469,247	1,949,891	492,100	414,345	Estimated 20% equipment cost
Engineering services	$	186,459	416,789	586,559	2,437,364	615,125	517,931	Estimated 25% equipment cost. Includes design and construction.
Total Capital Cost	$	2,166,251	4,101,023	5,527,091	21,073,853	5,767,054	4,950,618	

Parameter	Unit	Boiler	Gas Engine	Microturbine	MCFC	Biogas bottling[1]	Grid Injection[1]	Comments
Tax credit	$	649,875	1,230,307	1,658,127	6,322,156	1,730,116	1,485,186	Source: Inflation Reduction Act incentive - 30% tax credit (H.R.5376, 2022)
Real Capital Cost	$	1,516,376	2,870,716	3,868,964	14,751,697	4,036,937	3,465,433	Total Capital Cost minus tax credit incentive
Annualized CAPEX	$/yr	121,678	230,354	310,456	1,183,714	323,934	278,075	

[1]Capacity and unit capital equipment shown in Nm3/h and $/Nm3, respectively.

Table 40 shows the OPEX for the scenarios considered. The operation and maintenance (O&M) for the boiler system has the lower cost while the biogas bottling, and grid injection scenarios had the highest O&M cost. This is due to the high operating cost of the PSA unit to removed CO_2 prior to bottling or grid injection. MCFC had the second highest O&M cost, significantly higher than other cogeneration methods. This is likely due to the complicated process behind MCFC and the need for expertise personnel to work on the cogeneration.

Table 40. Annual OPEX for biogas use in boilers, gas engine, microturbine, MCFC, biogas bottling, and grid injection.

Parameter	Unit	Boiler	Gas Engine	Microturbine	MCFC	Biogas bottling[1]	Grid Injection[1]	Comments
Energy Maximum Capacity	kWh/d	24,946	38,389	35,233	44,699	5,440	5,440	Source: Mass and Energy Balance - electrical
Unit Operational Cost	$/kWh	0.002	0.023	0.020	0.041	0.430	0.430	Source: Monteith et al. (2005) and Ullah Khan et al. (2017)
O&M Yearly Cost	$/yr	18,210	322,273	257,204	668,923	853,876	853,876	
Iron Sponge O&M	$/yr	11,000	11,000	11,000	11,000	11,000	11,000	
Total O&M	$/yr	29,210	333,273	268,204	679,923	864,876	864,876	

1Capacity and unit capital equipment shown in Nm3/d and $/Nm3, respectively.

Table 41 shows the annualized revenue for the scenarios considered. Due to the high electrical efficiency of the MCFC, it is expected that this cogeneration method gives more than $2M of revenue annually. Gas engine and microturbine have similar revenues nearing the $2M, while the boiler has the lowest revenue of $200k.

Table 41. Annualized revenue for biogas use in boilers, gas engine, microturbine, MCFC, biogas bottling, and grid injection.

Parameter	Unit	Boiler	Gas Engine	Microturbine	MCFC	Biogas bottling	Grid Injection	Comments
Electricity Production	kWh/d	-	38,389	35,233	44,699			Source: Mass and Energy Balance - electrical
Biogas produced	m3/d					5,440	5,440	Source: Mass and Energy Balance - electrical
Savings	$/yr	228,778	228,778	228,778	228,778			Natural gas purchased at $0.025/kWh. Source: City Data
Revenue	$/yr	-	1,751,484	1,607,526	2,039,399	1,386,059	542,764	Source: Table 29
Total revenue	$/yr	228,778	1,980,261	1,836,304	2,268,176	1,386,059	542,764	Sum of revenue and savings.

The net cost for the six different scenarios studied is presented in Figure 21. The only option expected to have an annual cost is injecting the biogas into the grid with a $600,187 annual cost. Therefore, injecting biomethane into the grid is not an economical viable option without considering potential subsides.

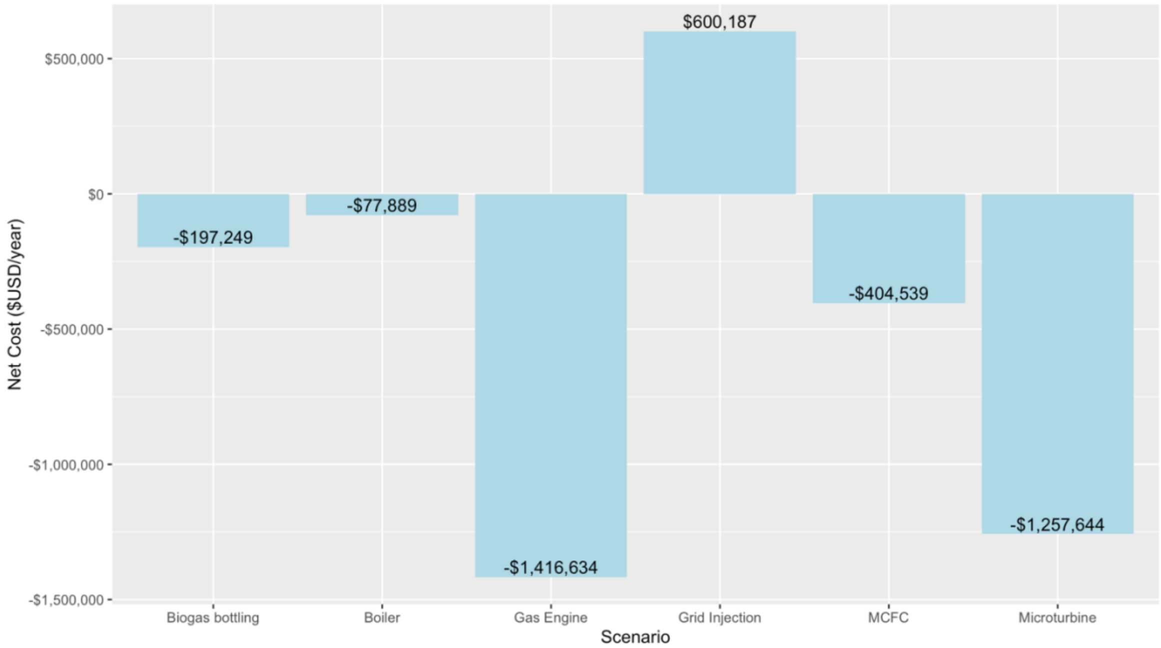

Figure 21. Net cost for biogas use in boilers, gas engine, microturbine, MCFC, biogas bottling, and grid injection.

The gas engine CHP unit is the most financially advantageous option, generating an annual profit exceeding $1.4M. The microturbine is also a viable alternative. Refurbishing the existing boiler yields the lowest profit among the profitable options but utilizing the excess biogas within the plant could potentially enhance the financial benefits. Biomethane bottling, however, is not a profitable option due to the high operational and capital costs, as well as the complexity of selling bottled biomethane to end-consumers. MCFC could be profitable, despite its high capital costs make it an unfeasible option.

4. Sustainability analysis and ethical implications

A sustainability analysis was done on the scenarios explored for biogas use and for the process of creating this thesis document. There are no ethical implications in the scenarios explored for biogas use nor in the way this master's thesis was created.

In Virginia, an average of **291 g CO_2 eq/kWh** was produced considering all energy sources throughout the state (U.S. Energy Information Administration, 2023). This value is used as the emission factor to calculate the CO_2 emissions for the anaerobic digestion process. This value was used to calculate the CO_2 emissions during AD in the scenarios considered for biogas use presented in Table 42. A negative value in the table represents neutral CO_2 emissions given that the combustion of biogas does not release anthropogenic CO_2 given that the biogas comes from waste streams. A positive value in the table represents an increase in CO_2 emissions given that energy produced is not directly used in the WWTP and therefore the WWTP increases its use of natural gas.

Table 42. CO_2 emissions (kg CO_2/d) in the anaerobic digestion process for biogas use in boilers, gas engine, microturbine, MCFC, biogas bottling, and grid injection.

Month	Gas engine	Microturbine	Fuel Cells	Boiler	Gas bottling	Injection to grid
January	-3,881	-2,963	-5,719	-4,953	7,890	7,829
February	-4,256	-3,337	-6,093	-5,328	7,515	7,454
March	-5,181	-4,263	-7,019	-6,253	6,590	6,529
April	-6,367	-5,448	-8,205	-7,439	5,404	5,343
May	-7,383	-6,464	-9,220	-8,455	4,388	4,328
June	-8,392	-7,473	-10,229	-9,464	3,380	3,319
July	-8,875	-7,956	-10,713	-9,947	2,896	2,835
August	-8,711	-7,792	-10,548	-9,783	3,061	3,000
September	-7,933	-7,014	-9,770	-9,005	3,839	3,778
October	-6,601	-5,682	-8,439	-7,673	5,170	5,109
November	-5,287	-4,368	-7,125	-6,359	6,484	6,423
December	-4,346	-3,427	-6,183	-5,417	7,426	7,365

As expected, fuel cells give the highest CO_2 reduction given that it is the most efficient CHP unit. Also, as expected, the month of July yields that highest CO_2 reductions given that the sludge requires less energy to achieve mesophilic temperatures during the warmest month. In the contrary, in December there are the least CO_2 reductions and the highest CO_2 emissions for those scenarios where the energy is not utilized in the WWTP. Fuel cells, followed by the boiler, produced the highest CO_2 emissions reductions due to its energy reductions in the WWTP.

Considering that the values in Table 42 are in kg CO_2/d, the yearly values were also calculated in this sustainability analysis. These yearly values are presented in Table 43.

Table 43. Yearly CO_2 emissions for biogas use in boilers, gas engine, microturbine, MCFC, biogas bottling, and grid injection.

	Gas engine	Microturbine	Fuel Cells	Boiler	Gas bottling	Injection to grid
tons CO_2/year	-2,594	-2,224	-3,333	-3,025	2,143	2,118

These values are considerable and should be considered when proposing a recommendation to the WWTP for its biogas use.

The sustainability analysis for the completion of this project was done using the power consumption for a MacBook Air (M1, 2020). The power consumption was 0.21W when the computer was on sleep mode and 3.30W when the computer was with the display on (Apple Inc, 2020). Work on the project started on 2/14/2024 and was completed by 6/26/2024. This is equivalent to 96 business days and 37 weekend days. During a business day, the computer was with the display on for 4 hours and on Sleep Mode for 20 hours. During the weekend, it was on Sleep Mode for 24 hours. The CO_2 emissions factor in Spain is **260 g CO_2/kWh** (CNMC, 2024). For the completion of this project, *830 g CO_2* were produced. This value is negligible when compared to the daily or yearly values shown in Table 42 and Table 43, respectively. Therefore, it is concluded that the completion of this thesis project had little to no impact on the environment.

5. Discussion

The stoichiometry results show theoretical values of biomethane production rates under ideal conditions within the digestor. It is concluded that the complete degradation of organic matter only happens to a portion of the sewage sludge, probably around the peak of the 2012 data shown on Figure 18. Most of the organic matter in the sludge gets partially degraded. Further sludge sampling could determine the percentage of organic matter that is completely degraded in the process. The mass balance results are also theoretical values using literature kinetic constants to approximate the amount of biomethane produced. The three calculated rates where above the average values measured in 2012. pH, temperature, and alkalinity are well within the expected range; therefore, these are not limiting the methane production reaction rate. The lower average biogas production range when compared with theoretical values could be attributed to the presence of inhibitory organic compounds that are limiting the growth rate of methanogenic bacteria. It is suggested to the WWTP to sample sludge prior and post digestion to report the presence of the inhibitory organic compounds shown on Table 2. Sampling should also include total N and total P in sludge. It is also recommended to the WWTP to add an automatic biogas reader to have real-time data for biogas production rate, especially considering that the use of biogas within the plant varies seasonally. This way the WWTP can react proactively when there is a change in the biogas production rate due to inhibitory organic compounds, temperature fluctuations, pH changes or any other issue within the digestor.

The energy balance results yield positive results for all scenarios considered because they produce electricity, heat, biomethane, or a combination of those. It is important to note that injecting biomethane into the grid or compressing them into gas cylinders would increase the electricity demand for the plant. This makes these scenarios not energetically favorable in the complete WWTP energy balance. These two scenarios are not recommended for implementation in the WWTP when only considering economic aspects. However, biomethane production can be important to replace fossil natural gas and promote future decarbonization and defossilization scenarios. Fuel cells are the most efficient CHP technology and yield higher energy savings that any of the other scenarios considered. The problem is that the MCFC technology is still in development and not widely used in US WWTPs, as seen in Table 7.This increases the complexity of the installation, and O&M for MCFC as there are limited demonstration plants within US WWTPs. Therefore, it is not recommended as an option for biogas use in 2024. It could become a viable option in the future once it is widely implemented.

Using boilers to generate heat, has the lowest annualized CAPEX, OPEX, but it also gives the lowest revenue. Another issue with boilers is that they only produce heat. The heat requirements of the plant are not the same as the electrical requirements of the plant. Therefore, the heat produced by the boiler can only be used to processes that require heat within the WWTP. Adding a boiler into the WWTP would only be viable if there are other processes within the plant that can use the heat. This would depend on the sources of energy for the other WWTP processes. It is recommended to the WWTP to evaluate the heat and electric demands within the WWTP, using consumption data and equipment in use data, to see if there are ways to valorize the heat produced by the boiler.

Nonetheless, the most viable options, energetically and economically, are adding a microturbine or an internal combustion engine as CHP units, to produce both heat and electricity for the WWTP to use. The revenue presented by this option represent more than $1.8M annually. When looking at the next cost of implementing this option, it would generate $1.4M and $1.2M annually for gas turbine and microturbine. Considering the net cost of the implementation, it is recommended to the WWTP to add a gas turbine to generate heat and electricity. This technology is widely available, widely used, and can be implemented easily at large scale to reduce the energy demands of the WWTP, reduce WWTP annual costs, and reduce the CO_2 emissions. This CO_2 emissions reduction comes from the natural gas that is not combusted, and from electricity produced by a renewable source of energy for WWTP processes. Overall, adding an internal combustion engine at the WWTP would be beneficially considering both environmental and economic factors.

6. Conclusion

The WWTP studied has various options, with different energy consumption requirements, annual costs, and CO_2 emissions when considering what to do with the biogas it is producing. When looking at the energy production of CHP units (microturbines, fuel cells and internal combustion engines) and the boiler system, it is evident that the WWTP should start utilizing the biogas produced to reduce the energy demands of the WWTP. It would provide savings to the WWTP of $228,778/y without considering the revenue generated. Once capital costs and O&M are considered, the innovative technologies are too expensive for the WWTP and it is not feasible to implement fuel cells, nor microturbines. Biogas bottling and injection to the grid add a level of complexion into the process, which is not even fully considered in this analysis, as well as an increase in energy consumption by 18,000 kWh/d and CO_2 emissions by 2,000 tons CO_2/y, that make these two scenarios not economically feasible yet. Therefore, it is concluded that adding an internal combustion engine with enough capacity for the maximum biogas produced is the recommendable option, followed by adding boilers, one for the AD process, and another for other processes within the WWTP that could use heat to reduce the CO_2 emissions in the plant, and reduce its dependency on fossil fuels.

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