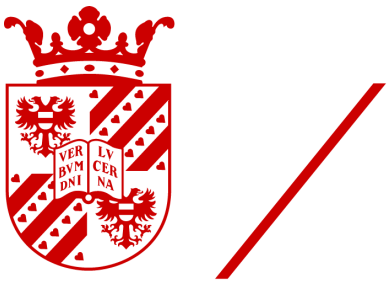

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Valorization of Biogas from Anaerobic Digestion through in-situ Addition of Hydrogen

Internship at Centre of Expertise Water Technology (CEW)

Jarmo de Graaf S3948145

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1 Abstract

Anaerobic digestion is a common technology to remove organic pollutants from wastewater. In this process a mixture of 75% methane and 25% CO_2, called biogas, is formed. In this project, hydrogen was dissolved in the effluent of the anaerobic digester and recirculated back in order to grow hydrogenotrophic methanogens, which should increase the methane fraction in the biogas by converting CO_2 to methane. It was found that by adding hydrogen in a dissolved state in a hydrogen to CO_2 ratio between 1 to 1 and 2 to 1, the methane fraction increased by 4% and increased the pH value from 8.04 to 8.16. This increase did not last long due to material failure. This research shows a proof of concecpt, but there is still a lot left to do in order to optimize this process.

2 Introduction

Water is an incredibly important resource in life.[1] Water is also an increasingly scarce resource in life. Only a tiny fraction of the water in the world is consumable for human beings. Billions of people experience water scarcity, and this number is projected to only go up from today. One of the reasons why this is the case is that the quantity of wastewater generation is ever increasing. It is therefore important to treat this wastewater in order to reclaim consumable water. In addition, as of mid-2021, we have entered a global energy crisis.[2] The prices of conventional energy increased due to a damaged economy from COVID-19, horrid weather conditions, and political instability. As such, water treatment needs to be cheaper than ever, preferably energy-efficient. Water treatment is a multi-step process.[1] One such step is anaerobic fermentation. Anaerobic fermentation can be used to generate methane from the bio waste contained in wastewater.[3] This allows us to increase the amount of water available to humans, as well as increase the amount of energy regained from wastewater. In this research project (CREATE), we aim to optimize the methane production from bio waste using a bioreactor with membrane attachment by optimizing the reaction conditions, primarily the addition of hydrogen. We aim to answers the following questions. Does the introduction of hydrogen in-situ increase the methane concentration? And if so, how much can we increase the methane concentration through in-situ hydrogen addition?

3 Literature

3.1 Biological Wastewater Treatment

In this research, the focus of wastewater treatment lies in the biological anaerobic fermentation of biomass to methane using hydrogen to upgrade the biogas quality. Anaerobic fermentation is a type of biological treatment for wastewater.[1] Using bacteria, fungi, and similar organisms, water is cleared of pollution. This treatment type is especially effective for wastewater with high organic content. The anaerobic fermentation converts organic materials primarily into mineralized compounds, carbon dioxide, and methane.[3]

Figure 1 shows the carbon and energy flows of aerobic and anaerobic treatment. In aerobic treatment, air is added to the system using compressors, which adds an energy cost.[3] In addition, heat is lost, and a lot of worthless sludge is produced. This sludge must be further processed. In some countries, the sludge can be landfilled for a low cost. In other countries, like the Netherlands, excess sludge and waste has to be processed, which is expensive. Aerobic treatment does have the upside of cleaning the water better, as is indicated by the lower COD (chemical oxygen demand) value. COD is a measurement that shows how much oxygen is required to chemically oxidize the organic pollutants in the water. A high COD value often means that the water is polluted. In anaerobic treatment, the wastewater is treated without any oxygen present.[3] Under these conditions, the amount of COD is unchanged as there is no oxidant present. The water can still be cleaned, as under these conditions the pollutants are transformed into methane and carbon dioxide (as well as mineralized compounds and trace materials). These gasses easily separate from the water, thus reducing the COD value in the water stream. Anaerobic treatment saves a lot of costs by not needing aeration as well as producing less sludge. Not only is less sludge produced, but the sludge is also considered to be valuable. Anaerobic treatment also has high COD loading rates, uses little to no chemicals, and volumetrically efficient. It should be no surprise that anaerobic treatment is so popular. Figure 1 shows the carbon and energy flows of both wastewater processes.

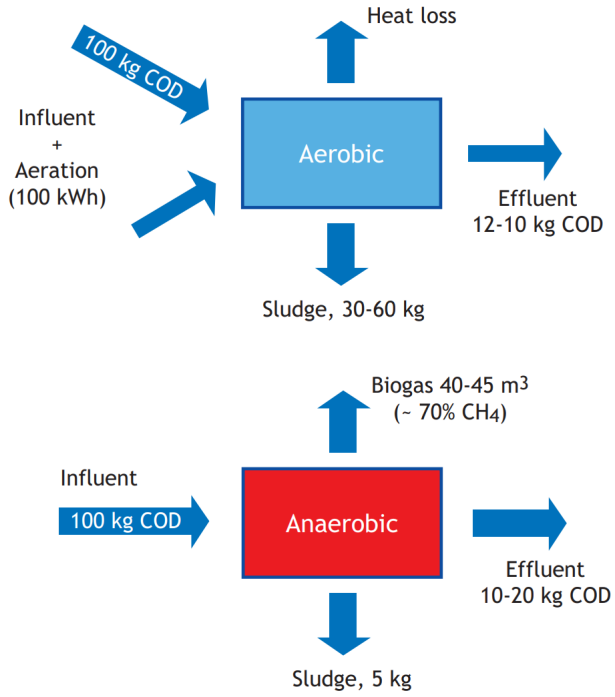

Figure 1: Carbon and energy flows of aerobic and anaerobic wastewater treatment.[3]

3.2 Anaerobic Fermentation

Anaerobic fermentation is a complex process consisting of multiple reactions and organisms.[3] Figure 2 shows a schematic route of the entire process.

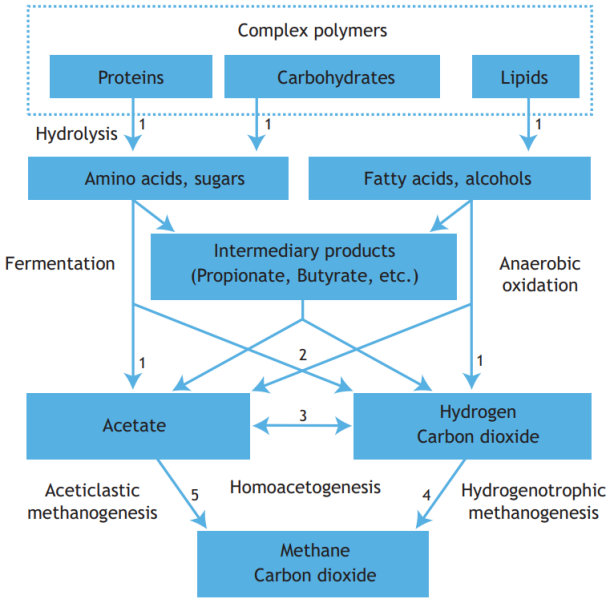

Figure 2: Anaerobic digestion scheme. 1:Hydrolytic and fermentative bacteria, 2:Acetogenic bacteria, 3:Homo-acetogenic bacteria, 4:Hydrogenotrophic methanogens, 5:Aceticlastic methanogens. [3]

First, long complex polymeric substrates are "cut up" through hydrolysis.[3] Hydrolysis is a type of reaction where water is used to split a molecule into smaller molecules. As a result, the polymers are transformed in monomers, and dimers. Since one polymer needs to undergo hydrolysis multiple times, this process is often the slowest in the overall fermentation system. It should be noted that this process is not present in the setup for this project, but is important in commercial anaerobic digesters.

After the hydrolysis, the biomonomers and biodimers (amino acids, sugars, fatty acids, alcohols) are available for acidogenesis (fermentation/anaerobic oxidation).[3] Acidogenesis is performed by a large amount of bacteria (1% of all known bacteria) including some that can perform hydrolysis, so it is easy to perform these reactions in one system. Acidogenesis produces small organic compounds like VFAs (volatile fatty acids), hydrogen, carbondioxide, lactic acids, ethanol, and ammonia. Figure 3 shows the acidogenic reactions with sucrose as reagent including their respective Gibbs free energy. Based on the Gibbs free energy, the lowest energy reaction is expected to be the main reaction (synthesizing propionic acid). In reality, this is dependent on the concentration of hydrogen. If hydrogen is consumed and therefore hydrogen concentration is low, the reaction with a higher hydrogen production becomes more dominant. This happens as long as the methanogenesis reaction (read ahead) can consume the hydrogen.

Reactions	ΔG°' (kJ/mol)
$C_{12}H_{22}O_{11} + 9H_2O \rightarrow 4CH_3COO^- + 4HCO_3^- + 8H^+ + 8H_2$	- 457.5
$C_{12}H_{22}O_{11} + 5H_2O \rightarrow 2CH_3CH_2CH_2COO^- + 4HCO_3^- + 6H^+ + 4H_2$	- 554.1
$C_{12}H_{22}O_{11} + 3H_2O \rightarrow 2CH_3COO^- + 2CH_3CH_2COO^- + 2HCO_3^- + 6H^+ + 2H_2$	- 610.5

Figure 3: "Acidogenic reactions with sucrose as the substrate and the corresponding free energy change at 25 °C."[3]

Acidogenesis is the fastest process in the digestion scheme.[3] Due to this, the bacteria responsible for acidogenesis have a higher growth rate. Anaerobic reactors therefore sour when overloaded. The pH starts to drop with the consequence that a higher concentration of VFAs become non-dissociated. These non-dissociated VFAs inhibit the methanogens, resulting in less hydrogen consumption, and more souring. This becomes a negative spiral, which kills the reactors ability to generate methane (see figure 4).

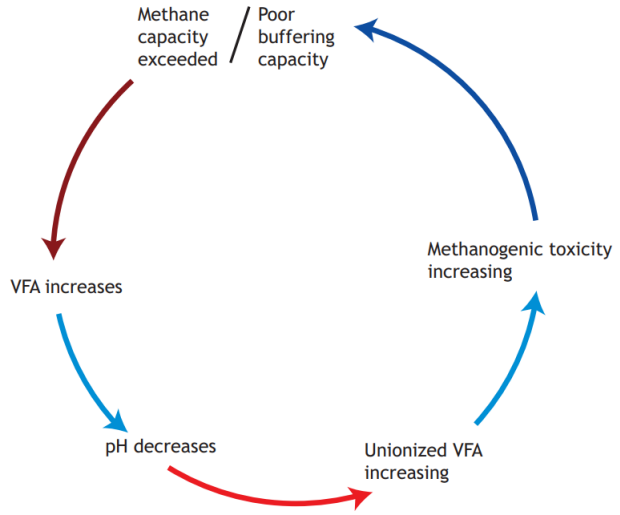

Figure 4: Reactor death spiral due to VFA accumulation.[3]

Short chain fatty acids (SCFA) produced in the acidogenesis step are converted into acetate, hydrogen, and carbon dioxide through acetogenesis. Propionate and butyrate are the most dominant SCFAs. For most compounds, acetogenesis is not a favorable reaction (see figure 5). In order to make them favorable, products of the reaction, like hydrogen, need to be removed. Methanogens require hydrogen in order to function, so acetogenesis has a symbiotic relationship with acidogenesis. If all goes well, the hydrogen pressure should stay between 10^{-4} and 10^{-6} atm. In this partial pressure range, the acetogenesis reactions for the the dominant SCFAs become exergonic, allowing them to proceed. The acetogenesis process is typically limited by long chain fatty acids (LCFA) as they are more complex to process.

Compound	Reaction	ΔG°' (kJ/mol)
Lactate	$CH_3CHOHCOO^- + 2H_2O \rightarrow CH_3COO^- + HCO_3^- + H^+ + 2H_2$	-4.2
Ethanol	$CH_3CH_2OH + H_2O \rightarrow CH_3COO^- + H^+ + 2H_2$	+9.6
Butyrate	$CH_3CH_2CH_2COO^- + 2H_2O \rightarrow 2CH_3COO^- + H^+ + 2H_2$	+48.1
Propionate	$CH_3CH_2COO^- + 3\,H_2O \rightarrow CH_3COO^- + HCO_3^- + H^+ + 3H_2$	+76.1
Methanol	$4\,CH_3OH + 2\,CO_2 \rightarrow 3CH_3COOH + 2H_2O$	-2.9
Hydrogen-CO_2	$2\,HCO_3^- + 4\,H_2 + H^+ \rightarrow CH_3COO^- + 4\,H_2O$	-70.3
Palmitate	$CH_3\text{-}(CH_2)_{14}\text{-}COO\text{-} + 14H_2O \rightarrow 8CH_3COO\text{-} + 7H\text{+} + 14H_2$	+ 345.6

Figure 5: "Acetogenic reactions and the corresponding free energy change at 25 °C."[3]

Methanogenesis is the final step in order to generate methane.[3] Methanogens are very particular. The amount of types of substrates a single methanogen can utilize is very limited. Figure 6 shows the Gibbs free energy and some kinetic properties of the most important methanogenic reactions.

Functional step	Reaction	ΔG°' kJ/mol	μ_{max} 1/d	T_d d	K_s mgCOD/l
Acetotrophic methanogenesis*	$CH_3COO^- + H_2O \rightarrow CH_4 + HCO_3^-$	-31	0.12[a] 0.71[b]	5.8[a] 1.0[b]	30[a] 300[b]
Hydrogenotrophic methanogenesis	$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$	-131	2.85	0.2	0.06

* Two different methanogens belonging to [a]*Methanosarcina* spec. and [b]*Methanosaeta* spec.

Figure 6: "Methanogenic reactions and the corresponding free energy change and kinetic properties."[3]

3.3 Process Limiters

An anaerobic digester (AD) can be run at either mesophilic (20-45 °C) or thermophilic (46-75 °C) temperatures.[4] Thermophilic reactors have shown to have a higher quality digestate as well as faster kinetics. The gas produced also contains more methane and less hydrogen sulphide. Mesophilic systems on the other hand cost less to operate due to lower temperatures. Generally, mesophilic systems are also more stable than thermophilic ones, which is why mesophilic systems are more common.

The growth rate and tenacity of the microorganisms is an important limiting factor when it comes to the rebustness of the system, and ability to research the system. Acidogenesis is considered the fastest step in anaerobic digestion. The bacteria responsible for Acidogenesis have a regeneration time of less than 36 hours.[5] Methanogens are the most important microorganisms in the system, and are highly sensitive to oxygen.[5]

The pH of the system is among the most important factors.[5, 6] Many microorganisms are sensitive to a change of the pH value and operate (live) only within a certain region. The hydrolysis microorganisms have been stated to thrive optimally within a pH range of 5-7, although no improved hydrolysis rate has been observed below a pH of 7.[5] Similarly, acidogenesis also improves at a neutral pH compared to acidic conditions.[7] The pH value also influences the

VFA concentration due to improvements of the reaction rate, although there has been no clear relation between pH and the VFA concentration. Acetogenesis has been reported to favor acidic conditions (pH 5-6)[6] Finally, methanogenic activity is theoretically possible from a pH value of 5.5 to 9.0, but is the activity is considerably lower in acidic conditions.[8] The optimal pH value for anerobic digestion has been determined to be around 7 ($\pm$0.2).[6] It is important to prevent local acidic regions as these regions would not generate methane and generate large amounts of VFAs instead. This in turn will kill the reactor.

Similar to the pH, the temperature is also an important factor for the system. The system is operating at mesophilic temperatures with an optimum of 37 °C. Hydrolysis has been noted to have optimum temperatures between 30 and 50 °C.[5] This makes the choice of the mesophilic temperature range attractive, as the hydrolysis process is a rate-limiting one.

3.4 Hydrogen Addition

The addition of hydrogen gas to the anaerobic system has already been demonstrated to increase the methane content of biogas.[9] Hydrogenotrophic methanogens use the added hydrogen in order to synthesize methane from hydrogen and carbondioxide. Alternatively, homoacetogens convert hydrogen and carbondioxide to acetate, which is subsequently converted to methane through acetoclastic methanogenesis. This decreases the carbondioxide content in the system. This decrease of carbondioxide mixed with high hydrogen partial pressures may lead to to an increase in VFA or pH. This might not be a problem when this is done ex-situ, but in-situ this can lead to reactor instability.

Since the rate-limiting step for the biogas upgrading is the introduction of hydrogen to the aqueous system, this should be the primary focus to solve.[9] Hydrogen needs to be dissolved in water for the microorganisms to have access to the hydrogen. Unfortunately, the solubility of hydrogen in water is quite low (1.6 mg/L[10]).

4 Methodology

4.1 Reactor Upkeep

Before improving the anaerobic digester (AD), it is important to be able to monitor the health of the AD. Previous work on this particular AD had a standard protocol to monitor the health, which is followed in this research. The following were tested on a regular basis, most of which were daily, some weekly. The influent flow rate, pH, electrical conductivity, sCOD, and sulfate concentration were measured. For the effluent the VFA concentration, pH, electrical conductivity, sCOD, ammonia (weekly), water hardness (weekly), and ortho-phosphate (weekly). Finally, the reactor temperature, pH, gas flow, and gas composition exiting the reactor were monitored. The chemical test for sCOD, sulfate concentration, ammonia, water hardness, and ortho phosphate were performed using standard Hach Lange Cuvette tests.

4.2 Reactor Setup

Figure 7 shows the PFD of the setup. Influent is pumped from the influent tank into the anaerobic digester along with the recirculation stream of effluent. The digester effluent is pushed up towards the lamella separator. Since the separator was of low quality, the liquid and solids continue down towards the settler, and the gas is partially leaked to the atmosphere and partially captured towards the gas flow sensors (Cubic SJH-100-DK, and SprintIR-6S-100), and composition sensor. In the settler, granules and flocs are stopped from continuing towards the hollow fibre membrane. At the hollow fibre membrane, hydrogen from the hydrogen generator and the effluent from the settler combine to saturate the effluent with hydrogen. Due to high pressures on the effluent side, the effluent is pushed towards the hydrogen tubes. This was temporarily solved by making a bypass back to the recirculation stream.

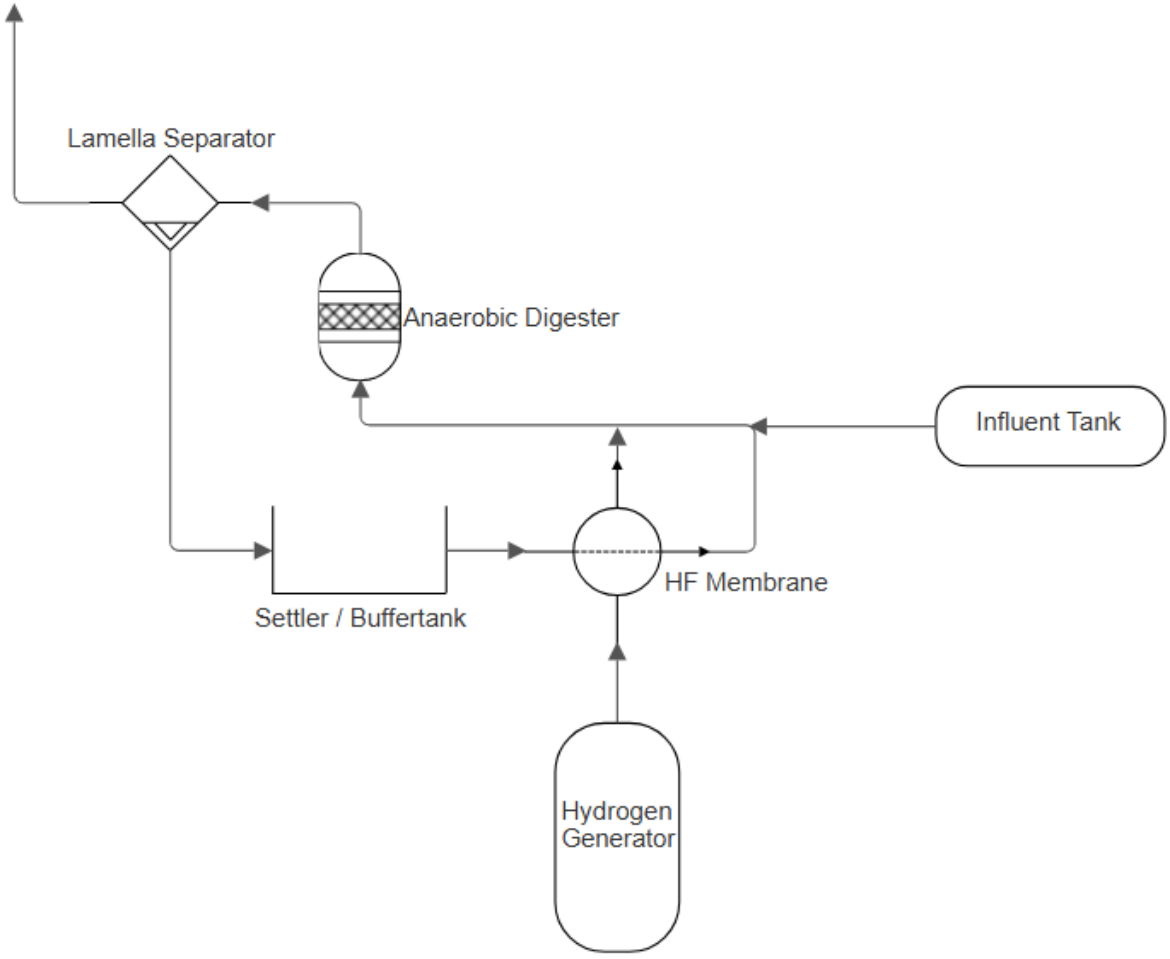

Figure 7: PFD of the anaerobic digester.

Figure 8 shows the P&ID of the system. Additional details compared to the PFD include the locations of the peristaltic pumps, the sampling port right after the lamella clarifier, the flow indicator and pressure controller for the hydrogen, the temperature and pH indicator in the digester, along with a check valve. The influent is pumped into the system at 10 L/hr, and there is a recirculation of 47 L/hr. The digester is a 40 L reactor with a diameter of 0.2 meter. This results in a superficial upflow of 1.5 m/hr.

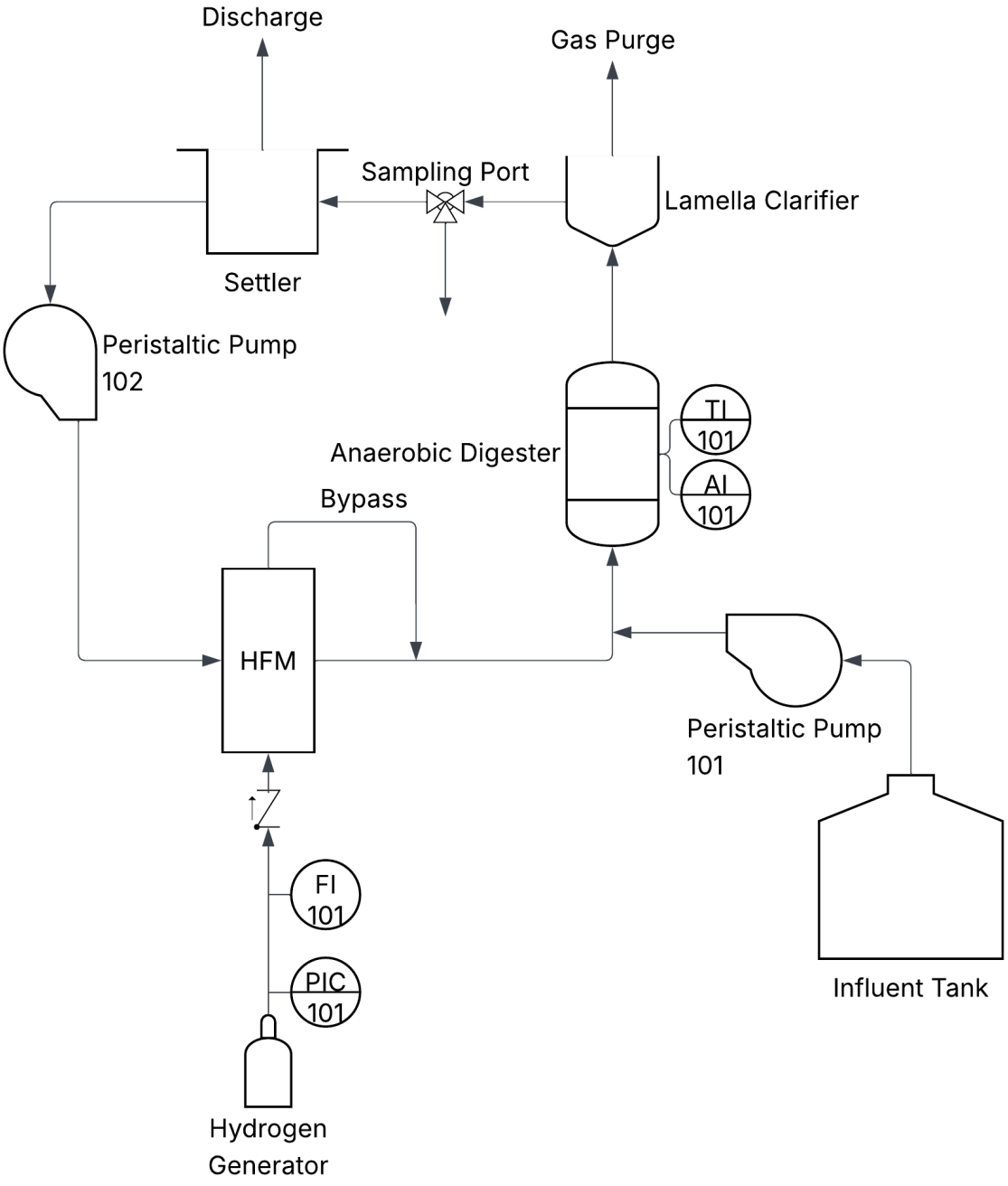

Figure 8: P&ID of the anaerobic digester.

4.3 Membrane Setup

The relationship between hydrogen pressure, hydrogen flow rate, and water recirculation rate was determined for the membrane (NAGASEP M60-B & NAGASEP M80-B) in order to determine the optimal conditions for the reactor. This test was done using process water as well as effluent from the reactor. The maximum saturation of hydrogen in water was used to determine the minimum amount recirculation required assuming 100% saturation. This is important to prevent hydrogen from entering the reactor as a gas rather than dissolved and bioavailable. Since the membrane has been replaced multiple times, and the setup has changed to have different working pressures, the usefulness of these results were limited.

Since the hydrogenotrophic methanogenic reaction is a 4 to 1 ratio between hydrogen and CO_2, this is the recommended ratio for the digester.[3] The hydrogen pressure and flow rate is measured by the hydrogen generator. The pressure is set to 1.22 bara, which should result in a pressure of 1.02 bara at the membrane due to 0.2 bara pressure loss from the check valve. The amount of hydrogen that can be dissolved in the recirculation loop (47 L/hr) can be calculated using the solubility of hydrogen in water (1.6 mg/L, 0.8 mmol/L, or 19.8 mL/L STP) by multiplying the amount of H_2 which can be dissolved in a liter of water by the amount of water per time unit. This results in a feed of dissolved hydrogen of roughly 0.9 mol/day. This is enough to achieve the 4:1 ratio for a biogas production of 22 L/day. In reality, the biogas production is higher, at around 30 L/day. Not all of the biogas is measured so this is likely even higher. Based on the amount of COD converted, the amount of biogas produced is expected to be between 60 and 70 L/day, depending on how much COD is used for micro organism growth. This means that the actual ratio between hydrogen and carbondioxide is between 1 to 1 and 2 to 1, assuming 75% of the biogas is methane. Assuming all of the hydrogen is consumed, and no bicarbonate is turned in to CO_2, the methane concentration can be increased to 81.25% and 87.5% respectively. In reality, these values are smaller due to the bicarbonate equilibrium with CO_2. Since the sensors have an inaccuracy of 5% each, this will be difficult to note using only gas composition sensors. The pH should also rise due to the equilibrium of the bicarbonate, and thus the gas composition sensors and the pH can both be used to prove the presence of this reaction.

5 Results

Figure 9 shows the COD value over time. The influent COD value hovered around 14000 mg/L ±1000. The amount of COD in the influent often was lower than the expected 15000 mg/L. Consumption of COD in the (semi-open) influent tank only covers a part of the reason why the COD of the influent is lower. The consumption is due to the fact that the influent gets tested a day after it is made. The rest of the value of decrease is unaccounted for. One can speculate this to be human error, but the difference is still over 5%. At day 45 the amount of COD in the influent is extremely high. This was likely human error in the standardized tests.
The COD value of the effluent steadily decreased from roughly 2000 mg/L to around 900 mg/L as the digester stabilized.

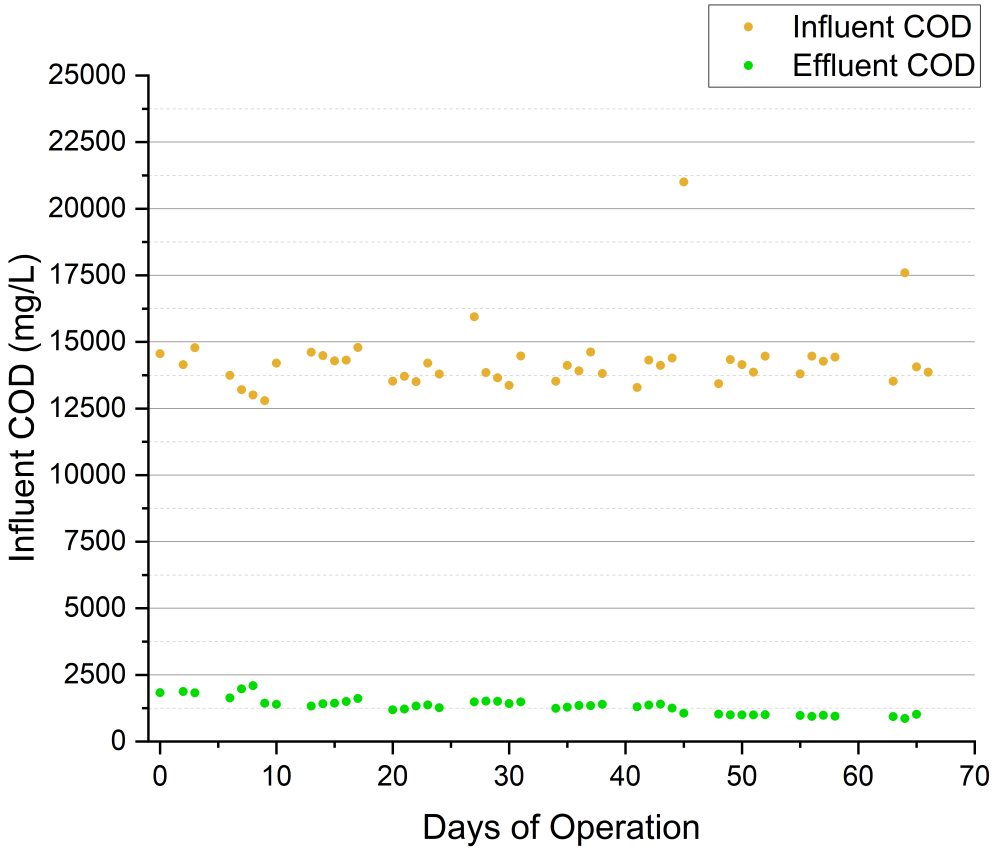

Figure 9: COD value of Influent and Effluent over Time

The research was distributed over 3 phases. Phase 1 consisted of just the anaerobic digester without hydrogen. Phase 1.5 was the construction phase of the hydrogen utilities. During this phase some hydrogen entered the system. Finally Phase 2 is when the hydrogen entered the system continuously. During the first days of phase 2, the system was unstable. This was solved at day 58. Figure 10 shows the relative amount of COD removed from the system. This steadily increased over time, indicating once again that the system became more stable over time.

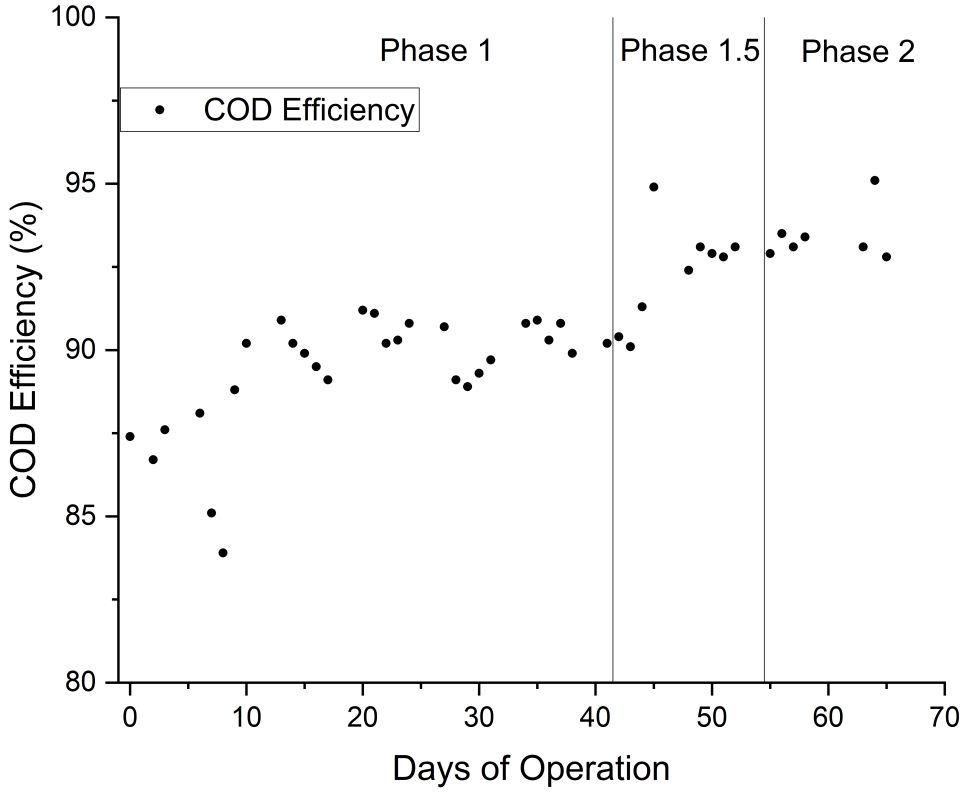

Figure 10: COD Removal Efficiency over Time

Figure 11 shows the normalized gas composition of the biogas over time. Note that towards the end of phase 1, the increase of methane fraction is due to the system not working correctly due to a power outage. We assume that methane and CO2 are the only gases present and thus total to 100% when added together. The ratio between these 2 gasses can be reliably calculated using these measurements, but microGC (micro Gas Chromatography) is needed to be used for more insight.

Three days after steadily injecting hydrogen into the digester, a change in CO_2 was seen. The first data point for this is at day 63. The (small) increase in normalized methane (to 79.45%) in addition to the increase of pH from 7.96 to 8.14 suggests that the growth of hydrogenotrophic methanogens was succesful. Unfortunately the very next day this effect was diminished as little to no hydrogen was entering the system for unknown reasons. This shows that an increase is possible, but there is much to be done in this specific setup in order to show the potential of this technique (see Internship & Recommendations).

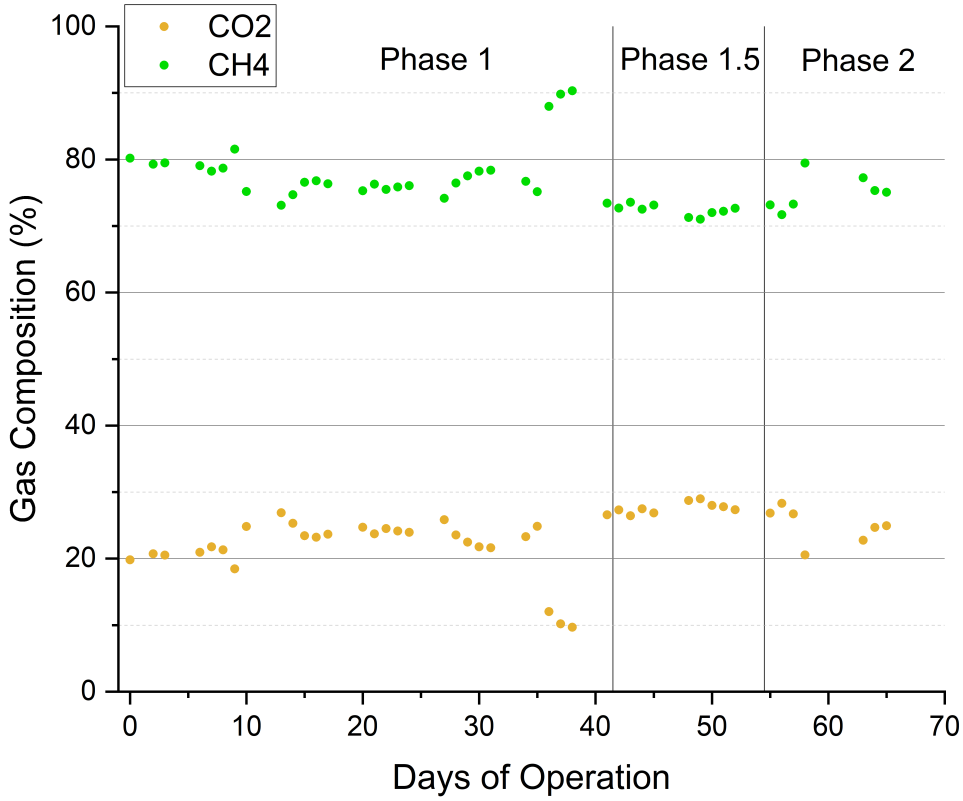

Figure 11: Normalized Gas Composition over Time

Figure 12 shows the gas production over the course of the project. At the start of the project, the digester was not healthy due to air entering the system. As time went on, without air, the digester recovered, producing more biogas. It is important to note that not all the biogas was collected due to a leaking lamella clarifier.

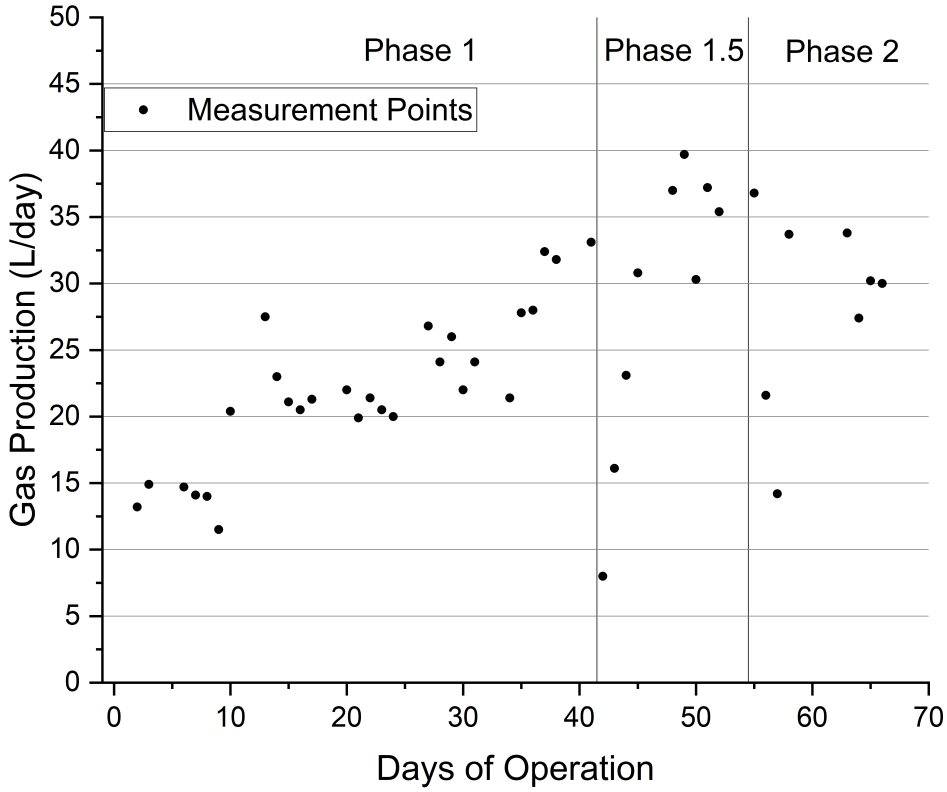

Figure 12: Gas Production over Time

6 Internship & Recommendations

In this section I will discuss the many things I have done during my time here at CEW and what my recommendations are in order for this research project to succeed.

6.1 Internship

When I first arrived at the lab, I was shown the digester. It was in a sub-optimal state. A significant amount of air was entering the anaerobic digester, leading to reduced biogas production. This happened due to a filter being clogged. This filter served no real purpose at the time, and there I swiftly removed it. The filter was there to prevent granules from re-entering the system. This is needed to protect the membrane, but the membrane was not attached at the time.
Something was still required in order to prevent granules from going to the membrane, once the membrane was attached. It was decided to make a settler using the limited resources available. Figure 13 shows a picture of the settler during cleaning. At the back of the picture you can see the inlet of the settler. Here the momentum is reduced with a barrier. The water is guided down towards a hole in the first barrier. The hole was sized such that the velocity through the hole was around 1 mm/s. A second barrier was installed to fully stop the granules. This settler

works decently well, but if the digester is in poor health, a lot of floaters appear. These will not be stopped by the settler all the time.

Figure 13: Settler

A large part of my internship was researching and installing the membrane part of the setup. This consisted of doing simple permeability tests, and pressure management. The tubing connections to the membrane were quite problematic. They often sucked in air. The best solution was to use heat shrinking tubing, and to put the pump before the membrane. This did come with a major problem of high pressure on the water side. My recommendations to upgrade the membrane setup can be found in section 6.2. Finding ways to deal with the pressure, and keeping air out of the system used most of my time.

The final major part of my internship was organizing the project. This organization con-

sisted of keeping stock, sourcing parts, organizing the inventory, making a weekly planning, and managing another intern. When I started working on the project, random parts and tools were placed messily. I organized these parts and tools and this sped up the tinkering progress significantly. Sourcing parts was also important. The parts I sourced needed to be chemically compatible and I needed to make sure all the properties were correct.

I leave this project behind in a state where it is almost ready to permanently add hydrogen to the system. The digester is healthy, everything is organized, and I have made many plans to move forwards and showed all the problems of the current state of the membrane setup.

6.2 Recommendations

There are many things that need to change in order to successfully end this project. The main focus points should be organization, ratios, and pressure control.

The introduction of hydrogen was difficult due to the previously mentioned focus points. Pressure control and everything surrounding the membrane should be the biggest priority. In the current setup, water is likely pushed through the membrane towards the lumen side. Although the pressure was not measured properly, based on the pushing force of the hydrogen, the pressure at the shell side was estimated to be between 1.2 and 1.3 bara. The hydrogen gas is at a pressure of only 1.02 bara. This means that the water is being pushed through the membrane.

This could potentially be solved by using a different more water-resistant membrane material, but this could be expensive and difficult to acquire. The easiest immediate solution would be to move the pump from right before to right after the membrane. This will create an underpressure instead of an overpressure at the shell side of the membrane. This should prevent water from being pushed to the lumen side. This setup has been used before, but this allowed air into the system through the connection points at the membrane. The hoses need to be gas tight in this situation. The inlet hose was replaced with a heat shrink before, and this could be done again for the outlet to prevent air from entering. Preferably a different type of hose is used due to the temperature limit of the membrane.

Another source of water accumation, albeit a significantly lesser amount, is through condensation of effluent to the lumen side. This is due to a temperature difference between the lumen and shell side. The temperature of the lumen side should be equal to, or higher than the shell side water. Although cooling down the effluent could work, this would reduce the reactor temperature or require reheating. A more effective approach, which would also heat the water more in order to get the temperature of the reactor correct, is to heat up the entire membrane, and preferably also part of the hydrogen tubing going into the membrane. This could be through (silicone) heating pads, or even better would be to place the membrane inside an insulated box (such as a cooler box), and heating it using an enclosure heater or something similar.

Another problem to be adressed is the inflow of hydrogen through the membrane. As it stands, the amount of hydrogen flowing through the membrane is exceeding the amount that could be dissolved into the amount of water that flows by. The hydrogen generator indicates at flow of roughly 19 ml/min whereas the maximum hydrogen dissolved would achieved at roughly 15 ml/min. As a result, bubbles formed at the membrane and entered the anaerobic digester, which can be toxic. Based on the results, the amount of hydrogen bubbles was not significant enough to noticeably effect the digester negatively. This small amount of bubbling can therefore be

accepted, but is not recommended.

The hydrogen flow rate needs to be reduced. The hydrogen generator is already set to a minimum, so adjustments there will not be possible. A flow regulator could potentially work. That way the hydrogen flow rate could be manually reduced, and subsequently, the partial pressure of hydrogen would stabilize to the amount required for the flow rate. Alternatively, the membrane material could be thickened, or switched for a less permeable material. Getting a flow regulator is likely the easier option, and such is the recommended option due to the limited time.

When hydrogen was introduced into the system, the amount of hydrogen was sub-optimal. The amount of hydrogen needed is 4 times the amount of CO_2 in the system based on stoichiometry. the amount of hydrogen introduced to the system is based on the amount of water that can be saturated with hydrogen (recirculation rate). For the amount of biogas produced in this setup, the recirculation rate should be increased nearly three-fold in order to dissolve enough hydrogen for this 4 to 1 hydrogen to CO_2 ratio. Aside from the fact that this increased flow rate might damage the membrane, the superficial upflow velocity will also increase. As a result, the granules in the sludge are even more likely to dislodge, as has already been happening. The upflow velocity can not increase, if the system needs to be stable. It is not possible to increase the flow rate with a set cross sectional area without increasing the velocity. The only thing I can suggest is to either accept the reduced hydrogen ratio, or increase the diameter of the reactor. The latter option does not seem feasable to me. It might be possible to allow a small amount of (micro) bubbles to be injected into the system. This should be done carefully in order to balance the poisoning of the system with the amount of additional hydrogen.

Currently, the membrane is getting damaged whenever granules flow through the shell side. This is due to 2 factors. Firstly, the settler is quite fragile. Whenever the digester is under stress, the amount of granules become too high and the granules decrease in density, allowing them to float through the settler and continue to the membrane. The settler will need quite some adjustments in order to function under these conditions. The second factor, which is more important, is the lamellar clarifier. Normally, the clarifier is supposed to separate the three phases. Currently, it leaks part of the biogas, and does not separate solids and liquids.

A handful of mechanical engineers are currently working on a replacement lamella clarifier. This replacement part has to be replaced as soon as possible. A proper clarifier will solve many issues. The biogas production can be properly recorded, once the clarifier is installed. The settler can be replaced with a smaller closed buffertank. This would lead to less oxygen dissolved in the water, but, more importantly, this would also lead to a higher maximum temperature. Currently a lot of heat is lost due to the large open settler. I recommend to wait for the new lamella clarifier, and place it before running the setup with hydrogen again.

7 Conclusion

The introduction of hydrogen in-situ to an anaerobic digestion has shown to be able to increase the methane concentration by roughly 4%. Unfortunately, the amount of data points that support this conclusion is extremely limited, and thus this is not a concrete conclusion.

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8 Appendix

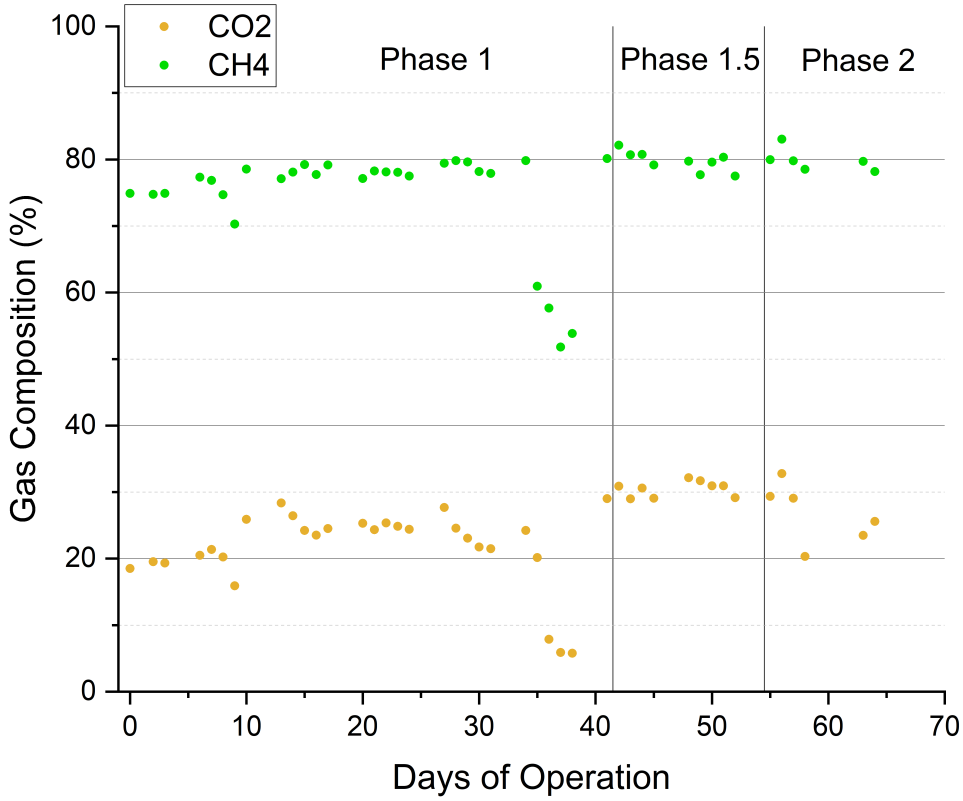

Figure 14: Gas Composition over Time (Raw Data)