

Letter of Transmittal

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University of British Columbia, Department of Chemical and Biological Engineering
April 16th, 2020

Dear Dr. Baldwin, Dr. Lim, Dr. Posarac, Dr. Verrett, Mr. Berretta, Mr. Dixit:

The enclosed report, titled “Production of Renewable Natural Gas: Methanation of CO2 Using H2 Obtained Through Water Electrolysis”, is intended to report on Group P9’s capstone project and present all the deliverables completed throughout the academic year. The report contains the deliverables presented in the progress report as well as the equipment specification sheets, HAZOP analysis, start-up and shut-down procedures, plant layout, environmental impact assessment, and an economic analysis of the process.

The aim of the project is to design a modular process to produce renewable natural gas from the CO2 byproduct of an existing biogas upgrading process. This modular add-on process is being designed in response to the societal problem of excessive CO2 emissions, which is driving the climate change phenomenon being faced by the planet. The end-goal is to design a process that can be appended to current biogas treatment facilities in order to increase their renewable natural gas production. As such, it can be applied by FortisBC’s renewable natural gas suppliers and help reach FortisBC’s 30BY30 goal to reduce their consumers’ CO2 emissions by 30% by the year 2030.

We certify this report is being submitted in accordance with the University of British Columbia’s *Academic Code of Conduct* and take full responsibility for the contents herein.

Sincerely,

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Production of Renewable Natural Gas: “Methanation of CO₂ Using H₂ Obtained Through Water Electrolysis”

Final Report

Submitted: April 16th, 2020

Group P9

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Executive Summary

Carbon Dioxide is one of the significant contributors to climate change. Certain efforts in developing novel and innovative technologies have been applied to find a sustainable use for Carbon Dioxide. FortisBC's 30BY30 goal calls for an action of discovering pathways of addressing one of the biggest world's challenges. Biogas facilities in British Columbia explore avenues to utilize Carbon Dioxide from anaerobic digesters. Methanation Reaction can be a potential key to sustainably reducing Carbon Dioxide emissions. This report proposes the design of a unique Methane production from a Carbon Dioxide plant. The plant is broken into five main sections: Pre-treatment, Carbon Dioxide and Methane Separation, Hydrogen Production, Sabatier Reactor and Gravity Separation. The process begins with Biogas feed from an anaerobic digester that consists of 60% of Methane and 40% Carbon Dioxide. Carbon Dioxide is separated from the Methane gas and sent to the pre-treatment section of the facility then to the Sabatier reactor. Hydrogen is required for the Sabatier reaction to take place. Water is fed to the PEM electrolyzer, where Oxygen and Hydrogen are produced. Hydrogen is supplied to the reactor along with Carbon Dioxide to produce Water and Methane. Methane is then separated from Water and sent to the pipeline to customers. The process has a Capital Expenditure (CAPEX) of \$36.7 million, which is calculated using Aspen Plus, Lang, location and scaling factors, and literature. The project is eligible for up to 12.8 million of Total Capital Expenditure from the CleanBC Fund. The Operating Expenditure (OPEX) of the plant is \$6 million per year, which consists of operations, maintenance, replacements, utilities, insurance, raw material cost. The total loss of the plant is estimated to be \$77 million over 20 years of operation. The project can be still feasible over 20 years if:

1. The biogas feed of more than 3,000 kg per hour is available. This accounts for a 2.1 times increase in the plant's capacity.
2. The Renewable Natural Gas cost is \$0.91 per kilogram. The current Renewable Natural Gas cost is \$0.66 per kilogram.
3. Oxygen obtained from PEM electrolyzer is upgraded to medical-grade, which currently sells for a much higher price than the process grade. The design and cost estimation of such a process is not performed due to project scope limitations

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| | |
|-------|----------------------------------|
| GHG | Greenhouse Gases |
| CO2 | Carbon Dioxide |
| RNG | Renewable Natural Gas |
| AD | Anaerobic Digester |
| TEG | Triethylene Glycol |
| AC | Activated Carbon |
| DI | De-Ionized |
| PEM | Polymer Electrolyte Membrane |
| PFD | Process Flow Diagram |
| P&ID | Piping & Instrumentation Diagram |
| HAZOP | Hazard and Operability |
| O2 | Oxygen |
| H2 | Hydrogen |
| H2O | Water |
| CH4 | Methane |
| SMR | Steam Methane Reforming |
| LNG | Liquified Natural Gas |
| BC | British Columbia |
| H2S | Hydrogen Sulfide |
| CO | Carbon Monoxide |
| NH3 | Ammonia |
| PSA | Pressure Swing Adsorption |
| HYSYS | Aspen HYSYS |

| | |
|-----|---------------------|
| KOH | Potassium Hydroxide |
| Ni | Nickel |
| | |

1. Introduction and Project Charter

The climate change crisis [1] that is currently occurring has driven the need to explore new avenues to reduce the amount of greenhouse gases (GHG) released into the atmosphere. While Canada is the seventh largest producer of renewable energy [2], it is also the fourth largest oil [3] and natural gas [4] producer in the world. This oil industry accounts for 26% of the total GHG emissions in Canada [5], of which two-thirds are composed of carbon dioxide (CO₂) [1]. Consequently, the application of CO₂ Capture and Utilization technologies has become paramount to curb the impact of CO₂ emissions on the planet. FortisBC, as part of the oil and natural gas industry has set a 30by30 target, in which they aim to reduce their customers' CO₂ emissions by 30% by 2030; as well as have 15% of their natural gas supply be renewable by 2030 [6]. To work towards this goal, the modular process aims to produce renewable natural gas (RNG) from CO₂ byproducts of anaerobic digesters (AD), that would otherwise be released into the atmosphere. The location for this add-on module is the Fraser Valley Biogas plant located in Abbotsford, BC, which is one of FortisBC's RNG suppliers. The production rate of RNG from the modular process is 2380 tonnes per year, this leads to a 54% increase in the RNG produced at the Fraser Valley plant. The scope of the project includes triethylene (TEG) dehydration unit, activated carbon (AC) adsorber, pressure swing adsorber, Sabatier reactor, DI water purification, PEM electrolyzer and flash drums. The complete design of the electrolyzer and TEG dehydration unit are outside the scope of the project.

The table below indicates the timeline of the project over the course of term 1. The initial step was to decide on a topic and perform an initial research on the technologies available.

Table 1: Term 1 project timeline

| September | October | November | December |
|--|---|--|--|
| <ul style="list-style-type: none"> Initial FortisBC meeting Project Idea Selection Block Flow Diagram | <ul style="list-style-type: none"> Proposal Report Proposal Presentation Units Selection | <ul style="list-style-type: none"> Initial calculations Initial PFD Initial P&ID Control narrative | <ul style="list-style-type: none"> Progress presentation Progress report |

Table 2 indicates the project progress over the second term. The finalized P&ID and the Cause-and-Effect matrix were initially performed. The equipment sizing and selection were submitted at the end of January. The HAZOP was then performed and submitted on February 5th. The reactor was selected as the node for the analysis since it is the main part of the process. The next deliverables were the start-up and shut-down procedure, the plant layout, and the environmental analysis performed in March. After a meeting with FortisBC, the economic analysis was performed and submitted. Lastly, during April, the major deliverables were the final presentation, the poster and recording and the final report.

Table 2: Term 2 project timeline

| January | February | March | April |
|---|---|--|--|
| <ul style="list-style-type: none"> Finalized P&ID Cause and Effect Matrix Equipment sizing | <ul style="list-style-type: none"> Initial HAZOP Start-up and shut-down | <ul style="list-style-type: none"> Plant layout Environmental analysis Economic analysis Finalized HAZOP | <ul style="list-style-type: none"> Final presentation Poster and recording Final report |

2. Process Synthesis and Innovation Map

The Sabatier reaction produces methane from carbon dioxide and hydrogen by the following reaction:



This process can achieve very high conversion and is highly selective towards biomethane formation when using nickel-based catalysts [7]. This is an innovative process that has not been implemented in Canada, however, some cement plants in Switzerland have implemented similar processes to reduce their carbon emissions through methanation [8]. There are nonetheless differences between the Swiss design and the one described in this report, including the use of the water formed. Canadian households tend to use forced-air furnaces, unlike Swiss residential heating which has a hot water radiator infrastructure [8]. This project aims to make the Sabatier process economically viable without the sale of hot water byproducts, by selling the O₂ produced in electrolysis [8]. Producing biomethane from CO₂ posits the Sabatier reaction as an alternative to carbon sequestration methods [8]. The hydrogen consumed in the methanation of CO₂ is generated through PEM electrolyzers. When powered by renewable sources of energy, electrolysis produces green hydrogen, which refers to hydrogen produced without any CO₂ emissions [9]. In essence, it is the cleanest method of producing hydrogen. This technology is significantly different from conventional ways of producing hydrogen such as steam methane reforming (SMR), partial oxidation and gasification. These methods of hydrogen production are major sources of CO₂ emission and account for 99% of current hydrogen production [10]. However, key improvements have been made in the field of electrolysis with developments being made to scale up the process. PEM technology is chosen in the design of this process as it has several advantages, such as high current density, high cell efficiency, relatively low operating temperature and very high purity of products (~99.99%) [11].

3. Market and Competitive Analysis

There are currently very few operating Sabatier reactors. Their most notable use right now is in water production aboard the International Space Station, as well as a source of methane fuel aboard the same [12]. There are a few smaller-scale Sabatier reactors built, notably in Switzerland, where the Sabatier

reaction is being used to provide natural gas for energy, and the hot water generated as a byproduct is used for residential heating. This would be the first industrial-scale Sabatier reactor in Canada, and as such would be a novelty. As our planet approaches a climate catastrophe, emphasis on cleaner forms of energy is a must. Canada is a particular case as a significant portion of its energy is fully reliant on natural gas, particularly in more remote communities. This presents three challenges, the first one is making existing infrastructure work with renewables; the second is transporting renewable energy to aforementioned remote communities; and the third is storing renewable energy. This process provides a solution to all three. Canada already has a large network of pipelines compatible with LNG transport, particularly along BC's Interior and Alberta. The renewable natural gas produced in this process is indistinguishable from that currently in use, and no changes would be required to existing infrastructure in order to implement its use, transport, and storage. Moreover, the energy density of natural gas far exceeds that of currently existing batteries, and it does not require the importation of lithium nor the use of toxic lead. These factors all make the Sabatier process worthy of consideration for the storage of energy produced by renewable sources.

4. Customer Requirements

Figure 4.1 below highlights FortisBC's standards for their RNG product. Due to Fraser Valley Biogas using agricultural and food products in their anaerobic digester, hydrogen sulfide (H₂S) is present in the biogas. Also, it is key that the carbon dioxide and water level in the process meet FortisBC's standards. Therefore, the three main considerations for the inlet stream pretreatment in this project are the removal of hydrogen sulfide, carbon dioxide and water content. As shown in figure 4.1, FortisBC's requirements for H₂S, CO₂ and water are less than 6 mg/m³, less than 2% by volume and less than 65 mg/m³, respectively [13].

| Contaminant Property | Specification | Recommended Measurement Frequency |
|---|--|---|
| Sand, dust, gums, oils and other impurities | <i>Free from any impurities</i> | |
| Hydrogen Sulphide (H ₂ S) | Less than 6 mg/m ³ | Continuous |
| Water | Less than 65 mg/m ³ of water vapour and no liquid water | Continuous |
| Hydrocarbon dew point | Be free of hydrocarbons in liquid form and not have a hydrocarbon dewpoint in excess of minus 9°C at the delivery pressure | Periodic |
| Total Sulphur | Less than 23 mg/m ³ | Periodic |
| Carbon Dioxide (CO ₂) | Less than 2% by volume | Continuous |
| Oxygen (O ₂) | Less than 0.4% by volume | Continuous |
| Temperature | 54°C maximum | Continuously |
| Calorific power | 36.00 MJ/m ³ minimum (15°C, 101.3kPa) | Calculated based on data collected continuously |
| Siloxanes | Less than 1 mg/m ³ | Periodic |
| Carbon monoxide (CO) | Less than 2% by volume | Periodic |
| Inert gasses | Less than 4% volume | Nitrogen periodically |
| Ammonia (NH ₃) | 3mg/m ³ | Periodic – semi-annually |
| Bacteria and pathogens | Impurity filter (0.3 to 5 microns) | Semi-annually |

Figure 4.1: FortisBC's Natural Gas Product Requirements [14]

5. Assembly of Database

The database presents the relevant physical and chemical properties of components in this process and can be found in Appendix H. Values in this database are used to perform energy and material balances, as well as used to calculate the yield of our reaction. They are also used to size all equipment. The values are all taken from Aspen PLUS using the Peng-Robinson and STEAM-TA free-water methods. The reaction rate law was taken from Marocco et al. and the equilibrium constant was taken from Miller et al [H1] [H2].

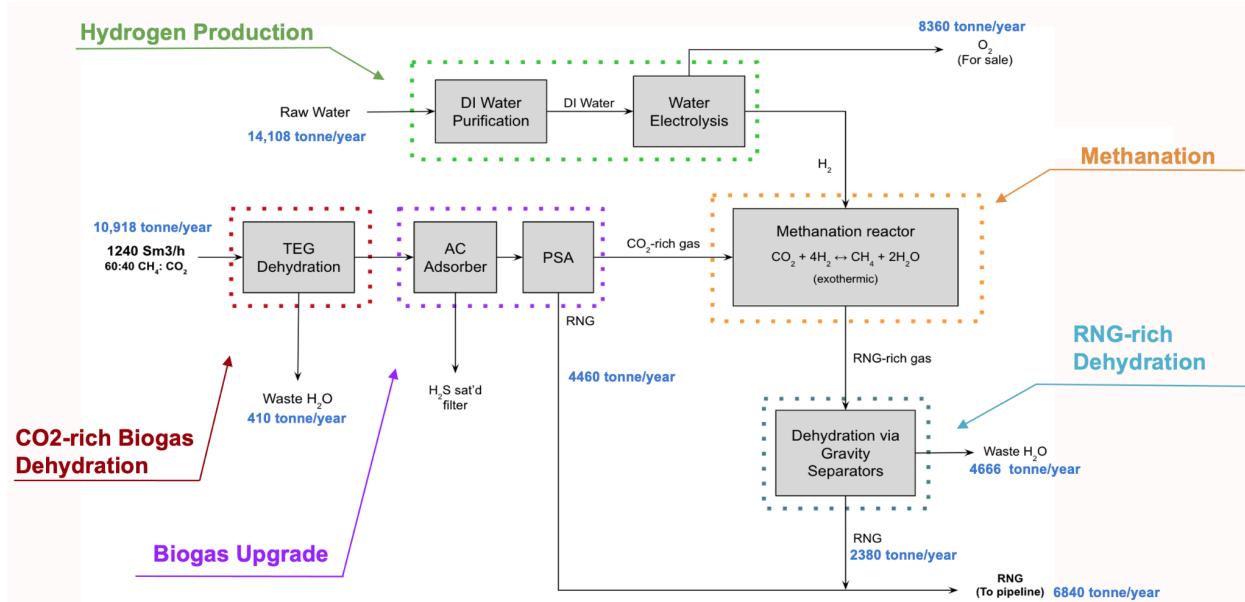
6. Process and Unit Description

Process Overview

The overall process is divided into five sections as shown in the figure below and consists of five drawings: PFD 100 - Biogas Dehydration; PFD 200 - Biogas Upgrade; PFD 300 - Hydrogen Production; PFD 400 - Methanation; and PFD 500 - Post-Treatment. The PFD stream tables can be found in Appendix A. Simulation software such as HYSYS and Aspen Plus is used to analyze the process, determine optimum conditions using sensitivity analyses, and to determine the heat and utility requirements to

maintain these conditions. Furthermore, substantial literature research is conducted for equipment selection, to obtain estimates for operating conditions, to develop process simulations, and to ensure the product meets RNG standards.

The process begins when biogas obtained from anaerobic digesters enters the front end of the plant and undergoes a dehydration process involving a triethylene glycol (TEG) contactor. The moisture content of the incoming biogas is greater than the product specification requirements provided by Fortis BC (water vapor < 65 mg/m³) hence it must be reduced prior to the biogas upgrade stage (PFD-200) as some methane (RNG) is sent directly to the pipeline from that unit. Furthermore, the biogas also contains hydrogen sulfide (H₂S) in trace amounts which must be removed according to product specifications (H₂S < 6mg/m³). The technology chosen for this process is physical adsorption using activated carbon (AC) which also requires dehydration as water has a greater affinity toward activated-carbon than H₂S hence, it makes sense to have dehydration as the first stage of the process. The dried biogas stream then passes through an AC absorber for desulfurization where H₂S, water residue, and oxygen (if present) are removed. The desulfurized biogas with methane (RNG) and carbon dioxide (CO₂) being the major constituents is introduced in a pressure-swing-adsorption (PSA) unit for separation. The RNG is sent directly to the pipeline as it meets product specifications and CO₂ is sent to the methanation reactor for production of additional RNG according to the Sabetier reaction (CO₂ + 4H₂ ⇌ CH₄ + 2H₂O). The required hydrogen is generated in PFD-300 using a PEM electrolyzer to conduct electrolysis of water. This process can be regarded as ‘green’ hydrogen production as electricity in British Columbia is obtained from renewable sources. Finally the exit stream from the methanation reactor (PFD-400) undergoes a post-treatment process in PFD-500 where water is removed such that product specifications are met prior to injection in the natural gas distribution pipelines.



PFD - 100: TEG Dehydration

Water is known to hinder the adsorption of hydrogen sulfide on activated-carbon filters therefore, it must be removed before desulfurization [15]. A glycol (TEG) dehydration system consisting of a contactor column and a regeneration section, shown in PFD-100 (figure X), is used to remove water from the biogas stream. For effective dehydration, the biogas must enter the TEG contactor at 800 kPa and 38°C therefore, a compressor [C101] and a cooler [E101] are placed upstream. A flash-drum [V-101] is placed to effectively remove **51 kg/h** of water before the flashed biogas undergoes TEG dehydration for further removal of water.

The glycol contactor [T-101] operates at 800 kPa which is significantly lower than a conventional natural gas dehydration process [16]. This is primarily due to the absence of other organic compounds that are commonly present in the raw natural gas. Furthermore the contactor tower is modeled in HYSYS and the desired separation is achieved at 800 kPa upon successful convergence of the absorber column. The pressure of the contactor tower is obtained from a sensitivity analysis performed in HYSYS. The flashed biogas stream (**1313.48 kg/h** and **0.87 mol% water**) enters the glycol tray tower at 38°C and 800 kPa where it is contacted counter-currently and dehydrated using lean TEG (**208.1 kg/h**). The mass flow rate

and temperature of lean glycol are calculated based on industry standards and best practices to obtain successful results. It is desirable to set the lean glycol circulation rate at 3-5 gallons/lb_{H2O} and the temperature 5-10°C higher than the biogas stream for effective dehydration [16]. This indicates that the flowrate of TEG depends on the amount of water to be removed therefore, a surge tank located downstream is equipped with a control valve to meet TEG requirements. The dried biogas stream (1306 kg/hr. and 0.09 mol% water) exits the contactor from the top and is sent to the desulfurization and upgrading process. The TEG-rich stream (215.5 kg/hr. and 26.78 mol% water) exiting the contactor undergoes the regeneration process which occurs at 100 kPa or just above atmospheric pressure. The pressure is reduced using a throttle to ensure they enter the regeneration tower at the same pressure as the tower stage.

A regeneration system consisting of a stripper integrated with a reboiler is used to vaporize the water in the rich TEG stream and recirculate glycol in the system. Rich TEG is preheated in a glycol-glycol heat exchanger to reduce the energy requirements of the reboiler which operates at 200-204°C to prevent glycol degradation [16]. Following the removal of water, the lean TEG exiting the surge tank is pressurized to 800 kPa by a reciprocating pump and cooled to 48°C in the glycol-glycol heat exchanger before entering the biogas dehydration tower. The stripper column is modeled in HYSYS as a reboiled absorber where the mole fraction of water leaving the absorber (0.01) and the reboiler temperature (200°C) are specified for available degrees of freedom.

Process modelling of C-101, E-101, V-101, and T-101 is carried out in HYSYS, and sensitivity analysis is conducted to determine working pressure, pressure drop, and the number of stages of T-101. HYSYS is also used to determine the utility requirement and equipment specification (sizing) which are discussed in the relevant sections of the report.

PFD - 200: Desulfurization and Biogas Upgrade

Biogas upgrading process involves purification of high carbon dioxide (CO₂) rich biogas to biomethane. It also contains a minor volume of hydrogen sulphide (H₂S). BC Oil and Gas Commission has set-up mandatory guidelines for H₂S processing treatment, as H₂S is a toxic and extremely harmful gas and must be removed prior to biogas utilization[17]. The dehydrated biogas leaves the glycol contactor (T-101) and enters the Activated Carbon Adsorber tower (V-201) at 300 kPa. This treatment is an industrial-wide favoured process as it is a relatively safe operation and is highly effective. 95% of H₂S present is removed from the biogas stream using an activated carbon filter with Potassium Hydroxide (KOH) impregnation that promotes higher adsorption rates [18]. The final trace of H₂S is under 0.002 kmol/hr which is far below FortisBC's gas spec of 4 ppm H₂S.

Next step in the upgrading is the removal of CO₂ which occupies almost 33% by volume in the biogas using the pressure swing adsorption (PSA) process. Using commercial adsorbent zeolite 13X molecular sieve, 98% of CO₂ in the biogas is recovered and 95% of CH₄ is separated which is suitable for pipeline injection [19]. This process has been black-boxed as it is very complex to model the multi-tower PSA operations. One of the reasons for its selection over other upgrading options is that FortisBC's established biogas refining processes use this operation. The biogas upgrading process follows Skarstrom's cycle sequence for separation of RNG and CO₂: (1) pressurization; (2) feed; (3) equalization; (4) high-pressure blowdown; (5) low-pressure blowdown; (6) purge; (7) equalization [20]. The unit operates at 200 kPa and 30°C for both towers V-202 and V-203 because CO₂ adsorption is not favourable at high temperatures nor high pressures [19]. Biomethane from PSA is compressed to pipeline spec of 420 kPa via C-201. A cooler E-201 is required to reduce the temperature of the gas to 30°C from the compression stage.

PFD - 300: Water electrolysis

The hydrogen required for the methanation of CO₂ is produced using a Polymer Electrolyte Membrane (PEM) electrolyzer. PEM technology is novel and still in the process of development for large scale use [26]. It has high efficiency, current density and has a high purity of products [26].

A PEM electrolyzer requires deionized water as the feed to split into hydrogen and oxygen. Water is first passed through an Ion Exchange Resin in order to deionize the water, and stored in a tank TK-301 to supply to the electrolyzer as needed.

Compressor C-301 is used for the hydrogen stream from the electrolyzer to store the hydrogen in a high-pressure tank V-302. Compressing and storing the hydrogen is done to store enough hydrogen for 48 hours of operation. Since compressing and storing hydrogen is an expensive process, a continuous production and usage is used. However, in the case of any maintenance or breakdown of the electrolyzer, a 250 kg hydrogen tank is installed to allow operation to continue and is held at a pressure of 10 MPa [21]. The stored hydrogen can also be used for the start-up procedure. The hydrogen is fed into the Sabatier reactor for methanation, the oxygen produced is used to generate revenue, and the excess water is sent back to the water storage tank.

Assuming 50% excess water is provided, 1763.50 kg/hr of water is required to generate 133.2 kg/hr of H₂.

PFD - 400

The CO₂-rich stream described in PFD-200 has an estimated flow rate of 746.6 kg/hr and is at 30°C and 200kPa. Given the optimum reactor conditions (270°C, 1000kPa) the stream temperature and pressure must both be raised. The pressurization is done in a two-stage compressor [C-401 and C-402] with interstage cooling [E-401]. Both compression stages have a compression ratio of 2.236, raising the pressure to 447 kPa in the first stage, and then to 1000kPa in the second. The interstage cooler lowers the temperature of the stream [402] from 108.8°C to 30°C. The stream [404] exiting the second stage is at 109°C and 1000kPa. This stream is then mixed with the hydrogen stream described in PFD-300, which is already at high pressure and temperature. The combined stream [406] consists of a 4:1 molar ratio of H₂:CO₂, and is heated to 270°C in two heaters [E-402, E-403] before being sent to the reactor [R-401].

The reactor is a jacketed fixed-bed reactor packed with a Ni/ γ -alumina catalyst, and is estimated to measure 4m in length, and 0.5m in diameter. Here the CO₂ is reduced to methane gas, forming water vapor as a byproduct. According to literature kinetics, the expected single-pass conversion of CO₂ is upwards of 99% [22]. This is supported by Aspen Plus simulations. The CH₄-rich stream [408] is sent to post-treatment for the removal of the water, as well as residual hydrogen and carbon dioxide.

Heating the stream being sent to the reactor is key to achieving the desired conversion. On startup the stream is heated almost entirely by the electric furnace E-403. Once the process has started heat integration is possible. The combined stream of Hydrogen and Carbon Dioxide (87°C) and the reactor outlet stream (270°C) are passed through a heat exchanger [E-402], where the reactor outlet heats the combined Hydrogen and Carbon Dioxide stream to about 237°C, reducing the heat required from the furnace. This serves to condense some of the water being sent to PFD-500 making separation easier. The interstage cooler [E-401] and reactor jacket are both supplied with cooling water from City of Abbotsford water lines. Both cooling water outlets are at 80°C, making them suitable for heating the anaerobic digesters if desired, or simply discharged to a sewage line.

PFD - 500: Post-Treatment

The product stream from PFD-400 contains 62.3mol% water which must be removed to meet product specifications prior to injection of RNG in the distribution pipelines. Separation using flash drums/ gravity separator is sufficient at this stage as most of the unwanted species have been stripped off from the biogas in the earlier process stages (PFD-100 and PFD-200). The product stream from the methanation reactor is cooled to 0°C to condense the water vapor and form a two-phase flow for vapor-liquid separation in the first flash drum. The vapor stream (mostly RNG) leaving this unit is introduced in an expander and the pressure is reduced to pipeline pressure (420 kPa). The RNG stream at the pipeline pressure undergoes another vapor-liquid separation process in the second flash drum to remove any liquid

residue and the dry RNG is then introduced in the distribution pipeline. The post treatment process is simulated in HYSYS and the details can be found in Appendix I.

7. Energy Balance and Utility Requirements

PFD - 100

The biogas enters the plant at 108 kPa which is compressed to the operating pressure of the glycol contactor tower (800 kPa) using compressor [C-101]. The wet biogas compressor uses 3154 kWh of electricity to accomplish this task. The biogas compression stage increases the temperature to 248°C which is significantly higher than the required inlet temperature of the glycol contactor (38°C). As such, biogas cooling is necessary and requires approximately 29,000 kg/hr of cooling water. Additionally a pump is required to increase the pressure of lean glycol stream from 102 kPa to 800 kPa which is equivalent to the top stage pressure of the glycol contactor. The power requirement of this pump is quite small (1.32 kWh/day) as only 209 kg/h of lean glycol is circulated in the system.

The rich glycol stream exiting from the bottom of the contractor tower at ~45°C needs to be heated to 200°C in the reboiler, and the lean glycol stream from the surge tank (TK-301) needs to be cooled to 45°C for effective absorption of water. Therefore, a glycol-glycol heat exchanger is used to minimize the power requirement of the reboiler. The lean glycol stream (hot fluid) enters from the shell side at 200°C and the rich glycol stream (cold fluid) enters from the tube side at 45°C. The temperature of the lean glycol stream is reduced to 48°C and the temperature of the rich glycol stream is increased to 188°C, which dramatically reduces the heat duty of the reboiler. The HYSYS simulation is still able to converge at these temperatures and effective removal of water from biogas is achieved.

PFD - 200

Biogas upgrading process is an expensive process that requires significant utility usage. Since this section contains Activated Carbon Adsorber along with multiple Adsorbers in a PSA unit, most of the electricity is consumed by these units in this PFD. A single AC Adsorber consumes about 358kWh/day [23] and total PSA requires approximately 7038 kWh/day. PSA utility requirement is very high because the process itself requires drastic pressure changes in multiple cycles. Since the upgrading columns have been blackboxed, these values are taken from literature sources [24]. Biomethane compressor (C-201) has an electricity usage of 25.21 kWh which is calculated via HYSYS. Lastly, Biomethane cooler (E-201)

requires cooling water flow of 4404 kg/hr as it cools down the biomethane stream temperature from 102.1 °C to 30°C.

PFD - 300

A large quantity of water is required for the electrolysis unit to produce hydrogen for the methanation process. A raw water stream of 1764 kg/hr is required for the electrolysis process. Additionally, a pump is required to feed the water to the electrolyzer at the operating pressure of 3 MPa. The water pump uses 54 kWh/day to supply the water to the electrolyzer. A similar pump is used to supply the water to the deionizer unit. Moreover, the electrolyzer consumes a significant amount of electricity to produce hydrogen with 10,000 kWh/day consumed. Lastly, the compressor is estimated to consume about 19,580 kWh over a year, since it is only occasionally operated for back-up hydrogen storage and the start-up process.

PFD - 400

A significant amount of both heating and cooling are required in this section. The reaction is quite exothermic, so the reactor must be cooled. The input is 11,537kg/hr of water at 20°C, which then exits the operation at 82.5°C, removing a total of 908kW. The interstage cooler takes in 200kg/hr of water at 20°C and outputs the same mass flow at 81°C, removing a total of 15.35kW. All these streams are expected to be almost entirely liquid, and were estimated to both enter and leave the heat exchangers at 1bar. Heating in this section is provided by heat integration (discussed further on), and an electric furnace. The furnace supplies 25.63kW during regular operation, heating 879.8kg/hr of mixed gaseous hydrogen and carbon dioxide from 236.67°C to 270°C.

Proposed Heat Integration (PFD 400 and PFD 500)

The reactor outlet stream (PFD-400) is at 270°C, and must be cooled to dehydrate the biomethane-rich reactor outlet in PFD-500. As such, it is applied to a heat integration system. The reactor out stream is contacted with the furnace inlet stream in a shell and tube heat exchanger. This heat integration allows for the furnace's duty to be decreased by 112.86kW which translates to an 81.5% reduction.

8. P&ID and Control Narrative

P&ID Control Strategy

Control systems are divided into five sets, whose diagram can be found on B-1:

1. Control Strategy for the first compressor stage (colored in red)

2. Control Strategy for the interstage Cooler (colored in brown)
3. Control Strategy for the second compressor stage and ratio control (colored in blue)
4. Control Strategy for the reactor feed temperature (colored in purple)
5. Control Strategy for the reactor temperature (colored in green)

First Compressor Stage

The main control objective for this loop is to ensure the safety of the first compressor [C-401] operation.

The feedback control strategy is utilized to ensure the safe operation of the compressor [C-401]. The adequate pressure is maintained via the controller [PIC-401] which receives a signal from the pressure transmitter [PT-401] downstream of the first compressor stage [C-401]. Pressure controller [PIC-401] transmits the signal to Variable Frequency Driver (VFD) to adjust the rotations of C-401. The high alarm sends the warning to the control room in case the pressure downstream of C-401 is too high. The high trip is installed to stop the first compressor stage and consequently the process to inspect the potential issues upstream of the C-401. It is done to protect C-401 as possible pipe plugging can occur in the process.

Interstage Cooler

The control objective for this loop is to protect the second compressor stage [C-402]. The temperature from the outlet of the interstage cooler needs to be around 30°C. The conventional feedback loop ensures that an appropriate amount of cooling water is supplied to ensure that the carbon dioxide stream is cooled down. The temperature controller [TIC-402] receives the signal from the temperature transmitter [TT-402] downstream of the interstage cooler [E-401] to adjust the flow of cooling water by manipulating the control valve [CV-402]. The high and low alarms are installed to transmit the signal to the control room.

Second Compressor Stage and Ratio Control

The control objective for this loop is to ensure the safe operation of the second compressor stage [C-402] and molar feed to the reactor is followed at 4:1 Hydrogen: Carbon Dioxide. The same strategy is applied for the second compressor stage [C-402] as for the first compressor stage [C-401]. The pressure transmitter [PT-403] sends the signal to the pressure controller [PIC-403]. The Variable Frequency Driver (VFD) adjusts the speed of the compressor [C-402] based on the signal from PIC-403. The high alarm sends the warning to the control room in case the pressure downstream of the compressor stage [C-402] is too high. The high trip is installed to stop the second compressor stage [C-402] and consequently the process to inspect the potential issues upstream of the second compressor stage [C-402].

Also, the same signal from PT-403 is sent to the pressure ratio control [PIC-404]. PIC-404 also receives the signal from the pressure transmitter [PT-404]. The control valve [CV-401] is adjusted according to the readings from two pressure transmitters. The ratio control ensures that molar feed to the reactor is kept at 4:1 of Hydrogen to Carbon Dioxide.

Reactor Feed Temperature

The control objective for this loop is to ensure the temperature of the reactor feed is at least 270°C. If the temperature is below 270°C then liquid water is formed in the reactor. Also, the reactor feed is undesired to be above the temperature of 300°C as run-away reaction can occur in the reactor if the feed temperature exceeds 300°C. It is also undesirable to exceed the 300°C as the equipment downstream of the reactor outlet will not be functional anymore due to raised temperature. For instance, water will not condense to liquid and different separation methods will be required for water and methane.

A conventional feedback loop is utilized to ensure that the temperature of the reactor feed is above 270°C and below 300°C. Therefore, the temperature controller [TIC-406] receives a signal from TT-406 downstream of the Furnace [E-403] to adjust the heat output by manipulating the electricity supply to the

furnace. The high and low alarms can potentially send warnings to the control room in case the temperature of the reactor feed is not within the acceptable range. The high and low trips are installed to stop the supply of electricity. This is done to protect the Sabatier reactor [R-401] from run-away reactions.

Reactor Temperature

The control objective for this loop is to ensure the produced heat from the exothermic reaction is removed by the cooling water so that overheating does not occur.

The feedback plus feedforward control strategy is utilized to ensure the safety of the process. Temperature transmitter [TT-405] measures the temperature inside the reactor [R-401] and sends the signal to the temperature controller [TIC-405]. TIC-405 transmits the setpoint temperature controller [TIC-418] which adjusts the flow of the cooling water to the reactor jacket. Temperature transmitter [TT-418] measures the temperature of the cooling water as it changes depending on the ambient temperature and season (can possibly vary from 15°C - 25°C). TT-418 transmits the signal to the TIC-418. TIC-418 manipulates the control valve [CV-403] which is Fail-To-Open to ensure that the cooling water is being supplied to the reactor [R-401] in case of failure.

Pipe Sizing

The piping sizes indicated on the P&ID are obtained from Heuristics. [25]

$$\text{For viscous flow (Re} < 2100 \text{) and } D_i \leq 0.0254 \text{ m} \quad (2)$$

$$D_{i,\text{opt}} = 0.133 \dot{m}_v^{0.40} \mu_f^{0.13}$$

$$\text{For turbulent flow (Re} > 2100 \text{) and } D_i \geq 0.0254 \text{ m} \quad (3)$$

$$D_{i,\text{opt}} = 0.363 \dot{m}_v^{0.45} \rho^{0.13}$$

9. HAZOP Study

The HAZOP study is conducted on the drawing P&ID 4001. Only one node was chosen to undergo an in-depth analysis to address any potential hazards that can occur in the selected section of the process. This node covers the Furnace (E-403), Methanation Reactor (R-401), Cooling Water Control Valve (CV-403), feed line (CH-409-6"-SS), cooling water lines (CW-413-4"-CS, CW-414-4"-CS), and biomethane line (CH4-410-6"-SS). This node is selected because the methanation reactor is the vital piece of equipment for the production of biomethane and operates at extreme conditions.

The completed HAZOP analysis is presented in Appendix E, where the causes for each deviation, corresponding consequences and existing safeguards are identified. In addition, category and severity of each consequence are evaluated and ranked and recommendations are made in cases where the risk level is not acceptable. A summary of the major issues identified is shown in Table 9.1.

Table 9.1: Major Issues, their Consequences, and Safeguards

| Major Issue | Consequences | Existing Safeguards |
|---|--|---|
| Reactor feed temperature fluctuation | -Potentially causes a run-away reaction if the temperature is too high -Potentially decrease product quality and yield if the temperature is too low | - High and Low temperature alarms on reactor feed line and in R-401 (reactor) - Temperature controller on E-403 (furnace) - Cooling Water flow controller on CV-403 to reduce reactor's temperature (if needed) - Interlocks on both E-403 and R-401 |
| Feed flow fluctuation (CO ₂ and H ₂) | - Potentially causes the reaction rate to change and decreases the yield - Potentially causes the pressure to build up inside reactor leading to an explosion | - Flow ratio controller to maintain the desired ratio of CO ₂ to H ₂ - PSV installed prior E-403 - PSV installed on R-401 |
| High temperature equipments/surfaces | - Potentially causes lost time or severe injury to plant personnel | - Warning signs on all hot surfaces - Insulation on hot pipes - Safety barrier between hot equipment and access ways |

10. Economic Analysis

Project Summary

After obtaining the appropriate approvals and permits, the Total Capital Investment of \$36.7 million is required to accomplish the project's construction. An interest rate of 4% is assumed for the project to be completed. The analysis is conducted based on the 20-year lifetime. It is estimated that the plant's construction will take a year to complete, given the scale and the footprint of the installation. Also, it is important to note that no quotes are available to confirm the estimated equipment costs. All site improvements are performed and paid for by FortisBC. The cost estimate does not incorporate a structure for the snow isolation and temperature control and electrical grid required for the PEM electrolyzer. The equipment cost estimate is completed using Aspen Plus economic tools and literature. In order to estimate the cost for the Lower Mainland region, the appropriate location, Lang and capacity factors are utilized.

*All the costs are in Canadian dollars, or converted to CAD from USD based on the April 2021 conversion.

CAPEX

Appendix G summarizes the Total Capital Investment and equipment cost for each PFD. The equipment cost estimates are the crucial and the most cost-intensive expenditure. The other costs identified in CAPEX are functions of the equipment size and cost. Pressure Swing Adsorbers (PSA) and PEM electrolyzer costs are estimated using the available literature values and relevant factors. The rest of the equipment is calculated using Aspen Plus Economic Analyzer. The estimated total equipment cost for the project is \$16.9 million dollars for the plant. The elaborate equipment cost is provided in Appendix G.

Figure 10.1 demonstrates the Total Capital Investment breakdown in the pie chart form.

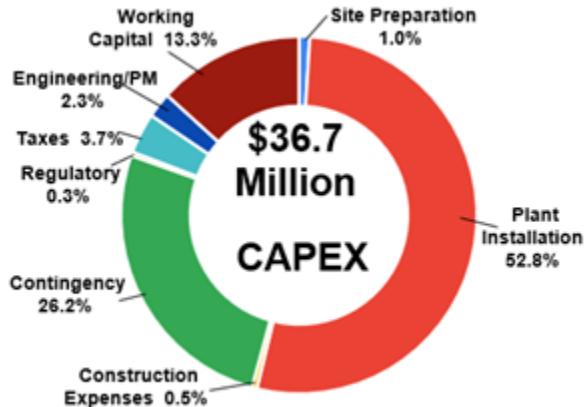


Figure 10.1: Total Project Capital Cost Breakdown

It is important to note that contingency is 26.2% of the Total Capital Investment. The reason for the contingency being so high is based on the unavailability of the quotes for the equipment and other pieces of the CAPEX. The CAPEX does not include costs associated with the process of capturing oxygen.

Funding

The purpose of the project is to increase the capacity to manage renewable energy and the generation of clean energy. The proposed plant converts carbon dioxide to methane gas that is utilized in the natural gas pipelines. These are the requirements for the CleanBC fund eligibility. The organization is structured to achieve profit; therefore, the project is eligible for up to 40% subsidy for the government [26]. This accounts for up to \$12.8 million in the governmental grant. The 60% of CAPEX is financed through FortisBC's funding and governmental loans.

OPEX

The annual operating expenses are summarized in the pie chart below. It is assumed that the plant will operate in the industry standard of an 8000 hour operational year. The remaining 760 hours will be spent on annual replacements and maintenance.

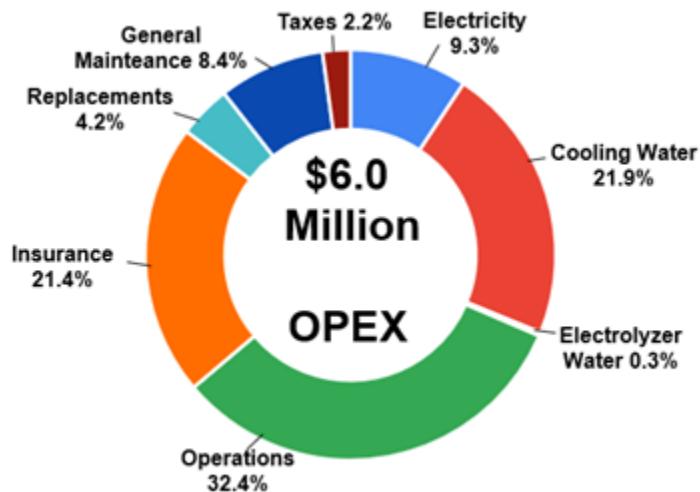


Figure 10.2: Total Annual Operating Cost Breakdown

General Maintenance

General Maintenance is estimated to be \$0.5 million dollars. This cost incorporates the fees that need to be paid for external audits to conduct safety checks as well as an internal audit of all the equipment. In

case the audit identifies required improvements, the technicians and contractors are dispatched to perform maintenance in the allocated period of time.

Replacements

Appendix G provides a detailed description of the required replacements. The replacements will be performed during the 760-hour window in a year. The main contributors to the cost are the cell replacement of the PEM electrolyzer, which occurs once in two years and resin replacement for the water purification system.

Operations

The operations are split into day and night shifts. The workdays are standardized to 12 hours for both shifts. It is estimated that seven employees are required on-site during the day. This includes three technicians, one safety and occupation representative, two control room professionals and one administrative staff. The safety and engineering managers are required to be present on-site during the day shift. The night shift will require one technician, one control room worker and a safety representative. Only one manager is required to be present on-site during the night shift. The hourly salaries are estimated with the overtime pay and standardized to hourly pay. The night shift hourly salary is 30% more than the day shift. The overtime is 1.5 times the 8-hour salary.

Table 10.1: Operations costs

| | People | Salary (CAD/hr) | Hourly Cost (CAD/hr) | Annual Cost (CAD) |
|------------------------------|---------------|----------------------------|---------------------------------|------------------------------|
| Day Shift Operating Labour | 7 | \$29.17 | \$204.17 | \$816,666.67 |
| Day Shift Management | 2 | \$46.67 | \$93.33 | \$373,333.33 |
| Night Shift Operating Labour | 3 | \$38.50 | \$115.50 | \$462,000.00 |
| Night Shift Management | 1 | \$70.00 | \$70.00 | \$280,000.00 |

Raw Materials

The only raw material required to be paid for is electrolyzer feed water. Given it is an add-on to the existing facility, the biogas feed is provided for no cost. The electrolyzer water is obtained from the City of Abbotsford at \$1.17 per cubic meter [27]. The total volume of water required per year is 14,193 cubic meters per year. The total cost for the raw materials is \$16,600 per year.

Utilities

The utilities include required cooling water and electricity. No heating utilities are not required due to performed heat integration. The detailed utility requirements for each piece of equipment are provided in Appendix G. The cooling water is supplied to the facility by the city of Abbotsford at the cost of \$1.17 per cubic meter [27]. The electricity is supplied to the plant by BC Hydro at the rate of 6 cents per Kilowatt hour at the commercial rate [28]. Table 10.2 summarizes the total expense for the utilities and their total requirements.

Table 10.2: Total Utility Requirements

| | Annual Electricity Usage (KW*h) | Annual Cooling Water Usage (kg) | Annual Electricity Cost (CAD) | Annual Cooling Water Cost (CAD) | Total Operating Utility Cost (CAD) |
|---------------------|---------------------------------|---------------------------------|-------------------------------|---------------------------------|------------------------------------|
| Subtotal | 9,145,939 | 1,113,786,104 | \$554,244 | \$1,307,051 | \$1,861,295 |
| 7% PST | | | \$38,797 | \$91,494 | \$130,291 |
| Total Including Tax | | | \$593,041 | \$1,398,544 | \$1,991,585 |

Project Economics

Revenue

The main revenue streams come from sales of Renewable Natural Gas and Oxygen from the electrolyzer. The oxygen is assumed to be process oxygen that sells for 2 cents a kilogram [29]. The Raw material costs are summarized in the table below.

Table 10.3: Revenue Streams Breakdown

| | Water | Oxygen | Methane |
|-------------------|-----------------|---------------|----------------|
| Mass Flow (kg/hr) | 1763.5 | 1045 | 854.7 |
| Cost (CAD/kg) | \$0.001174 [28] | \$0.02 [29] | \$0.66 [30] |
| Annual Cost (CAD) | \$16,556.03 | \$167,200.00 | \$4,512,816.00 |

The total stream revenue is estimated at \$4.7 million per year. There is a possibility to increase revenue by developing a process of capturing and upgrading oxygen to medical-grade, which currently sells for \$16 per kilogram [31].

Profitability

It is estimated that the project will make approximately \$77 million in losses in 20 years. The main source of revenue is methane sales. Figure 10.1 below illustrates the flow of cash over 20 years.

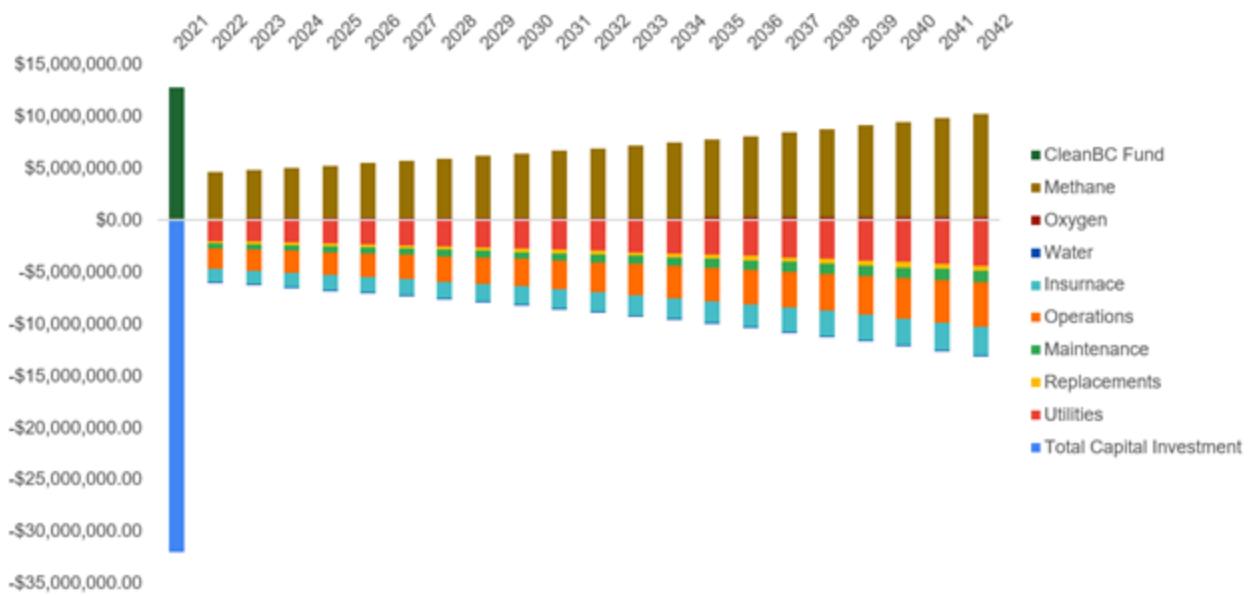


Figure 10.3: Cash Flow Diagram for the Plant over 20 Years

Operational expense outweighs the revenue obtained from the RNG sales. It can all be seen on the cash flow diagram.

Breakeven Scenarios

Economies of scale

Given the projected annual revenue and operational expense, the economies of scale can make the plant profitable over 20 years. The scaling factors were applied to the equipment and all the applicable expenses that are the equipment's functions. The power sizing exponent of 0.6 is utilized to find the associated costs of the equipment.

$$\frac{\text{Cost of A}}{\text{Cost of B}} = \left(\frac{\text{Capacity of A}}{\text{Capacity of B}} \right)^x \quad (4)$$

The plant needs to be scaled by 2.1 times to breakeven over 20 years. If the plant is scaled by a bigger factor, then the process becomes profitable. The biogas feed is required to be slightly less than 3,000 kilograms per hour. One of the proposed ways to achieve this scale is to build infrastructure to the

proposed facility that transports biogas from all the biogas facilities in the province of British Columbia. The cash flow diagram is demonstrated below for the scaled-up plant.

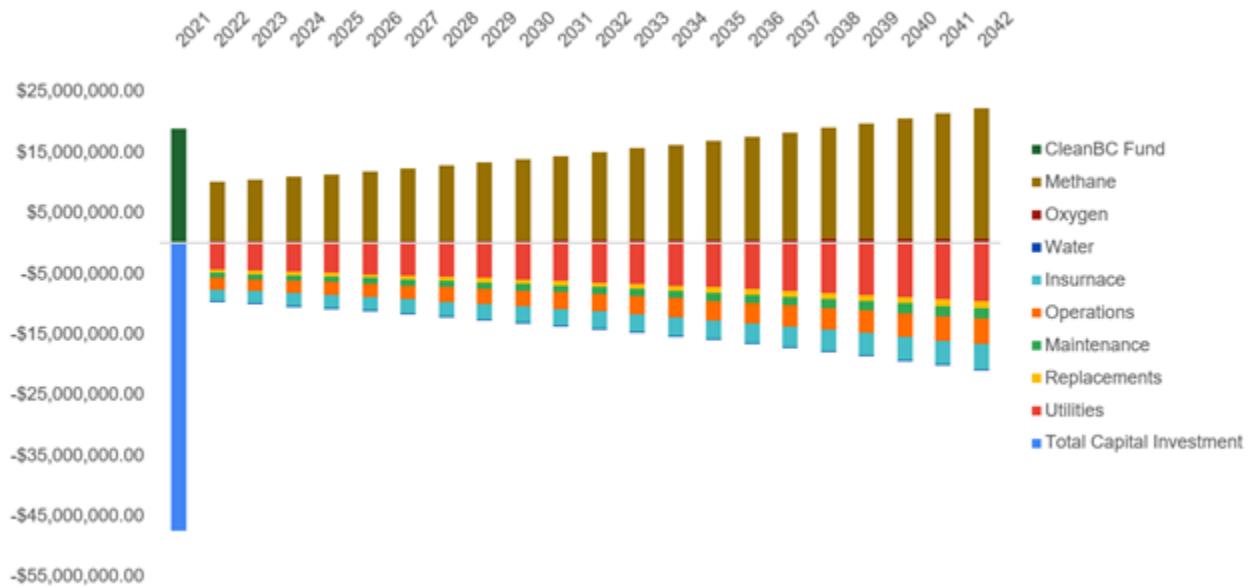


Figure 10.4: Cashflow Diagram for the 2.1 times the original Plant over 20 Years

Increase Cost of Renewable Natural Gas

The current cost of Renewable Natural Gas, according to FortisBC, is \$0.66 per kilogram [30]. After conducting simulations of the Renewable Natural Gas cost, the estimated cost to break even in 20 years is \$0.91 per kilogram. However, the cost for RNG is not projected to go up as competition in this sector is projected to increase.

Develop a Process for Medical Oxygen Production

The current cost for the process oxygen is \$0.02 per kilogram [29]. The process oxygen is usually 95 % pure, and 5 % are impurities [29]. The medical-grade oxygen sells for \$16 per kilogram [31]. It is 99.9% pure oxygen [31]. Developing a process for upgrading oxygen to medical-grade will involve capital investment, but the benefits may outweigh the expense.

*Modelling of the Oxygen Upgrading Plant is not performed due to scope limitations

11. Environmental Impact Assessment and Permitting

The plant will be located on a flat greenfield north of the currently existing Fraser Valley Biogas plant East of the city of Abbotsford. The location is shown by the red rectangle in figure 11.1. The RNG produced will be directly injected into the already existing pipeline running along the near side of the Interprovincial Highway and then sent to distribution pipelines. The installation of equipment and construction of the plant will require the following permits:

- Gas Installation (Technical Safety BC)
- Gas Operating Permit (Technical Safety BC)
- Electrical Safety Regulation (BC Utilities Commission)
- Activities Act Permit (BC Oil & Gas Commission)
- Industrial Building Permit (City of Abbotsford)
- Wastewater Discharge Permit (City of Abbotsford)

Additional permits will be required for the distribution of RNG, but that is outside the battery limits of this project. The majority of these permits are provincial, with only two requiring permission from the City of Abbotsford.



Figure 11.1: Area selected (red line) for the construction of the modular plant. Pre-existing plant (Fraser Valley Biogas Ltd.), near the center of the picture, consists of two anaerobic digesters, three storage tanks and a warehouse.

The sections below outline the environmental impacts of each stage of the process

PFD 100, PFD 500:

The first stage of the process (PFD-100) is biogas dehydration with triethylene glycol (TEG). Since it is a closed-loop system for TEG, the only exit streams are the dry biogas to PDF - 200 and water vapor from TEG stripper section. The water vapor stream has the following composition : 99 mol% H₂O, < 1 mol% TEG, and < 0.1 mol% CO₂. Given that this TEG is considered non-toxic and is present in concentrations under 4ppm, this can be safely discharged to the environment.

PFD 200:

The desulfurization process is facilitated by the Activated Carbon Adsorption tower (V-201) that removes the hydrogen sulfide (H₂S) using an activated carbon filter. In this sweetening and upgrading process, there are no gases that are venting off so that only waste is an AC filter that would be replaced once it reaches its capacity. GHG and H₂S emissions guidelines by BC Oil & Gas Commision do not necessarily apply here. To create a more sustainable process, these AC filters would be sent to recycle plants as activated carbon can be recycled or used as fuel in kilt in other processes.

PFD 300 - Deionizer:

The regeneration of the resins is performed by flowing hydrochloric acid (HCl) or sulphuric acid (H₂SO₄) through cation resins and caustic soda (NaOH) through anion resins [32]. Dilute solutions of 4-6% are passed through the resin bed to rinse it back. The deionizer unit requires 10 ft³ of cation and anion resin [33]. To perform the regeneration process, about 21 gallons of 30% HCl (diluted to 6% HCl) and 9.4 gallons of 50% NaOH are required (diluted to 4%) [32]. Since the frequency of the regeneration process depends on the purity of water available, it will be estimated that this process will be a maintenance procedure performed every month or once the water purity is lower than the PEM electrolyser requirement. To safely dispose of the acidic or basic solutions, they would have to be neutralized first before being sent to the sewage system [33]. To neutralise the hydrochloric acid, NaOH can be used until the pH is in the range of 6 to 8 before being disposed of. Similarly, the NaOH can be neutralised using HCl until the pH is in the range of 6 to 8 [35].

PFD 400 - Reactor

The reactor produces two products: methane and water. The methane gas is sent to the pipeline, and the water is condensed and discharged to the sewage main. The major waste in this section is in the form of spent catalyst. Due to the pretreatment process and the presence of a sulfated catalyst support, catalyst poisoning is unlikely and the main concern is coking. Once deactivated the catalyst can be recovered in a furnace, or simply disposed of. The catalyst is expected to be replaced once yearly, generating 350kg of catalyst waste. Depending on whether FortisBC would like to expand this project to include other biogas plants, it may be worth the costs to install their own recovery plant. Otherwise the spent catalyst can be sold off to specialized waste recovery sites which will recycle the catalyst. There are no specific regulations regarding catalyst disposal in British Columbia, but they are classified as hazardous recyclable materials, and an effort should therefore be made to regenerate and reuse these catalysts [36].

12. Start-up and Shut-down Procedures

START-UP AND SHUT-DOWN PROCEDURES

The start-up and shut-down procedure is a set of operating procedure guidelines that is an essential part of the plant process. Having a plant with a high pressurized unit operations dictates certain risks to plant personnel and other assets. Therefore, a specialized procedure is devised to ensure the safety of the plant and effectiveness of the subsequent unit operations. The commencement of the start-up and shut-down includes the preparation of emergency procedure and maintenance checklists by operating staff. Moreover, it is a good practice to inventorize spare parts and raw materials. The Block Flow Diagram represents five separate sections of the plant where the individual pieces of equipment need to be operated in order to startup or shutdown the process. All liquid inventories are required to be filled before performing the startup. In step 1, the start-up begins by turning on all utilities in the plant. The cooling water starts circulating around the system by starting the cooling water pump. In step 2, deionized water is being supplied to the electrolyzers and produced Hydrogen and Oxygen Are supplied to the storage tanks. In step 3, Carbon Dioxide and Hydrogen are supplied to the Jacketed Sabatier Reactor R-401 through the control valve CV-401. In step 4, both the AC Adsorber and PSA system start running. Lastly, the reboiler is started, TEG is circulated and the inlet is opened. The reason for starting the methanation reactor unit before the biogas-upgrading unit is to ensure the cooling water is evenly circulated throughout the reactor unit and the required temperature is maintained before the feed enters the inlet. The shut-down sequence follows a reverse order.

13. Plant Layout

13.1. General Layout

The plant layout for our process is specifically designed based on the layout of Fraser Valley Biogas Ltd.. As a modular process, optimization of plant layout and minimization of land usage are encouraged. Various factors were considered including the prevailing wind direction, the safe distances required between equipment posing higher fire risk, and the minimization of pipe length used. The add-on plant will be located north of the parent facility. A SOLIDWORKS 2-D drawing of the plant can be found in Appendix E.

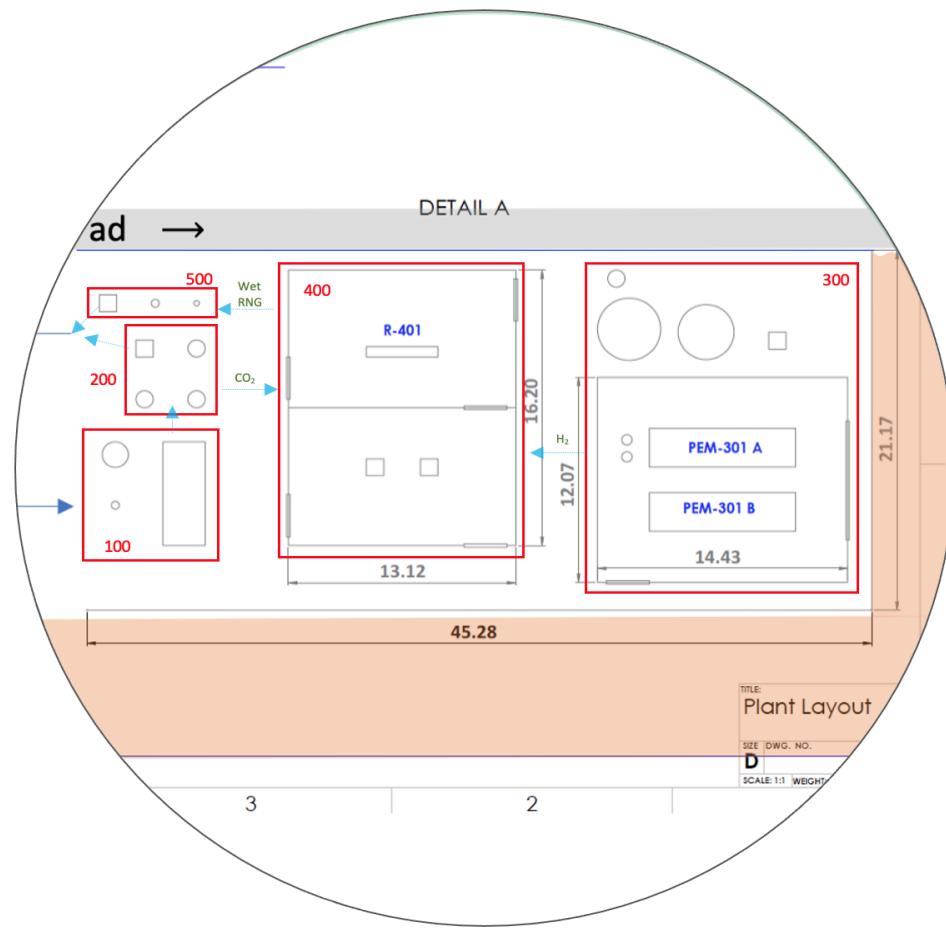


Figure 13.1: Zoom-in view of the stand alone process. The equipment in each section is boxed in red and the material flow is indicated by the blue arrows. Section 100, 200, 300, 400, and 500 refer to Biogas Dehydration, Biogas Upgrade, Hydrogen Production, Methanation, and RNG dehydration, respectively

The footprint of this plant is determined to be approximately 150m x 20m (3000m²). The parking lot, the office, the control room, and the warehouse will be located to the North West of the property. All of the process equipment will be placed 25m to the North East from the digesters. The layout of each section, the material flows between sections, and the inlet/outlet locations are indicated in Figure 13.1. The produced RNG are compressed and combined from section 200 and 500, which locations are closest to

the injection point of the pre-existing RNG pipeline that runs along Interprovincial Hwy. Section 300 is only involved in the process through the production of hydrogen, which is a feed for section 400, and therefore it is placed beside section 400 and does not need to be close to the remaining sections.

The majority of the equipment is located outdoors. Sufficient spacing is allowed between and around all equipment for maintenance and replacement purposes. The equipment from section 400 and the PEM electrolyzers from section 500 will be located indoors to better control the gas temperature and to follow the manufacturer's specification, respectively. The building that houses the reactor (R-401) will be constructed out of non-combustible and fire-resistive material in order to minimize the potential damage or fire spread to the surrounding equipment. Bridge crane systems will be installed for both buildings to aid the installation and removal of heavy equipment.

13.2. Wind direction

In this area, the average wind direction is from the South for an approximate 9 months (March to November), where the farming activity is most active. For the remainder of the year, data suggests Northeasterly winds to be common [37]. Understanding the prevalent wind directions assists in appropriate placement of equipment to minimize impact in case of an accident and to provide ease of access to rescue services. Direct vents of natural gas from flare lines of section 400 will be located downwind and be given a 4.5m radius from any potential flame, high heat, and electrical sparks sources. Hydrogen storage tank in section 300 poses the second highest risk of fire and is placed at least 3m away from any building and at least 7.5m away from the concentration of people [38].

13.3. Evacuation and fire-fighting plan

Pathways in all buildings will be clearly marked to high-visibility taped. Buildings are designed with two exit ways to provide sufficient escape routes for plant personnel . The fire lanes are selected to be upstream of the prevalent wind direction, bordering the South and the East sides of the new plant. All lanes within the property are 7m wide which give plenty of room for fire trucks and industrial trucks to access the equipment.

14. Conclusion

Climate change is a global issue that humanity attempts to tackle with innovative technologies. FortisBC's 30BY30 goal calls for action of discovering pathways of addressing one of the biggest world's challenges. This project provides one of the potential avenues of reducing Carbon Dioxide emissions through the Sabatier reaction by producing valuable Renewable Natural Gas that can be supplied to

customers. The proposed plant in Fraser Valley can reduce Carbon Emissions by around 6,000 tonnes per year. The technology of Sabatier reaction is not widely used globally, which brings high risks in terms of design and costs. The process has a Capital Expenditure (CAPEX) of \$36.7 million, which is calculated using Aspen Plus, Lang, location and scaling factors, and literature. The project is eligible for up to 12.8 million of Total Capital Expenditure from the CleanBC Fund. The Operating Expenditure (OPEX) of the plant is \$6 million per year, which consists of operations, maintenance, replacements, utilities, insurance, raw material cost. The total loss of the plant is estimated to be \$77 million over 20 years of operation.

This report presents the detailed design of the Methane from the Carbon Dioxide production plant. However, more research and more advanced engineering design are recommended to be completed. The research for finding reliable kinetic data for the Sabatier reaction and construction of the demonstration plant are desired to be conducted. The literature review showed many discrepancies among each other, which does not allow this report to evaluate the proposed reaction parameters adequately. However, all the literature reviews suggested that 99% conversion of Carbon Dioxide is achievable.

Another recommendation is recharging the produced Hydrogen from PEM Electrolyser. Currently, Hydrogen is supplied to the Sabatier Reactor to produce Methane. However, Hydrogen can be stored in the Hydrogen tanks and sold at the current Hydrogen price or be supplied directly to the pipeline. The concentration of Hydrogen in the Natural Gas pipelines may not exceed 10% by volume.

In order to make this process profitable over the next twenty years, the following suggestions are made:

1. The plant capacity needs to increase by more than 2.1 times. This will require a biogas feed of more than 3,000 kilograms per hour. It is advised to build more anaerobic digesters in Fraser Valleys or explore the option of transporting biogas from all the available biogas facilities. However, the latter option implies significant pipeline infrastructure development.
2. The cost of Renewable gas has to be more than \$0.91 per kilogram. The current price of Renewable Natural Gas is \$0.66 per kilogram according to FortisBC available rates. However, this scenario is unlikely as more producers of Renewable Natural Gas enter the market.
3. It is recommended to explore an option of upgrading Oxygen from PEM electrolyzer to medical-grade. The capital and operational costs are not estimated for the oxygen upgrading facility as it is outside of this project's scope. However, the comparison of cost process and

medical-grade oxygen show another source of revenue. The current cost of process and medical grade oxygen are \$0.02 per kilogram and \$16 per kilogram, respectively.

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17. Summary of Contributions

| | |
|----------------------------|---|
| Mikhail Antyukhov | Economic Analysis, Control Narrative, Appendix G, P&ID, Process description (PFD-400), Executive Summary, Conclusion |
| Bhushan Appadoo | Letter of Transmittal, Introduction and Project Charter, Process Synthesis and Innovation Map, Customer requirements, Energy Balance and Utility Requirements (PFD-300), Spec. Sheets |
| Hugo Dignoes Ricart | Market and Competitive Analysis, Environmental Impact and Permitting, Process Overview (sec. PFD-400), Energy Balance and Utility Requirements. Spec. Sheets, Appendix H, References, Edits |
| Andrea Hurtado Fuentes | Nomenclature/Abbreviations, List of Tables List of Figures, Introduction and Project Charter, Appendix I, Stream Tables, References, Final Revising and Formatting |
| Abhinav Kaushik | Process Description, Energy Balance and Utility Requirements, Start up & Shut down, Appendix D, Equipment spec sheets (PFD 200) |
| Nhi Nguyen | HAZOP Study, Plant Layout, Appendix A, Appendix B, Appendix C, Appendix E, Appendix F, Acknowledgements |
| Farooq Asif Randeo | Process overview, Process descriptions (PFD-100,200,500) utility and heat integration, startup & shutdown. Equipment spec sheets (PFD 100,500), HYSYS simulations/Appendix I (PFD100,500) |
| Vaishnavi Sivaramakrishnan | Process description (PFD 300), Energy Balance and Utility Requirement (PFD 300), Spec sheets, HAZOP, References, Appendix H |

18. Appendices

- A. PFDs (Nhi)
- B. P&ID and Cause and Effect Matrix (Nhi)
- C. Equipment List and Specification Sheets - done (Nhi)
- D. Detail Start Up and Shut Down (Abhi)
- E. HAZOP Study - done (Nhi)
- F. Plant Layout - done (Nhi)
- G. Economic Analysis (Misha)
- H. Chemical Database (Hugo)
- I. Sample Calculations and Simulations
- J. Any Additional Information (Add more if needed)

APPENDIX A

PFDs

APPENDIX B

P&ID and Cause and Effect Matrix

APPENDIX C

Equipment List and Specification

APPENDIX D

Start Up and Shut Down

PLANT START-UP

| Start Up Checklist | |
|--|--|
| Pre Start Up: | |
| <ol style="list-style-type: none">1. Flush all lines and purge with nitrogen2. Turn on all indicators/transmitters (temperature, pressure, flow) in the whole plant and set all controllers to operator manual control.3. Turn on ‘fire eyes’ (Heat detection system) | |
| Plant Start-Up: | |
| <ol style="list-style-type: none">1. Start DCS control system in manual mode to avoid trip interlocks due to empty tanks2. Fill tanks TK-101 and TK-5013. Circulate cooling water and refrigerant line to all respective heat exchangers4. Turn on boiler for steam production5. Circulate steam to all heating required element | |
| Start Up PFD-300 | |
| <ol style="list-style-type: none">1. Turn on pump P-301, feeding water to deionizer and storage tank TK-3012. Once TK-301 is at the appropriate level, turn on P-302 and electrolyzer unit3. Turn on compressor C-301 to store produced hydrogen for usage downstream4. Store discharge oxygen and cycle water produced to the raw water tank | |
| Start Up PFD-500 | |
| <ol style="list-style-type: none">1. Make sure all utilities are ‘on’ and the hydraulic equipment is running (K-501)2. Ensure the RNG heater E-502 and cooler E-502 are running and desired liquid temperature in the tank is achieved3. Once other sections of the plant are ready, the isolation valves should be at their normal positions | |
| Start Up PFD-400 | |
| <ol style="list-style-type: none">1. Start circulating cooling water through Cooler E-402 and Reactor R-4012. Turn on Compressors C-401 and C-4033. Set pressure control loops on Streams 401,402 and 4054. Set temperature control loops on Reactor R-401 and Interstage Cooler E-401 | |

Start Up PFD-200

1. Ensure the associated utility (electricity) for E-201 is turned on
2. Turn on compressor C-201
3. Once other sections of the plant are ready, the isolation valves should be at their normal positions

Start Up PFD-100

1. Make sure all utilities are ‘on’ and the hydraulic equipment is running[VJI]
2. Ensure the reboiler is running and desired liquid temperature in the tank is achieved
3. Turn on the pump to recirculate TEG
4. Introduce feed (biogas)

PLANT SHUT-DOWN

Shut Down Checklist**Shut Down PFD-100**

1. Close biogas feed inlet
2. Close the control valve of the TEG supply tank (TK-101)
3. Turn off Reboiler to stop stream feed.
4. Turn off the hydraulic (P-101)
5. Turn off utility supply to cooler (E-101) and heater (E-102)
6. Isolate and drain equipment

Shut Down PFD-200

1. Turn off the hydraulic equipment (C-201)
2. Turn off utility for cooler (E-201)
3. Isolate and drain equipment

Shut Down PFD-300

1. Turn off pump P-301, feeding water to deionizer and storage tank TK-301
2. Turn off P-302 and electrolyzer unit
3. Purge compressor C-301 with nitrogen
4. Turn off compressor C-301

- | |
|---|
| 5. Store discharge water from electrolyzer unit to the raw water tank |
| Shut Down PFD-400 |
| <ul style="list-style-type: none">1. Shut off feeds from PFD 300 and PFD 2002. Switch all control loops to manual3. Turn off Compressor C-401 and C-4034. Shut off cooling water and high pressure steam feeds5. Purge compressors E-401 and E-402, and reactor R-401 with nitrogen gas and it is sent flare6. Release pressure in Reactor R-401 and sent to flare |
| Shut Down PFD-500 |
| <ul style="list-style-type: none">1. Make sure all utilities are off (E-501, E-502)2. Ensure that Expander (K-501) is turned off3. Isolate and drain equipment |

- 1. Shut off feeds from PFD 300 and PFD 200
- 2. Switch all control loops to manual
- 3. Turn off Compressor C-401 and C-403
- 4. Shut off cooling water and high pressure steam feeds
- 5. Purge compressors E-401 and E-402, and reactor R-401 with nitrogen gas and it is sent flare
- 6. Release pressure in Reactor R-401 and sent to flare

Shut Down PFD-500

- 1. Make sure all utilities are off (E-501, E-502)
- 2. Ensure that Expander (K-501) is turned off
- 3. Isolate and drain equipment

APPENDIX E

HAZOP Study

APPENDIX F

Plant Layout

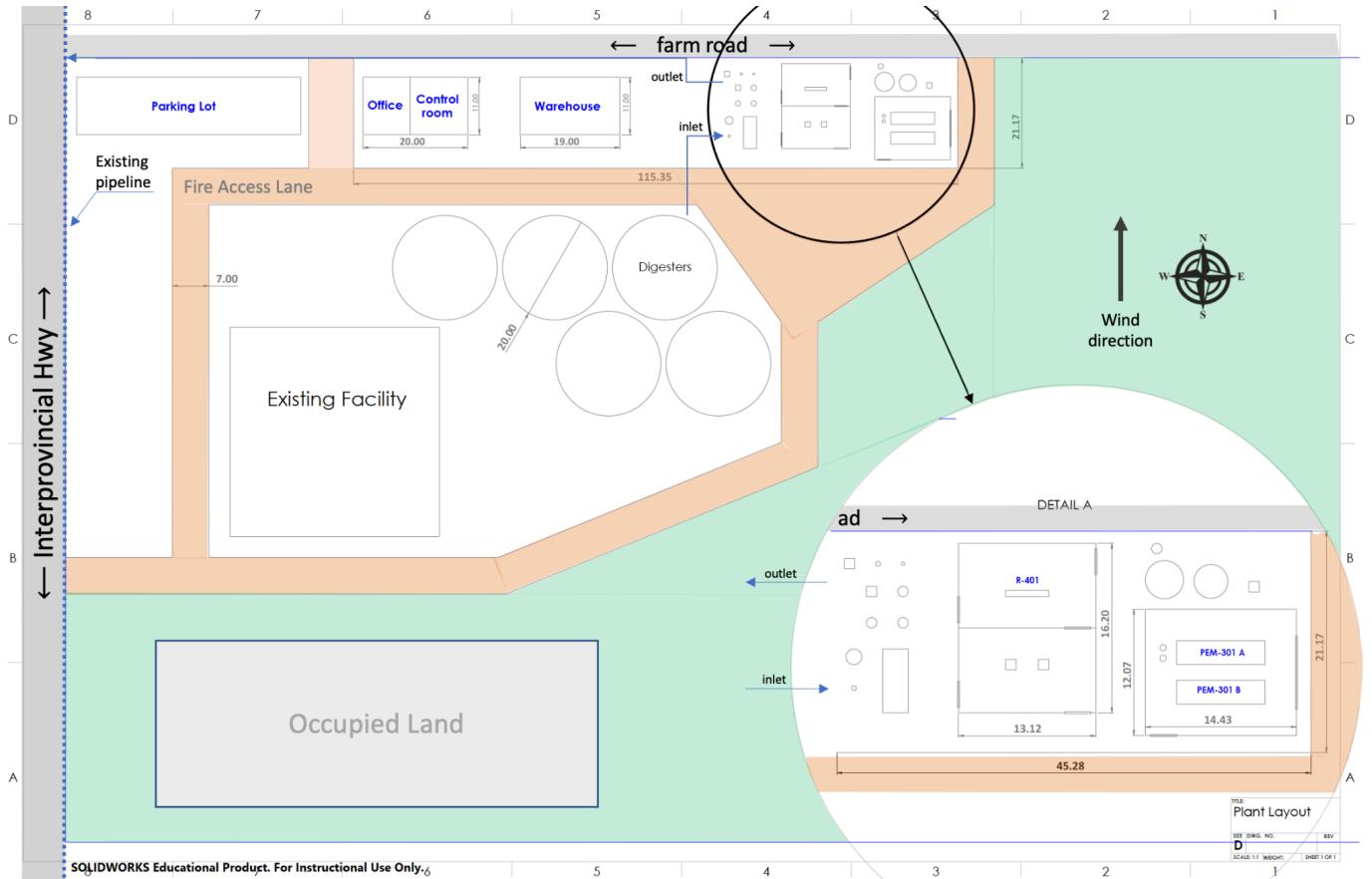


Figure E-1: SOLIDWORKS 2-D drawing of the plant layout. DETAIL A shows the layout of the equipment. Unit of measurement is in meters.

APPENDIX G

Economic Analysis

APPENDIX H

Assembly of Database

Table H-1: Physical Properties of All Components [H3]

| Property | Units | Components | | | | | |
|----------------|-------------------|------------|---------|-------|---------|--------|---|
| | | CO2 | H2 | H2O | CH4 | H2S | TEG |
| Formula | | - | - | - | - | - | C ₆ H ₁₄ O ₄ |
| Molecular Mass | kg/kmo | 44.01 | 2.02 | 18.02 | 16.04 | 34.08 | 150.17 |
| Boiling Point | °C | -78.45 | -252.76 | 100 | -161.49 | -60.35 | 288.35 |
| Mass Density | kg/m ³ | 2.44 | 0.11 | 1.01 | 0.89 | 1.89 | 11.54 |
| Heat Capacity | kJ/kg•K | 0.851 | 14.3 | 4.52 | 2.23 | 1.01 | 1.88 |
| Viscosity | cP | 0.015 | 0.009 | 0.913 | 0.011 | 0.013 | 37.422 |

All values are reported at 25°C, 1bar. They are reported for the prevalent phase under these conditions. Note that some values may disagree with literature. This is likely due to Aspen estimation deviations. They are purposefully reported as they are since these values were used in our analyses.

Table H-2: Reaction Rate Parameters, Equation, and Equilibrium Constant [H1] [H2]

| | |
|---|---|
| CO ₂ + 4H ₂ → CH ₄ + 2H ₂ O + heat | ΔH = -165 kJ/mol at 298 K |
| -r _a = k _a • P ^α _{H₂} • P ^β _{CO₂} • (1 - $\frac{P_{CH_4} \cdot P_{H_2O}^2}{P_{H_2}^4 \cdot P_{CO_2} \cdot K_{Eqlbm}}$) | α = 0.96 β = 0.41 $k_a = 1.94 \cdot e^{\frac{E_a}{8.314T \cdot 10^{-3}}}$ = 21711 at 270°C E _a = 42.1 kJ/mol |
| K _{Eqlbm} = approx. 2.2E+7 at 270°C | Given the size of the pre-exponential factor and equilibrium term, the last term of the rate equation can be removed (even at very low H ₂ & CO ₂ partial pressures). This allows the power law to be plugged into Aspen. |

[H1] Marocco, P., Morosanu, E., Giglio, E., Ferrero, D., Mebrahtu, C., & Lanzini, A. et al. (2018). CO₂ methanation over Ni/Al hydrotalcite-derived catalyst: Experimental characterization and kinetic study. *Fuel*, 225, 230-242. <https://doi.org/10.1016/j.fuel.2018.03.137>

[H2] Miller, J., Evans, L., Littlewolf, A., & Trudell, D. (1999). Batch microreactor studies of lignin and lignin model compound depolymerization by bases in alcohol solvents. *Fuel*, 78(11), 1363-1366.

[https://doi.org/10.1016/s0016-2361\(99\)00072-1](https://doi.org/10.1016/s0016-2361(99)00072-1)

[H3] Aspen Plus V11

APPENDIX I

Aspen Simulations

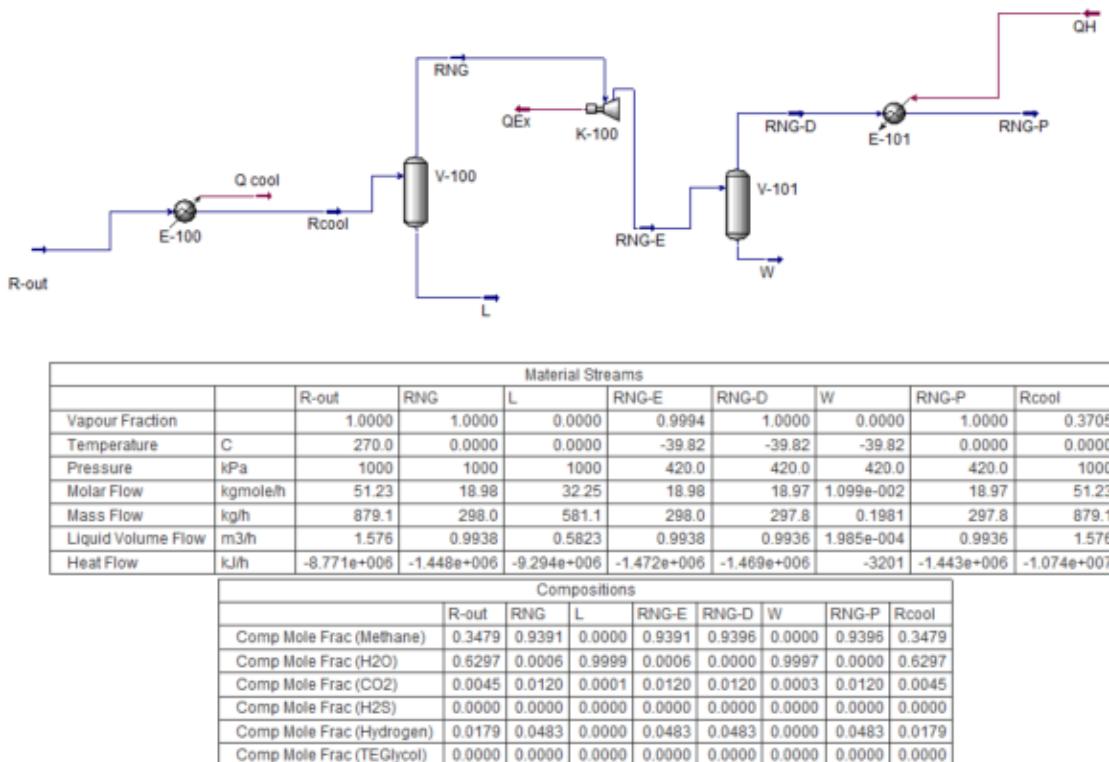


Figure I-2