April 16, 2021

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Mr. Sergio Berretta, P.Eng and Mr. Fuhar Dixit

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

The enclosed report, titled "Production of Renewable Natural Gas: Methanation of CO_2 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 CO_2 byproduct of an existing biogas upgrading process. This modular add-on process is being designed in response to the societal problem of excessive CO_2 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' CO_2 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,

Group P9: Mikhail Antyukhov, Bhushan Appadoo, Hugo Dignoes Ricart, Andrea Hurtado Fuentes, Abhinav Kaushik, Nhi Nguyen, Farooq Asif Randeo, Vaishnavi Sivaramakrishnan

CHBE 454

Final Report for the Process Design Project of "Production of Renewable Natural Gas: Methanation of CO_2 Using H_2 Obtained Through Water Electrolysis"

Presented to:

Presented to: Dr. Susan Baldwin
Dr. Jim Lim
Dr. Dusko Posarac
Dr. Jonathan Verrett
Mr. Sergio Berretta, P.Eng
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Submitted on April 16, 2021 by 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 2,100% 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 processing, 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.

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, HYSYS Simulations/Appendix I, Stream Tables, References, Formatting and Final Revision of Report
Abhinav Kaushik	Process Description, Energy Balance and Utility Requirements, Start-Up & Shut-Down, Stream Tables, 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

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Abbreviations/Nomenclature

Abbreviations	**Description**
AC	Activated Carbon
AD	Anaerobic Digester
BC	British Columbia
BFD	Block Flow Diagram
CH4	Methane
CO	Carbon Monoxide
CO2	Carbon Dioxide
DI	De-Ionized
GHG	Greenhouse Gases
H2	Hydrogen
H2O	Water
H2S	Hydrogen Sulfide
H_2SO_4	Sulfuric Acid
HAZOP	Hazard and Operability
HCl	Hydrochloric Acid
HYSYS	Aspen HYSYS
KOH	Potassium Hydroxide
LNG	Liquified Natural Gas
NaOH	Sodium Hydroxide
NH3	Ammonia
Ni	Nickel
O2	Oxygen
P&ID	Piping & Instrumentation Diagram
PEM	Polymer Electrolyte Membrane

PFD	Process Flow Diagram
PSA	Pressure Swing Adsorption
RNG	Renewable Natural Gas
SMR	Steam Methane Reforming
TEG	Triethylene Glycol

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 (CO_2) [1]. Consequently, the application of CO_2 Capture and Utilization technologies has become paramount to curb the impact of CO_2 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' CO_2 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 CO_2 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.

Table 1 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
• Initial FortisBC meeting • Project Idea Selection • Block Flow Diagram	• Proposal Report • Proposal Presentation • Units Selection	• Initial calculations • Initial PFD • Initial P&ID • Control narrative	• Progress presentation • Progress report

Table 2 shows 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
• Finalized P&ID • Cause and Effect Matrix • Equipment sizing	• Initial HAZOP • Start-Up and Shut-Down	• Plant layout • Environmental analysis • Economic analysis • Finalized HAZOP	• 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:

$$CO2 + 4H2 \rightarrow CH4 + 2H2O \; [14] \tag{1}$$

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 O_2 produced in electrolysis [8]. Producing biomethane from CO_2 posits the Sabatier reaction as an alternative to carbon sequestration methods [8]. The hydrogen consumed in the methanation of CO_2 is generated through PEM electrolyzers. When powered by renewable sources of energy, electrolysis produces green hydrogen, which refers to hydrogen produced without any CO_2 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 CO_2 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 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 (H_2S) 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 1, FortisBC’s requirements for H_2S, CO_2 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	*Free from any impurities*	
Hydrogen Sulphide (H_2S)	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 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

6.1 Process Overview

The overall process is divided into five sections as shown in Figure 2 below and consists of five diagrams: 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/m^3) 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 (H_2S) in trace amounts which must be removed according to product specifications ($H_2S < 6$mg/m^3). 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 H_2S 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 H_2S, water residue, and oxygen (if present) are removed. The desulfurized biogas with methane (RNG) and carbon dioxide (CO_2) 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 CO_2 is sent to the methanation reactor for production of additional RNG according to the Sabatier reaction ($CO_2 + 4H_2 \Leftrightarrow CH_4 + 2H_2O$). 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.

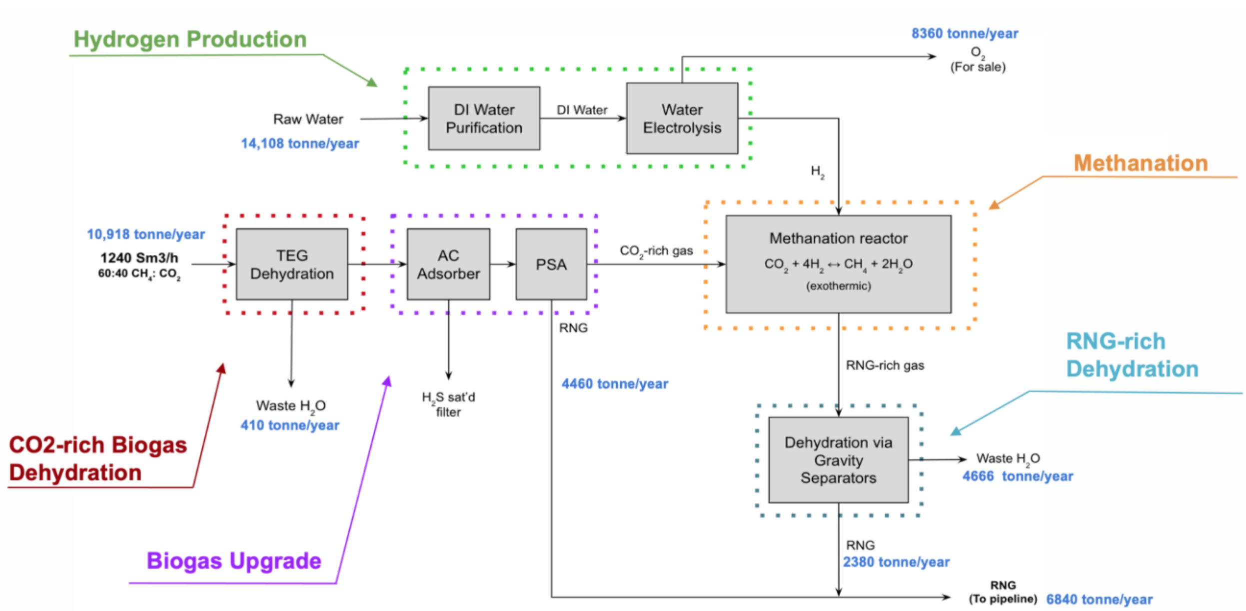

Figure 2. Block Flow Diagram (BFD) of main operations in this process

6.2 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 A1), 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.

6.3 PFD - 200: Desulfurization and Biogas Upgrade

Biogas upgrading process involves purification of high carbon dioxide (CO_2) rich biogas to biomethane. It also contains a minor volume of hydrogen sulfide (H_2S). BC Oil and Gas Commission has set-up mandatory guidelines for H_2S processing treatment, as H_2S 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 H_2S 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 H_2S is under 0.002 kmol/hr which is far below FortisBC's gas spec of 4 ppm H_2S.

Next step in the upgrading is the removal of CO_2 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 CO_2 in the biogas is recovered and 95% of CH_4 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 CO_2: (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 CO_2 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.

6.4 PFD - 300: Water electrolysis

The hydrogen required for the methanation of CO_2 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 H_2.

6.5 PFD - 400

The CO_2-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 H_2:CO_2, 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 CO_2 is reduced to methane gas, forming water vapor as a byproduct. According to literature kinetics, the expected single-pass conversion of CO_2 is upwards of 99% [22]. This is supported by Aspen Plus simulations. The CH_4-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.

6.6 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

7.1 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.

7.2 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 black boxed, 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.

7.3 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.

7.4 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.

7. 5 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

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

8.2 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.

8.3 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.

8.4 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.

8.5 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.

8.6 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.

8.7 Pipe Sizing

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

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

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

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

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

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 3.

Table 3. Major Deviations and their respective Consequences, and Safeguards

Major Deviations	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 equipment/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

10.1 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 used.

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

10.2 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 3 demonstrates the Total Capital Investment breakdown in the pie chart form.

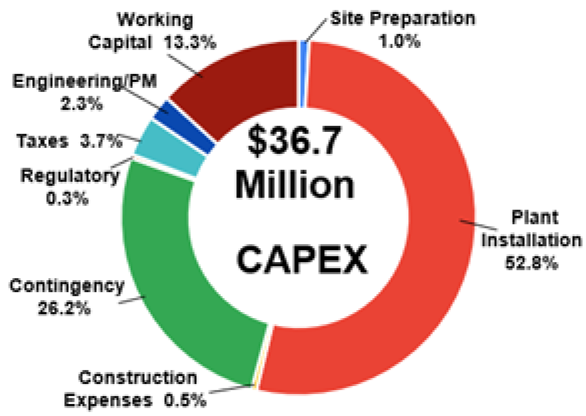

Figure 3. Total Project Capital Cost Breakdown

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.

10.3 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.

10.4 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.

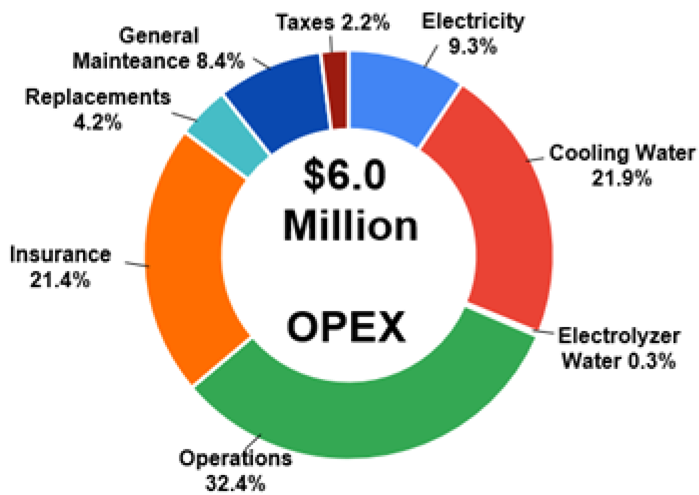

Figure 4. Total Annual Operating Cost Breakdown

10.5 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.

10.6 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.

10.7 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 4. Operation 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

10.8 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.

10.9 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 5 summarizes the total expense for the utilities and their total requirements.

Table 5. Total Utility Requirements

	Electricity (KWh/year)	Cooling Water (kg/year)	Electricity Cost (CAD/year)	Cooling Water Cost (CAD/year)	Total Operating Utility Cost (CAD/year)
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 (inc. tax)	–	–	$593,041	$1,398,544	$1,991,585

10.10 Project Economics

10.10.1 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 Table 6 below.

Table 6. 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].

10.10.2 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 5 below illustrates the flow of cash over 20 years. It can be observed that operational expense outweighs the revenue obtained from the RNG sales.

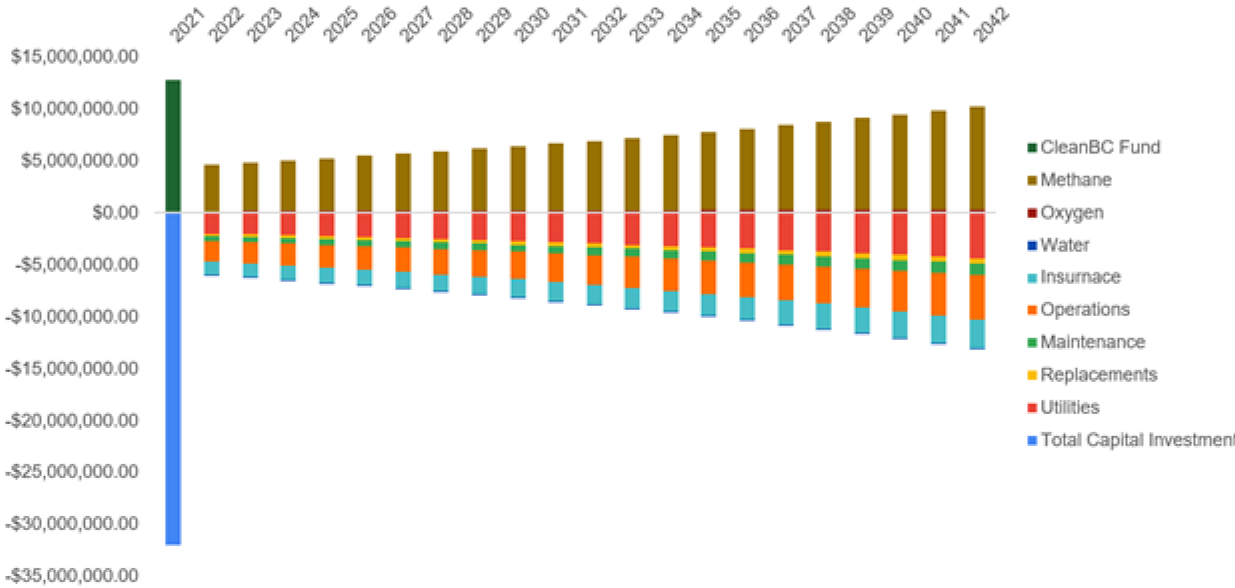

Figure 5. Cash Flow Diagram for the proposed process over 20 years

10.10.3 Breakeven Scenarios

10.10.3.1 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.

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

The plant biogas feed stream needs to be scaled by 2,100% 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 for the scaled-up plant is shown in Figure 6 below.

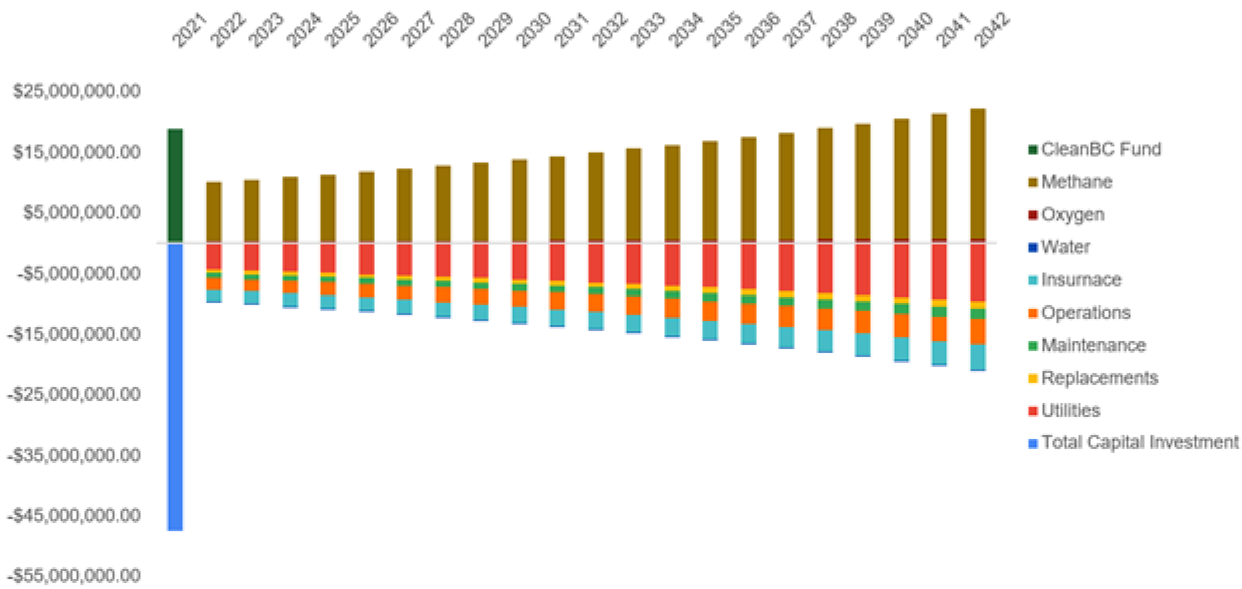

Figure 6. Cashflow diagram over 20 years for breakeven scenario where the biogas feed is increased by 2,100%

10.10.3.2 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.

10.10.3.3 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 7. 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 7. Area selected (denoted by 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

11.1 PFD 100 – TEG dehydration

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% H_2O, < 1 mol% TEG, and < 0.1 mol% CO_2. Given that this TEG is considered non-toxic and is present in concentrations under 4ppm, this can be safely discharged to the environment.

11.2 PFD 200 – Desulfurization

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. Thus, GHG and H_2S emissions guidelines by BC Oil & Gas Commission do not apply in this process. The AC filters used would be sent to recycle plants as activated carbon can be recycled or used as fuel in kiln in other processes.

11.3 PFD 300 - Deionizer

The regeneration of the resins is performed by flowing hydrochloric acid (HCl) or sulfuric acid (H_2SO_4) 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 ft^3 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 electrolyzer 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 neutralize 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 neutralized using HCl until the pH is in the range of 6 to 8 [35].

11.4 PFD 400 – Nickel based catalyst

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

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 highly pressurized 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 shutdown includes the preparation of emergency procedure and maintenance checklists by operating staff. Moreover, it is a good practice to keep an updated inventory of 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 electrolyzer and Hydrogen and Oxygen are produced and 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.

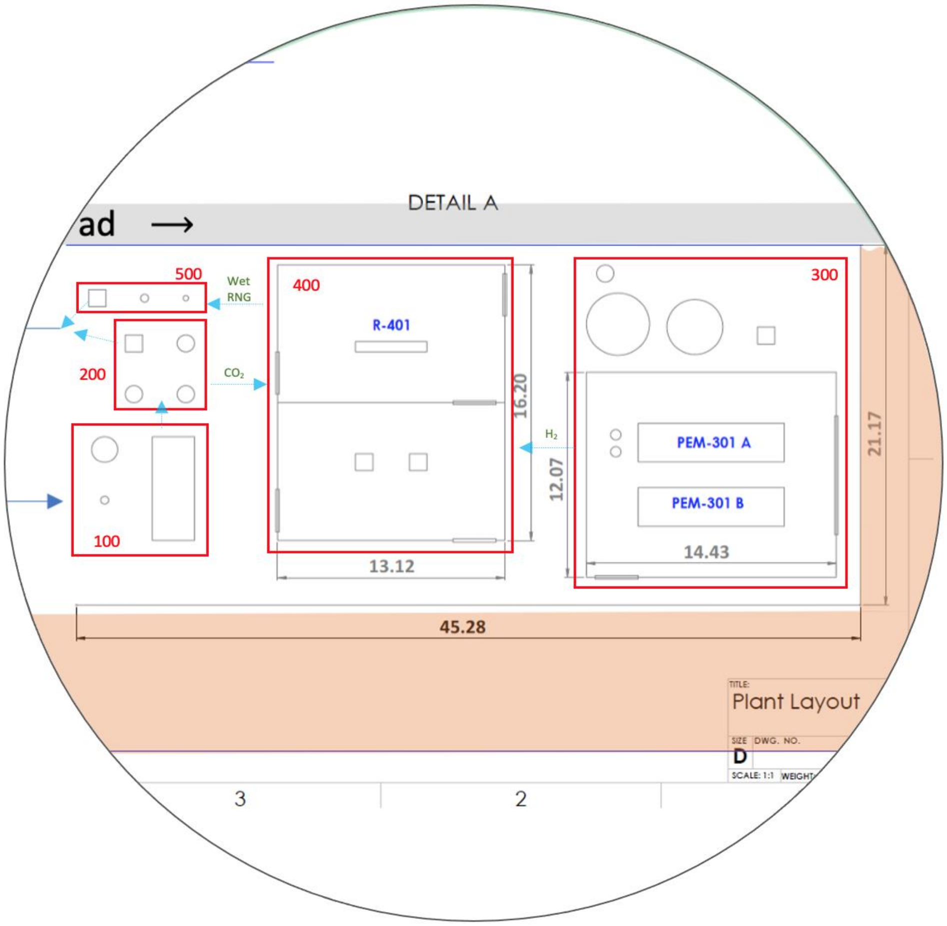

Figure 8. Zoom-in view of the stand-alone process. The equipment in each section is boxed in red and the material flow is indicated by the blue arrows. Section 100, 200, 300, 400, and 500 refer to Biogas Dehydration, Biogas Upgrading, Hydrogen Production, Methanation and Post-treatment.

The footprint of this plant is determined to be approximately 150m x 20m (3000m^2). 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 8. 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 using high visibility tape. 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 Electrolyzer. 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.

15. Acknowledgements

Group P9 would like to thank the following UBC faculty professors and advisors as well as our advisor from FortisBC for support, guidance, resources, and time they dedicated to our project:

Dr. Jonathan Verrett

Dr. Dusko Posarac

Dr. Susan Baldwin

Dr. Jim Lim

Sergio Berretta, P.Eng

Joseph Broda, P.Eng

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17. Appendices

A. PFDs

B. P&ID and Cause and Effect Matrix

C. Equipment List and Specification Sheets

D. Detail Start Up and Shut Down

E. HAZOP Study

F. Plant Layout

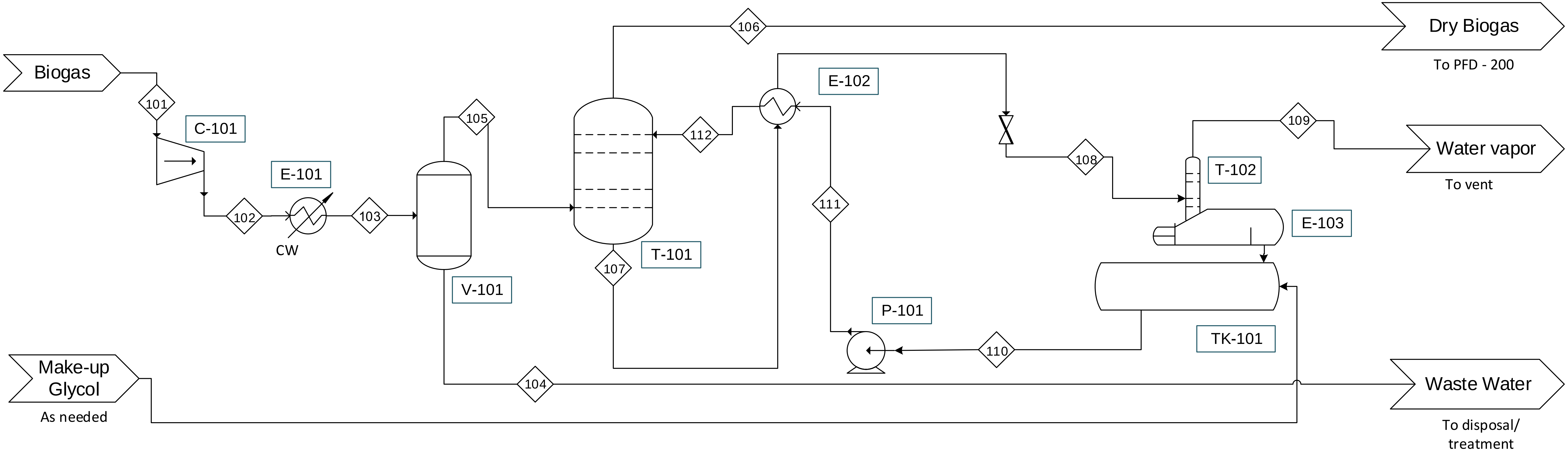
G. Economic Analysis

H. Chemical Database

I. Simulations

APPENDIX A

PFDs



Compressor	Biogas Cooler	Flash Drum	TEG Contactor Tray Tower	Glycol-Glycol Heat Exchanger	Still Column	Reboiler	Surge Tank	Lean Glycol Pump
C-101	E-101	V-101	T-101	E-102	T-102	E-103	TK-101	P-101

Stream numbers	101	102	103 (Liquid phase)	103 (Vapour phase)	104	105	106	107	108 (Liquid phase)	108 (Vapour phase)	109	110	111	112	113
Total mass flow	kg/hr	1364.84	1364.84	1313.48	51.36	51.36	1313.48	1306	215.5	215.5	215.5	9.15	208.1	208.1	208.1
Temperature	°C	38	247.63	38	38	38	38	47.65	44.71	188.6	188.6	188.6	200	200.1	48
Pressure	kPa	108	800	800	800	800	800	800	800	700.6	700.6	102	102	800	800
Biomethane	kmol/hr	34.64	34.64	0	34.64	0	34.64	34.64	0	0	0	0	0	0	0
Carbon Dioxide	kmol/hr	17.007	17.007	0.003	17.004	0.003	17.004	17.002	0	0	0	0	0	0	0
Water	kmol/hr	3.3	3.3	2.84	0.46	2.84	0.46	0.05	0.5	0.5	0	0.36	0.1	0.1	0.1
Hydrogen sulfide	kmol/hr	0.04	0.04	0.04	0	0	0.04	0.04	0	0	0	0	0	0	0
Hydrogen	kmol/hr	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Oxygen	kmol/hr	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nitrogen	kmol/hr	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TEGlycol	kmol/hr	0	0	0	0	0	0	0	1.37	1.37	0	0.02	1.37	1.37	1.37
Density	kg/m3	1.04	7.96	990.25	7.96	990.25	7.96	7.71	1,100.00	988.89	6.58	0.65	983.8	983.7	1,102.00
Viscosity	cP	0.01	0.02	0.69	0.01	0.69	0.01	0.01	13.98	0.84	0.02	0.02	0.78	0.78	13.89
Heat Capacity	kJ/kg•°C	1.14	1.53	3.78	1.13	3.78	1.13	1.15	2.08	2.6	1.07	1.54	2.56	2.56	2.05

Notes:

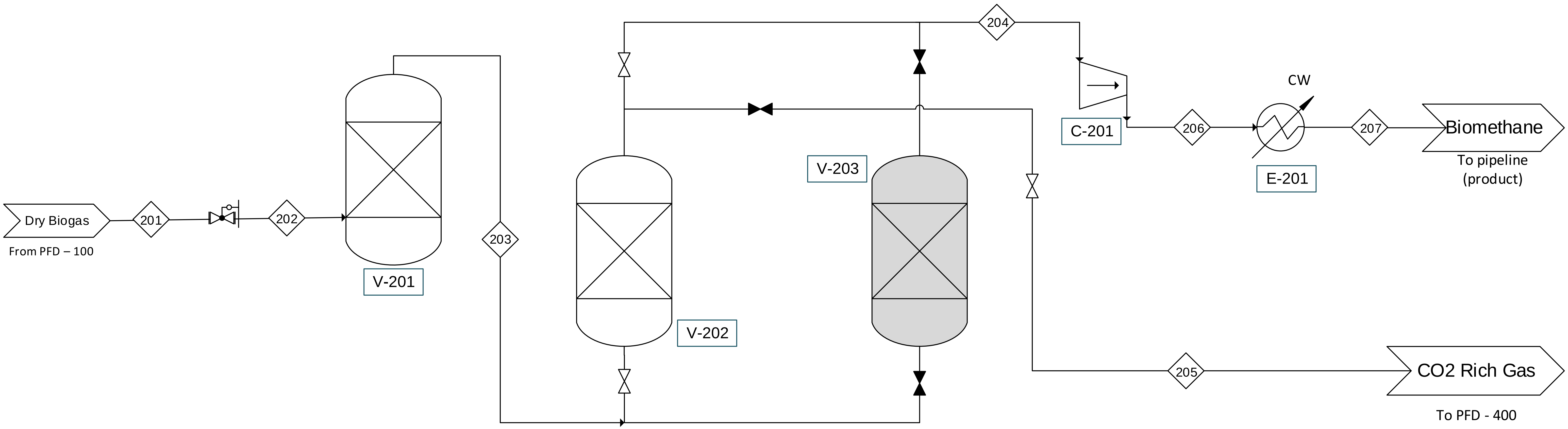
Revision	Description	Date	Worked by	Approved by
A	For Review	11-06-2020	FR	
B	For Review	12-11-2020	FR	
C	For Review	03-21-2021	AF	

UBC Engineering Ltd.

UBC Design Project - CO2 Methanation Plant

Gas dehydration & sweetening Process Flowsheett

Drawing No. D-1-1001



Activated Carbon Adsorber	PSA Adsorber	PSA Stripper	Compressor	Cooler
V-201	V-202	V-203	C-201	E-201

Stream Numbers		201	202	203	204	205	206	207
Total Mass Flow	kg/hr	1306.000	1306.000	1306.000	557.5	748.500	557.5	557.5
Temperature	°C	48.510	45.390	45.390	30.000	30.000	102.100	30.000
Pressure	kPa	800.000	300.000	300.000	200.000	200.000	420.000	420.000
Biomethane	kmol/hr	34.640	34.640	34.640	32.910	1.730	32.910	32.910
Carbon dioxide	kmol/hr	17.000	17.000	17.000	0.670	16.330	0.670	0.670
Water vapour	kmol/hr	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Hydrogen sulfide	kmol/hr	0.040	0.040	0.000	0.000	0.000	0.000	0.000
Density	kg/m3	2.880	2.880	2.880	1.320	3.310	2.240	2.790
Viscosity	cP	0.010	0.010	0.010	0.010	0.010	0.010	0.010
Heat capacity	kJ/kg°C	1.480	1.500	1.500	2.190	0.930	2.390	2.200

Notes:	Revision	Description	Date	Worked by	Approved by
	A	For Review	11-06-2020	AK	
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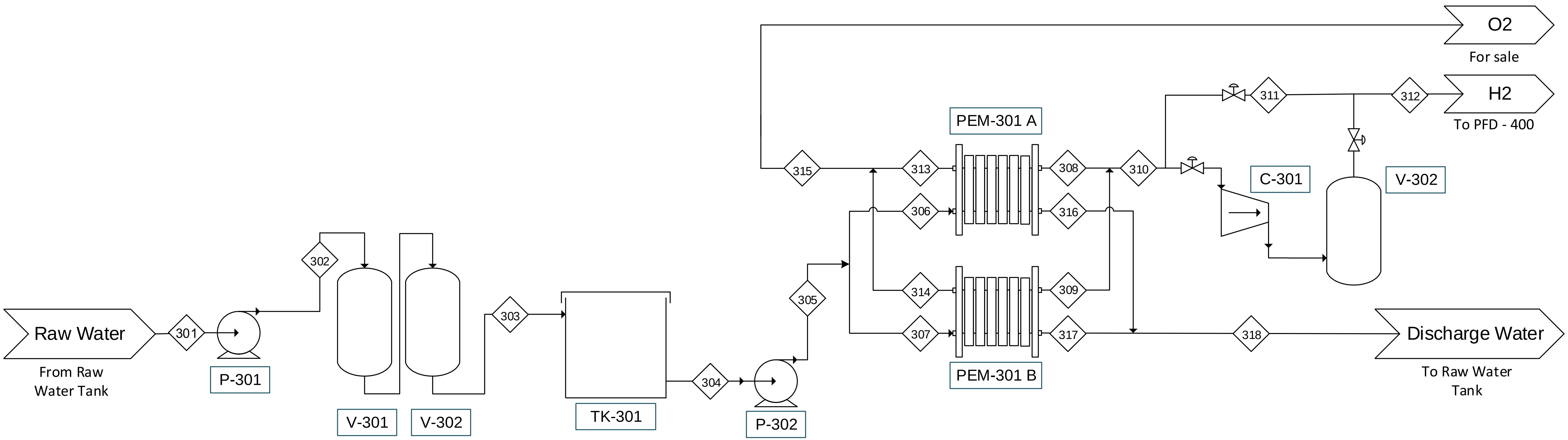
UBC Engineering Ltd.	
UBC Design Project - CO2 Methanation Plant	
Gas dehydration & sweetening Process Flowsheet	Drawing No. D-2-1001



Raw Water Pump	Water Purification System	Anion Exchange Column	DI Water Storage Tank	DI Water Pump	PEM Electrolyzer	Compressor	H2 Storage Vessel
P-301	V-301	V-302	TK-301	P-302	PEM-301 A/B	C-301	V-302

Stream Numbers		301	302	303	304	305	306	307	308	309	310	311	312	313	314	315	316	317	318
Total Mass Flow	kg/hr	1763.50	1763.50	1763.50	1763.50	1763.50	881.75	881.75	66.60	66.60	133.20	133.20	133.20	522.50	522.50	1045.00	294.20	294.20	588.40
Temperature	°C	25	25.4	25.4	25	26.2	26.2	26.2	80	80	80	80	80	25	25	25	25	25	25
Pressure	kPa	100	1030	1030	100	3000	3000	3000	3000	3000	3000	3000	3000	100	100	100	100	100	100
Water	kmol/hr	97.89	97.89	97.89	97.89	97.89	48.945	48.945	0	0	0.000	0.000	0.000	0	0	0	16.33	16.33	32.66
Hydrogen	kmol/hr	0	0	0	0	0	0	0	33.05	33.05	66.100	66.100	66.100	0	0	0	0	0	0
Oxygen	kmol/hr	0	0	0	0	0	0	0	0	0	0.000	0.000	0.000	16.33	16.330	32.66	0	0	0
Density	kg/m3	993.957	993.571	993.571	993.957	992.799	992.799	992.799	2.060	2.060	2.033	2.033	2.033	1.291	1.291	993.957	993.957	993.957	993.957
Viscosity	cP	0.912	0.905	0.905	0.912	0.889	0.889	0.889	0.010	0.010	0.011	0.011	0.011	0.021	0.011	0.913	0.913	0.913	0.913
Heat capacity	kJ/kg°C	4.120	4.121	4.121	4.120	4.124	4.124	4.124	14.416	14.416	14.483	14.483	14.483	0.917	0.917	4.120	4.120	4.120	4.120

Notes:

Revision	Description	Date	Worked by	Approved by
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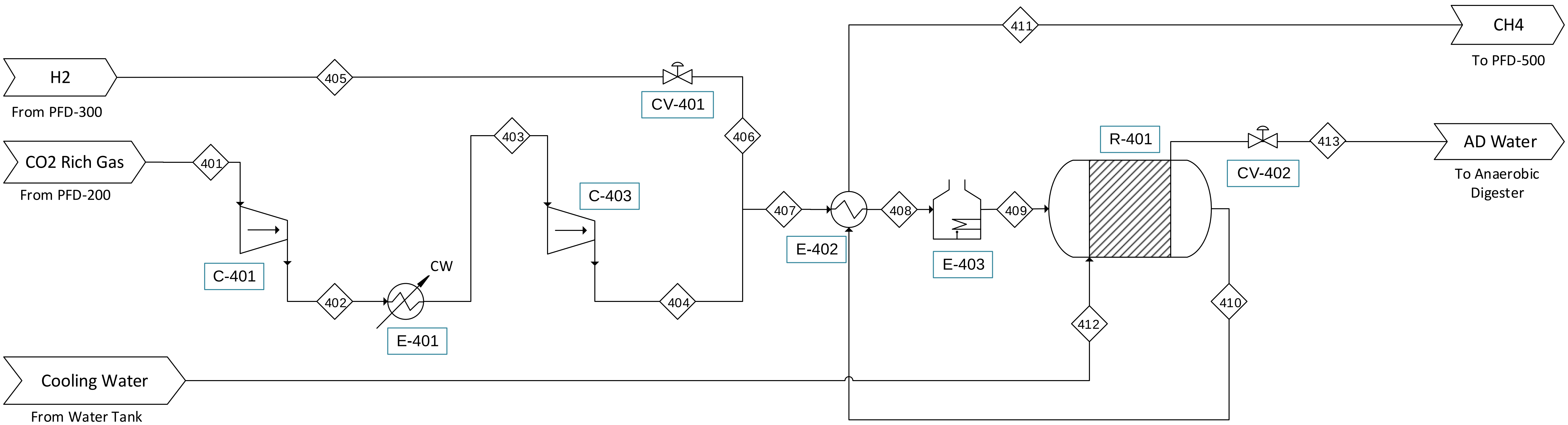
UBC Design Project - CO2 Methanation Plant

Water Electrolysis Process Flowsheet	Drawing No. D-3-1001



H2 Feed Control Valve	Cooling Water Control Valve	Interstage Cooler	Heat Exchanger	First Compressor Stage	Second Compressor Stage	Furnace	Jacketed Sabatier Reactor
CV-401	CV-402	E-401	E-402	C-401	C-402	E-403	R-401

Stream Numbers		401	402	403	404	405	406	407	408	409	410	411	412	413
Total Mass Flow	kg/hr	746.593	746.593	746.593	746.593	133.20	133.20	879.16	879.16	879.16	879.16	879.16	11530.00	11530.00
Temperature	°C	30.000	109	30	107	80	81	87	237	270	270	159	20	80
Pressure	kPa	200.000	447	447	1000	3000	1000	1000	1000	1000	1000	1000	100	100
Biomethane	kmol/hr	1.732	1.732	1.732	1.732	0.000	0.000	1.732	1.732	1.732	17.900	17.900	0.000	0.000
Carbon dioxide	kmol/hr	16.330	16.330	16.330	16.330	0.000	0.000	16.330	16.330	16.330	0.163	0.163	0.000	0.000
Water	kmol/hr	0.003	0.003	0.003	0.003	0.000	0.000	0.003	0.003	0.003	32.300	32.300	1.000	1.000
Hydrogen	kmol/hr	0.000	0.000	0.000	0.000	66.100	66.100	66.100	66.100	66.100	1.410	1.410	0.000	0.000
Hydrogen sulfide	kmol/hr	0.002	0.002	0.002	0.002	0.000	0.000	0.002	0.002	0.002	0.002	0.002	0.000	0.000
Density	kg/m3	3.311	5.910	7.487	13.286	2.033	0.682	3.480	2.580	2.310	3.820	5.170	958.767	939.182
Viscosity	cP	0.015	0.019	0.015	0.019	0.011	0.010	0.016	0.020	0.021	0.021	0.017	0.736	0.355
Heat capacity	kJ/kg°C	0.934	1.002	0.926	1.019	14.483	14.400	3.022	3.120	3.155	2.410	2.430	4.526	4.560

Notes:	Revision	Description	Date	Worked by	Approved by
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UBC Engineering Ltd.	
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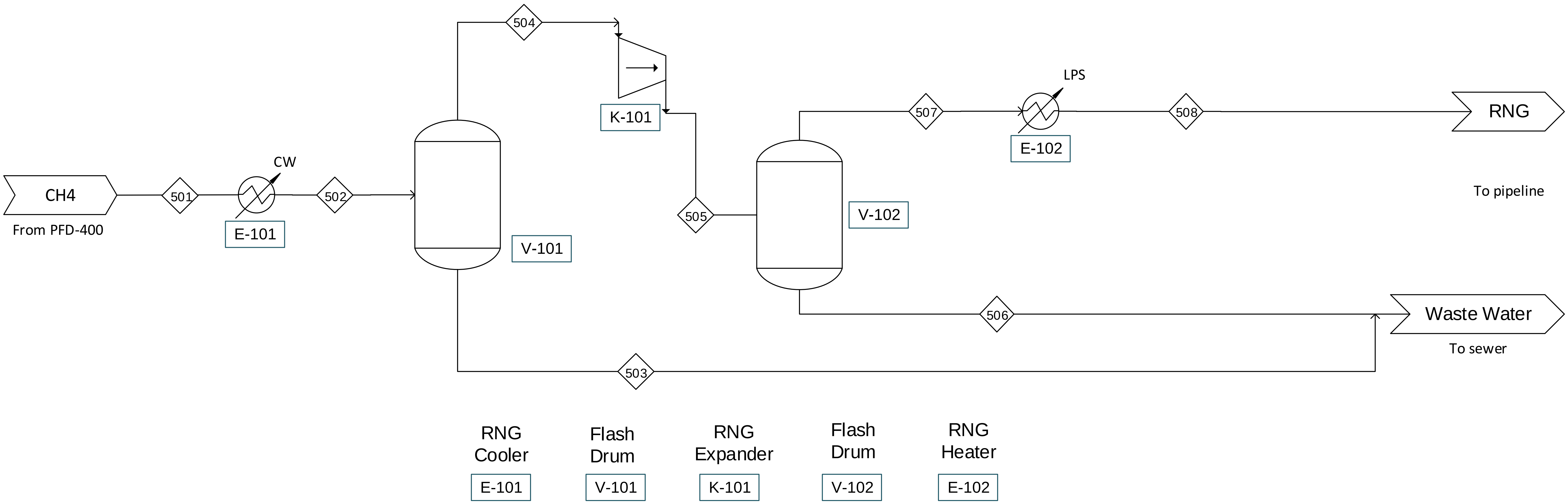
Methanation Process Flowsheett	Drawing No. D-4-1001



Stream Numbers		501	502	503	504	505	506	507	508					
Total Mass Flow	kg/hr	879.160	581.100	298.060	581.100	298.06	0.20	297.79	0.20	297.79	297.79			
Temperature	°C	270.000	0	0	0	0	-40	-40	-40	-40	0			
Pressure	kPa	1000.000	1000	1000	1000	100	420	420	420	420	420			
Biomethane	kmol/hr	17.820	0.000	17.820	0.000	17.820	0.000	17.820	0.000	17.820	17.820			
Carbon dioxide	kmol/hr	0.230	0.000	0.230	0.000	0.230	0.000	0.230	0.000	0.230	0.230			
Water	kmol/hr	32.260	32.250	0.010	32.250	0.010	0.010	0.000	0.010	0.000	0.000			
Hydrogen	kmol/hr	0.920	0.000	0.920	0.000	0.000	0.000	0.920	0.000	0.920	0.920			
Hydrogen sulfide	kmol/hr	0.000	0.000	0.000	0.000	0.920	0.000	0.000	0.000	0.000	0.000			
Density	kg/m3	3.850	1026.000	7.100	1026.000	7.100	1054.590	3.460	1054.590	3.460	2.940			
Viscosity	cP	0.020	1.750	0.010	1.750	0.010	5.130	0.010	5.130	0.010	0.010			
Heat capacity	kJ/kg°C	1.870	3.830	1.690	3.830	1.690	4.030	1.620	4.030	1.620	1.690			

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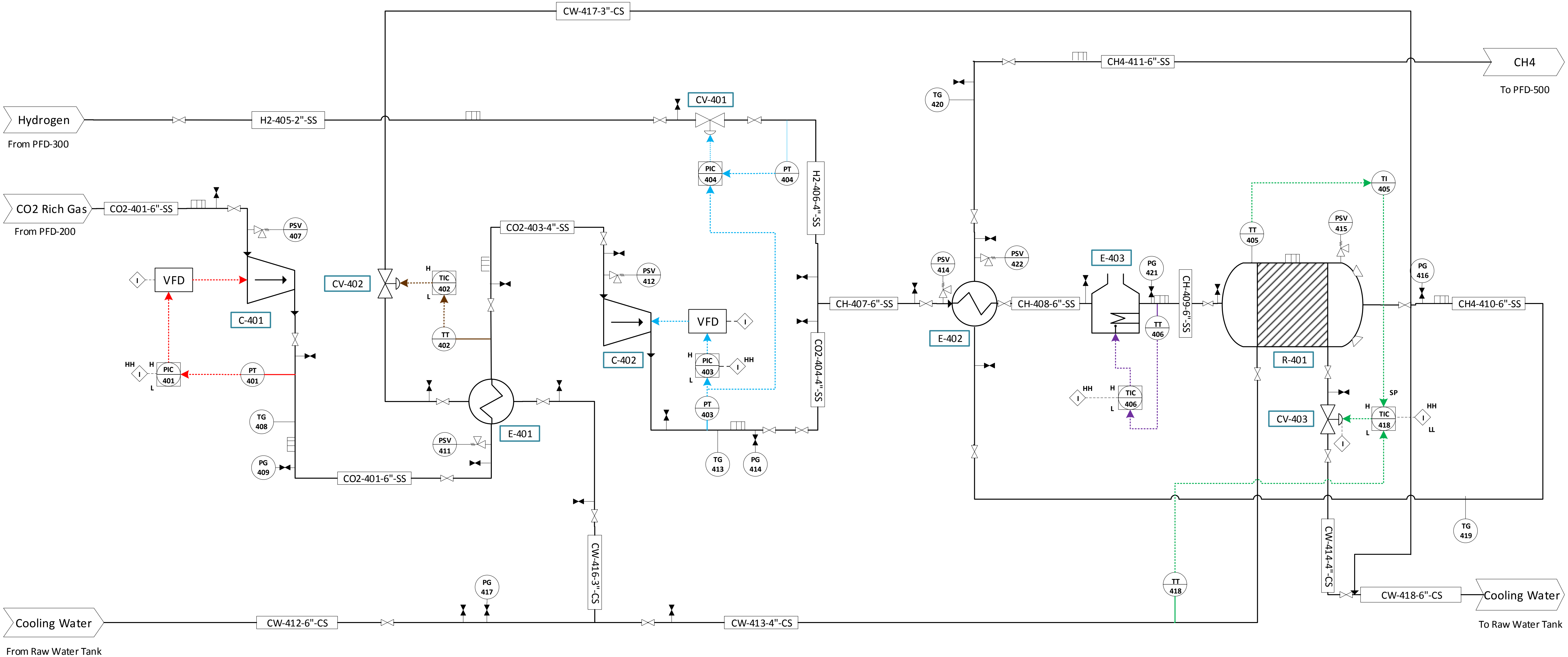
	B	For Review	12-12-2020	NN, AHF			RNG dehydration Process Flowsheett	Drawing No. D-5-1001
	C	For Review	03-21-2021	AHF, FR				

APPENDIX B

P&ID and Cause and Effect Matrix



Hydrogen
From PFD-300
H2-405-2"-SS
CO2 Rich Gas
From PFD-200
CO2-401-6"-SS
CW-417-3"-CS
CV-401
PIC 404
PT 404
H2-406-4"-SS
CO2-403-4"-SS
VFD
C-401
C-402
CV-402
TIC 402
TT 402
PIC 401
PT 401
PSV 407
PSV 412
PSV 411
TG 408
PG 409
E-401
PIC 403
PT 403
TG 413
PG 414
CO2-404-4"-SS
CW-416-3"-CS
PG 417
Cooling Water
From Raw Water Tank
CW-412-6"-CS
CW-413-4"-CS
CH4-411-6"-SS
CH4
To PFD-500
TG 420
PSV 414
PSV 422
CH-407-6"-SS
E-402
CH-408-6"-SS
E-403
PG 421
TT 406
TIC 406
CH-409-6"-SS
TT 405
TI 405
PSV 415
R-401
PG 416
CH4-410-6"-SS
CV-403
TIC 418
TT 418
TG 419
CW-414-4"-CS
CW-418-6"-CS
Cooling Water
To Raw Water Tank

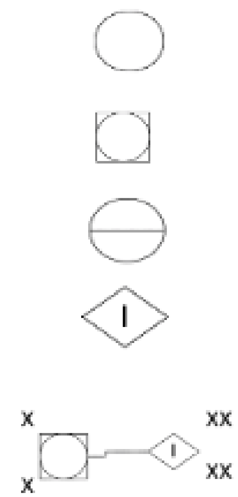
P&ID LEGEND

Instruments

XX:
- PG (Local Pressure Gauge)
- PSV (Pressure Safety Valve)
- FT (Flow Transmitter)
- CV (Flow Control Valve)
- PIC (Pressure Indicator and Controller)
- PC (Pressure Controller)
- PPIC (Ration Pressure Indicator and Controller)
- TC (Temperature Controller)
- TI (Temperature Indicator)
- TIC (Temperature Indicator and Controller)

Control Valve
Pressure Safety Valve

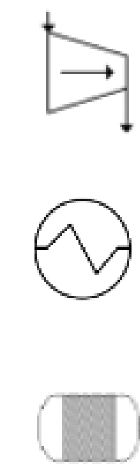
General Control Symbols



Locally Mounted Instruments
Remote Control System
Local Control System
Interlock

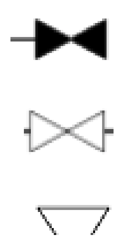
X: H (High alarm)
L (Low alarm)
XX: HH (High interlock)
LL (Low interlock)

Equipment Symbols



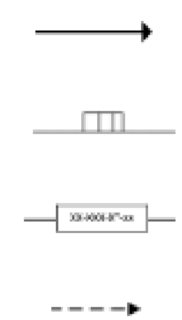
Compressor
Heat Exchanger
Reactor

Miscellaneous Symbols



Local Isolation Closed Valve
Local Isolation Open Valve
Man-Ways

Line Legend



Pipe
Insulation
Pipe Specifications
Electric Signal

XX	Service Description
CO2	CO2 Rich Line
H2	H2 Rich Line
CW	Cooling Water Line
HPS	High Pressure steam Line
CH4	Methane Rich Line
CH	Reactor Feed Line
XXX	Line Number
X	Line Size
xx	Material of Construction
CS:	Carbon Steel
SS	Stainless Steel

Notes	Revision	Description	Date	Worked By	Approved By		Group P9
	A	For Review	12/01/2020	MA			Production of Renewable Natural Gas: Methanation of CO2 Using H2 Obtained Through Water Electrolysis
	B	For Review	21/03/2021	MA, NN		This drawing is the property of UBC and its content is confidential and shall not be copied	Sabatier Reactor P&ID — Drawing No: D-400-1000

Cause & Effect Matrix

EFFECT (OUTPUTS)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	Rev
TAG No.	C-401	C-402	E-403	E-403	CV-403	CV-403													
P&ID	4001	4001	4001	4001	4001	4001													
SERVICE DESCRIPTION	First Compressor Stage	Second Compressor Stage	Furnance Electricity Supply	Furnace Electricity Supply	Cooling Water Supply Valve	Cooling Water Supply Valve													

LEGEND & NOTES

Legend:
C = CLOSED
O = OPEN
SP = STOP
ST = START
I = INTERLOCK ie AUTOMATIC RESTART OF DEVICE ONCE ALARM IS CLEARED

START TIME DELAY ALLOWS TRIPS TO BE BYPASSED ON START UP FOR XX SECONDS

Notes:
1) ALL TRIPS ARE SELF-RESETTING UNLESS OTHERWISE STATED.

Reference:

CAUSE (INPUTS)

	TAG No.	P&ID	SERVICE DESCRIPTION		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	Rev	COMMENTS
1	PAHH-401	4001	High High Pressure of VFD		SP	SP																		
2	PAHH-403	4001	High High Pressure of VFD		SP	SP																		
3	TAHH-406	4001	High High Temperature of reactor feed				C																	
4	TALL-406	4001	Low Low Temperature of reactor feed					O																
5	TAHH-418	4001	High High Temperature in R-401						O															
6	TALL-418	4001	Low Low Temperature in R-401							C														
7																								
8																								
10																								
11																								
12																								
13																								
14																								
15																								
16																								
17																								

UBC Engineering Ltd. / (Capstone Project Standard)

CAUSE & EFFECT TRIP MATRIX

CLIENT NAME	PROJECT NAME	PROJECT No.

REFERENCE No. -	REFERENCE DESCRIPTION -	No.	REVISION -	DRAWN BY:	CHECKED BY:	APPROVED BY:	DATE:	DRAWING No. CE-4-1001	REV B

APPENDIX C

Equipment List and Specification

PFD No.	Equipment Tag Number	Description
100	C-101	Wet Biogas Compressor
	E-XXX	Glycol-Glycol Heat Exchanger
	V-101	Flash Drum
	T-101	Glycol Contactor
	E-102	Biogas Cooler
	T-102	Glycol Regenerator (Stripper+Reboiler)
	TK-101	Surge Tank
	P-101	Lean Glycol Pump
200	V-201	Activated Carbon Adsorber
	V-202	Pressure Swing Adsorber
	V-203	Pressure Swing Stripper
	C-201	Biomethane compressor
	E-201	Biomethane cooler
300	P-301	Raw Water Pump
	V-301	Water Purification System
	TK-301	DI Water Storage Tank
	P-302	DI Water Pump
	PEM-301 A	PEM Electrolyzer
	PEM-301 B	PEM Electrolyzer
	C-301	Compressor
	V-302	H2 Storage Vessel
400	C-401	First Compressor Stage
	C-402	Second Compressor Stage
	CV-401	Hydorgen Feed Control Valve
	CV-402	Reactor Jacket Control Valve
	E-401	Compressor Interstage Cooler
	E-402	Reactor Heater Exchanger
	E-403	Furnace
	R-401	Jacketed Sabatier Reactor
500	C-501	RNG Cooler
	V-501	Flash Drum #1
	V-502	Flash Drum #2
	E-502	Dry RNG Heater
	X-501	Expander

Table C-1: Equipment List with description for each PFD section

DATA SHEET - KNOCK OUT DRUM

UBC Engineering Ltd. - Capstone Project Standard

Column Tag: **V-101**

PLANT: FortisBC RNG Plant Abbotsford	P&ID Number - 100	PROJECT No.1

Unit Name: Knock-Out-Drum

ISSUED FOR: ✓ PROPOSAL PURCHASE AS BUILT

SERVICE: H2O removal from biogas

OPERATING CONDITIONS AND

FEED FLOW RATE (KG/H): 1365.00

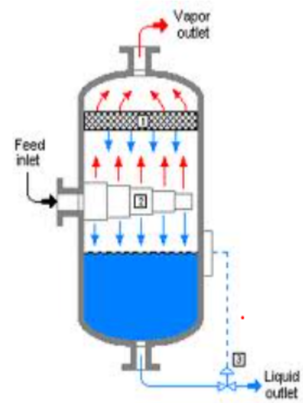
FEED COMPOSITION: Biogas 6 mol% H20

FEED TEMPERATURE - C: 38

	OUTLET CONDITIONS	
	PHASE 1	PHASE 2
	Vapor	Liquid
DESIGN FLOW RATES (KG/H)	1313	52
TEMPERATURE - C	38	38
PRESSURE - BARA	8	8
DENSITY - KG/M3	7.957	990.3
VISCOSITY (liq) - CP	-	0.6922

Phase 1 Composition: Biogas with 0.6 mol% H2O

Phase 2 Composition: Water with (0.0001 CH4 , 0.0011 CO2) mol%



KNOCK-OUT-DRUM MECHANICAL DETAILS

- DESIGN CONDITIONS -		- GEOMETRY -	
MAXIMUM DESIGN TEMPERATURE - C	100	DRUM POSITION	Vertical
MAXIMUM DESIGN PRESSURE - BARA	25	EXTERNAL DIAMETER - M	0.4572
MINIMUM DESIGN PRESSURE - BARA	1	LENGTH - M	2.515

MATERIAL OF CONSTRUCTION - SS 316

NO.	DATE	REVISION DESCRIPTION	BY	APVD.
	Jan 24 2021	For quotation purposes	AF/FR	
	March 29 2021	For quotation purposes	AF/FR/NN	

	DATA SHEET - Glycol Contactor	Column Tag
	UBC Engineering Ltd. - Capstone Project Standard	**T-101**

PLANT: FortisBC RNG Plant Abbotsford	P&ID Number - 100	PROJECT No.1

Unit Name: **Triethylene Glycol Contactor**

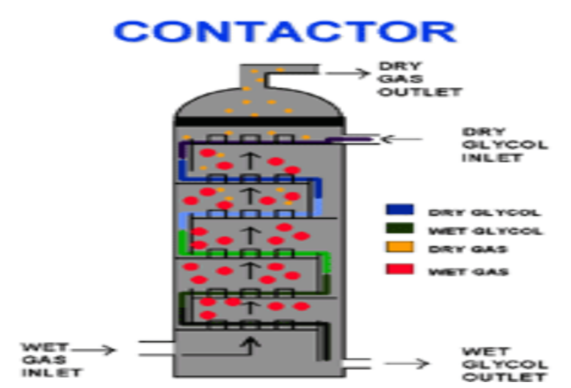
1	ISSUED FOR:	✓ PROPOSAL	PURCHASE	AS BUILT
2	SERVICE:	**Stripping of Water from CO2-rich Biomethane stream**		
3	COLUMN TYPE	✓ STRIPPER	✓ ABSORBER	
2	**OPERATING CONDITIONS AND FLUID PROPERTIES**			
3				
	FEED FLOW RATE (KG/H)	**1365**		
4	FEED COMPOSITION	**Biogas (63% CH4, 30% CO2 and 6% H2O)**		
3	FEED TEMPERATURE - C	**38**		
4				

		PACKING OR PLATE SECTION	
5		TOP	BOTTOM
4	DESIGN FLOW RATES (KG/H)		
5	VAPOR	**1307**	**-**
6	LIQUID	**-**	**216**
5	TEMPERATURE - C	**46 (dry gas outlet)**	**44**
6	PRESSURE - BARA	**8**	**8**
	DENSITY (LIQ.) - KG/M3	**-**	**1100**
7	VISCOSITY (LIQ) - CP	**-**	**14.02**
6			

OVERHEAD VAPOR COMPOSITION - **Dry Biogas (<<1% water)**

BOTTOMS COMPOSITION - **Lean Glycol (26.8 mol% water, 73.1 mol% glycol)**

7	**COLUMN MECHANICAL DETAILS**		
8	COLUMN DIAMTER - M	**1.50**	
7			
8	PACKING OR TRAY SECTION HEIGHT - M	**4**	
9	MAXIMUM DESIGN TEMPERATURE - C	**45**	
8	MAXIMUM DESIGN PRESSURE - BARA	**50**	
9	MINIMUM DESIGN PRESSURE - BARA	**6**	
10	RANDOM PACKING		TRAYS
9			
10	PACKING TYPE -	**1" Nutter Ring/ PALL**	
	NUMBER OF TRAYS -	**N/A**	
11			
10	MATERIAL OF CONSUCTRION -	**SS 316**	



	NO.	DATE	REVISION DESCRIPTION	BY	APVD.
12		**Jan 24, 2021**	**For quotation purposes**	**AF/FR**	
11		**March 29 2021**	**For quotation purposes**	**AF/FR/NN**	
12					

DATA SHEET	Pump Tag Number
UBC Engineering Ltd. - Capstone Project Standard	P-302

PLANT: FortisBC RNG Plant Abbotsford	P&ID Number - 300	PROJECT No.1

Unit Name: De-ionized Water Pump

1 ISSUED FOR: ✓ PROPOSAL PURCHASE AS BUILT

2 SERVICE: DI Water Pump

3 **OPERATING CONDITIONS**

		MAX.	NORMAL	MIN.	
5	CAPACITY:	3	2.2	1.9	M^3/H
6	DIFFERNTIAL HEAD	41			M
7	NPSH AVAILABLE:	11			M

10 Rating (design conditions)

3 **FLUID PROPERTIES**

4 FLUID DESCRIPTION: De-ionized water

	MAX.	NORMAL	MIN.	
PUMPING TEMP.:	45	25	10	ºC
SPECIFIC GRAVITY:	0.990	0.997	0.999	
VAPOR PRESSURE:	9.6	3.1	1.2	kPa-a
VISCOSITY:	0.61	0.91	1.31	cP
SPECIFIC HEAT:	4.2	4.2	4.2	kJ/kg ºC

12 CORROSION / EROSION CAUSED BY: NO

13 % SOLID: 0

12 **PUMP DETAILS**

13 INDOOR ✓ OUTDOOR

14 PUMP TYPE: Centrifugal Style Pump

15

16 ELECTRICAL CLASSIFICATION:

17 CL.: ____ GR.: ____ DIV.: ____

18 TRU NON HAZARDOUS

19

20 MATERIAL OF CONSTRUCTION: Stainless Steel 316 (wetted parts)

21

22 SPECIAL REMARKS: None

	NO.	DATE	REVISION DESCRIPTION	BY	APVD.
25		Jan 24 2021	For quotation purposes	NN	
26					
27					

	DATA SHEET - VESSEL	Tank Tag Number
	UBC Engineering Ltd - Capstone Project Standard	**V-301**
PLANT: FortisBC RNG Plant Abbotsford	P&ID Number - 300	PROJECT No.1

Water Deionizer

ISSUED FOR: ✓ PROPOSAL PURCHASE AS BUILT

SERVICE: **Water Deionization for Chemical Processing**

OPERATING CONDITIONS

	MAX	NORM.	MIN.
FLUID TEMPERATURE - C	38	25	1.6
SERVICE FLOW - GPM	35	11	9

OPERATING VOLUMES - M3: **Cation Resin Volume: 0.283 M3**; **Anion Resin Volume: 0.283 M3**

MATERIAL PROPERTIES

MATERIAL DESCRIPTION: **Fibre reinforced plastic tank**; **Corrosion resistant**

DESIGN FLUID DENSITY; **Water at 25C: 0.997 g/mL**

VESSEL DETAILS

✓ INDOOR OUTDOOR

- DESIGN CONDITIONS -

MAX DESIGN TEMPERATURE - C	100
MIN DESIGN TEMPERATURE - C	38
MAX DESIGN PRESSURE - BARA	10.34
MIN. DESIGN PRESSURE - BARA	1

VESSEL GEOMETRY -

VESSEL POSITION:	Vertical
VOLUME - M3:	2 x 0.51 M3 tank
VESSEL DIAMETER - M:	0.6
VESSEL TAN/TAN LENGTH - M:	1.8
MATERIAL OF CONSTURCTION:	Fibre reinforced plastic

NO.	DATE	REVISION DESCRIPTION	BY	APVD.
	Jan 27 2021	For quotation purposes	NN, BA	
	March 29 2021	For quotation purposes	BA	

	DATA SHEET - VESSEL	Tank Tag Number
	UBC Engineering Ltd - Capstone Project Standard	**V-302**
PLANT: FortisBC RNG Plant Abbotsford	P&ID Number - 300	PROJECT No.1

Unit Name: **Hydrogen Storage Tank**

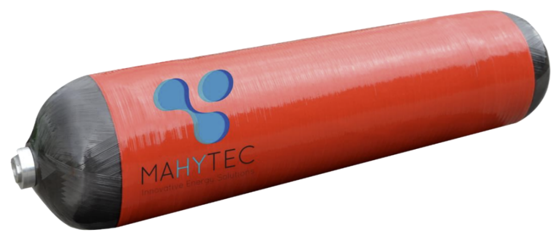
ISSUED FOR: ✓ PROPOSAL PURCHASE AS BUILT

SERVICE: **Hydrogen Storage for Sabateir reaction**

OPERATING CONDITIONS

	MAX	NORM.	MIN.
FLUID TEMPERATURE - C	**65**	**15**	**-40**

OPERATING VOLUMES - M3 **Tank Volume 0.3 M3**



MATERIAL PROPERTIES

MATERIAL DESCRIPTION: **Type IV polymer liner with**
Carbon composite. Stainless steel
Aluminium alloy

DESIGN FLUID DENSITY;

VESSEL DETAILS

INDOOR ✓ OUTDOOR

- DESIGN CONDITIONS -

MAX DESIGN TEMPERATURE - C	**65**
MIN DESIGN TEMPERATURE - C	**-40**
MAX DESIGN PRESSURE - BARA	**500**
MIN. DESIGN PRESSURE - BARA	**0**

VESSEL GEOMETRY -

VESSEL POSITION:	**Vertical**
VOLUME - M3:	**0.3**
VESSEL DIAMETER - M:	**0.48**
VESSEL TAN/TAN LENGTH - M:	**3.07**
MATERIAL OF CONSTURCTION:	**Stainless Steel -** **Aluminium alloy**

NO.	DATE	REVISION DESCRIPTION	BY	APVD.
	Jan 26 2021	**For quotation purposes**	**BA**	
	March 29 2021	**For quotation purposes**	**BA**	

DATA SHEET - HEAT EXCHANGER

UBC Engineering Ltd. - Capstone Project Standard

Exchanger Tag Number: **E-402**

PLANT: FortisBC RNG Plant Abbotsford	P&ID Number: 400	PROJECT No. 1

Unit Name: **Multipass Heat Exchanger**

ISSUED FOR: ✓ PROPOSAL PURCHASE AS BUILT

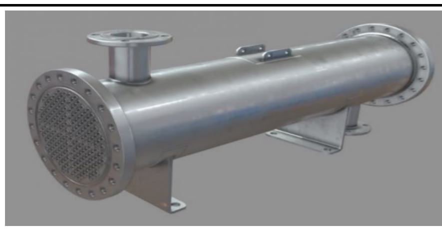
SERVICE: **Heat Integration**

OPERATING CONDITIONS

	HOT SIDE		COLD SIDE	
PHASE	MIXED		GAS	
FLUID FLOW - KG/H	880		880	
INLET PRESSURE - BAR-A	10		9.67	
ALLOWABLE PRESS DROP - BAR	0.26		005	
FOULING RESISTANCE - M2 C / W	0.00015		0.00021	
	IN	OUT	IN	OUT
TEMPERATURE - C	270	157	87	237

FLUID PROPERTIES

	HOT SIDE		COLD SIDE	
FLUID DESCRIPTION	H2/CO2/CH4/H2O MIX		H2/CO2 MIXTURE	
	IN	OUT	IN	OUT
DENSITY - KG/M3	3.82	5.27	3.37	2.35
VISCOSITY - CP	0.02	0.016	0.016	0.02
SPECIFIC HEAT - KJ/KG C	2.4	2.5	3.0	3.1
LATENT HEAT - KJ/KG	200.77		N/A	



HEAT EXCHANGER DETAILS

✓ INDOOR OUTDOOR

HEAT EXCHANGER TYPE: **SHELL AND TUBE**

	HOT SIDE	COLD SIDE
MATERIAL OF CONSTRUCTION	SS 316 L	SS 316 L
DESIGN TEMPERATURE - C	270	240
DESIGN PRESSURE - BARA	10	10
HEX AREA -M2		27.41
HEAT TRANSFER COEFF - KW/M2•K		0.215

NO.	DATE	REVISION DESCRIPTION	BY	APVD.
	Jan 26 2021	Preliminary Design	AK, MA, HD	JV
	Apr 15 2021	Preliminary Design	HD	

DATA SHEET - COMPRESSOR

UBC Engineering Ltd. - Capstone Project Standard

Unit Tag Number: **C-401**

PLANT: FortisBC RNG Plant Abbotsford	P&ID Number : 400	PROJECT No. 1

Unit Name: Two stage compressor

ISSUED FOR: ✓ PROPOSAL   PURCHASE   AS BUILT

SERVICE: Centrifugal gas compression-feed to methanation reactor system

EQUIPMENT TYPE: COMPRESSOR

OPERATING CONDITIONS

	MAX.	MIN.	
CAPACITY (@standard conditions):	300	175	M3/H
INLET TEMPERATURE	35	25	C

DESIGN SUCTION PRESSURE: 0.987 BAR-G

DESIGN DISCHARGE PRESSURE: 3.46 BAR-G

FLUID PROPERTIES

FLUID DESCRIPTION: CO_2 0.9 vol%, CH_4 0.096 vol%

MOISTURE CONTENT: Saturated

MOLECULAR WEIGHT: 44

COMPRESSOR MECHANICAL DETAILS

✓ INDOOR   OUTDOOR

UNIT TYPE: Centrifugal Style Compressor

ELECTRICAL CLASSIFICATION:

CL.: ______ GR.: ______ DIV.: ______

NON HAZARDOUS

Materials of Construction: Stainless Steel 316 SS (wetted parts)

MECHANICAL SEAL TYPE: Single Mechanical Seal

SPECIAL REMARKS: None

NO.	DATE	REVISION DESCRIPTION	BY	APVD.
	Jan 26 2021	For quotation purposes	AK, MA, HD	
	Apr 16 2021	For quotation purposes	HD	

DATA SHEET - REACTOR / PLUG FLOW	Reactor Tag
UBC Engineering Ltd. - Capstone Project Standard	**R-401**

PLANT: FortisBC RNG Plant Abbotsford	P&ID Number: 400	PROJECT No. 1

Unit Name: Sabatier Reactor

ISSUED FOR: ✓ PROPOSAL PURCHASE AS BUILT

SERVICE: **PRODUCTION OF METHANE**

OPERATING CONDITIONS

	MIN	MAX
FLUID TEMPERATURE - C	270	450
RESIDENCE TIME - MIN	0.124	
MIXING INTENSITY - KW/M3	-	

MATERIAL PROPERTIES

FEED CONTENT:

DESCRIPTION: 2.1 MOL% METHANE, 19.4 MOL% CARBON DIOXIDE 78.5 MOL% HYDROGEN, >0.1 MOL% WATER & H2S

DENSITY 2.31 KG/M3

OUTLET CONTENT:

DESCRIPTION: 34.6 MOL% METHANE, 62.4 MOL% WATER, 2.7 MOL% HYDROGEN, 0.3 MOL% CARBON DIOXIDE, H2S >0.01 MOL

5.72 KG/M3

REACTOR DETAILS

✓ INDOOR OUTDOOR

- DESIGN CONDITIONS -

MAX DESIGN TEMPERATURE - C	1150
MIN DESIGN TEMPERATURE - C	-10
MAX DESIGN PRESSURE - BARA	15
MIN. DESIGN PRESSURE - BARA	1

REACTOR GEOMETRY -

REACTOR VOLUME:	0.25M3
REACTOR DIAMETER:	0.5 M
REACTOR LENGTH	4 M
CATALYST LOADING	350 KG
BED VOIDAGE	0.4
MATERIAL OF CONSTRUCTION - WETTED PARTS:	Glass-Lined
MATERIAL OF CONSTRUCTION - NON-WETTED PARTS:	SS 310

NO.	DATE	REVISION DESCRIPTION	BY	APVD.
	Jan 26 2021	For quotation purposes	AK, MA, HD	
	Apr 15 2021	For quotation purposes	HD	

APPENDIX D

Start Up and Shut Down

PLANT START-UP

Start Up Checklist
Pre Start Up:
1. Flush all lines and purge with nitrogen 2. 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:
1. Start DCS control system in manual mode to avoid trip interlocks due to empty tanks 2. Fill tanks TK-101 and TK-501 3. Circulate cooling water and refrigerant line to all respective heat exchangers 4. Turn on boiler for steam production 5. Circulate steam to all heating required element
Start Up PFD-300
1. Turn on pump P-301, feeding water to deionzer and storage tank TK-301 2. Once TK-301 is at the appropriate level, turn on P-302 and electrolyzer unit 3. Turn on compressor C-301 to store produced hydrogen for usage downstream 4. Store discharge oxygen and cycle water produced to the raw water tank
Start Up PFD-500
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 arerunning and desired liquid temperature in the tank is achieved 3. Once other sections of the plant are ready, the isolation valves should be at their normal positions
Start Up PFD-400
1. Start circulating cooling water through Cooler E-402 and Reactor R-401 2. Turn on Compressors C-401 and C-403 3. Set pressure control loops on Streams 401,402 and 405 4. 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[VJ1] 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 deionzer 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
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

PHA Worksheet

Node	Node 1: Sabatier Reactor (R-401), including Furnace (E-403) and cooling water control valve (CV-403)	**Team Members:**	Mikkhail Antyukhov, Bhusan Appadoo, Hugo Dignoes Ricart, Andrea Hurtado Fuentes, Abhinav Kaushik, Nhi Nguyen, Farooq Asif Randeo, Vaishnavi Sivaramakrishnan
Reference Documents	P&ID 4001		
Design Intent Conditions / Parameters:	**DESIGN INTENT:** The Sabatier reactor reacts CO_2 and H_2 to produce CH_4 (Methanation). The furnace (E-403) heats the feed and maintain the reactor feed temperature at a suitable range. The cooing water valve CV-403 provides water through the reactor jacket to maintain the set temperature. **OPERATING CONDITIONS:** Sabatier Reactor (R-401) operates at 1000kPa and 270C. Total mass flow 879kg/h for the reactor. Cooling water valve (CV-403) operates with a flow rate of 120 m3/h at an average temperature of 20C. **PROCESS CONTROL:** Temperature of the reactor feed is controlled by the temperature control loop TIC-406/CV-406. Temperature inside the reactor is controlled by the temperature control loop TIC-405/CV-403. **HUMAN INTERACTION:** There is no preventative maintenance required, nor sampling requirement. The reactor and control valve is monitored daily and inspected through the regular annual plant maintenance shutdowns. **SAFE LIMITS:** The Sabatier Reactor (R-401) can operate between 270C and 290C, limited by HH trip on TIC-418. The Furnace (#-403) is allowed to operated up to 290C, limited by HH trip on TIC-406. **DESIGN CONDITIONS:** The Sabatier reactor (R-401) mechanical design conditions are 450C and 15 bara. **SAFETY DEVICES:** PSV-415 protects the Sabatier Reactor and has a set point of 12 barg.		

Deviation	Cause (Errors, Failures)	Consequences (without safeguards or operator)	Before Safeguards		Existing Safeguards (On P&ID or in place at facility)	After Safeguards			Recommendations / Comments	Responsibility
			Category	Severity		Category	Freq.	Risk Rank		
No/Less Flow [Cooling Water to R-401]	Blockage in pipe (E/M)	1: Overheating in reactor as the reaction is exothermic 2: Replacement of catalyst due to deactivation	H&S	3	TIC-418 HH temperature alarm and trip on CV-403	H&S	4	L	Installation of the bypass pipeline for the cooling water loop	
			FIN	2	Filtration of the water	FIN	4			
			REP	4		REP	5			
			ENV	4		ENV	4			
	Failure of valve, CV-403 (M)	1: Overheating in reactor as the reaction is exothermic 2: Replacement of catalyst due to deactivation	H&S	3	TIC-418 HH temperature alarm on CV-403	H&S	4	L	Install valve on the water return	
			FIN	2		FIN	4			
			REP	4		REP	5			
			ENV	4	Water is used as cooling agent	ENV	4			
	Physical damage to pipe	High possibility for the leaks from the pipeline due to increased pressure in the pipelines and formation of the turbulent flow	H&S	3		H&S	3	S	Install proper pipe rack to prevent accidental external damage	
			FIN	4	Installtion work is contracted	FIN	3			
			REP	3		REP	3			
			ENV	4	Carbon steel is used	ENV	3			
	Isolation valve in feed/return line were left closed (M)	Overheating of the reactor as the cooling water does not circulate in the system, reactor overheats that leads to reaction run-away	H&S	3	TIC-419, PSV-415 installed	H&S	2	H	Implement proper startup/shutdown check list	
			FIN	4	Cascade control	FIN	2			
			REP	1		REP	2			
			ENV	3		ENV	2			
No/Less Flow [Feed to R-401]	Failure of C-401 (M) Failure of C-402 (M)	1: High pressure buildup in the pipes prior to compressors may cause the pipe to burst 2: Changes in product quality may resulting in unplanned shutdown	H&S	2	PSV-407 installed (C-401) PSV-412 installed (C-402)	H&S	3	M	Ensure good PM practices are in place to identify issues that can cause compressor failure. Install a bypass line.	
			FIN	3	Preventive maintenance strategies	FIN	4	L		
			REP	3		REP	5	L		
			ENV	2	Bypass line to prevent CO2 venting.	ENV	4	L		
	Malfunction of CV-401 (M)	1: Hydrogen is explosive, can cause severe damages to equipment and personnel 2: Changes in product quality may resulting in unplanned shutdown	H&S	1	proper pipes	H&S	3	S	More info in Node X. Ensure that a bypass line to flare is installed as Hydrogen is explosive	
			FIN	1	bypass line to flare	FIN	3			
			REP	1		REP	3			
			ENV	1		ENV	3			

Deviation	Cause (Errors, Failures)	Consequences (without safeguards or operator)	Before Safeguards		Existing Safeguards (On P&ID or in place at facility)	After Safeguards			Recommendations / Comments	Responsibility
			Category	Severity		Category	Freq.	Risk Rank		
More Flow [Feed to R-401]	Malfunction in C-401, or C-402, or CV-401	Imbalance ratio of CO_2 and H_2 may causes changes in the rate of reaction leading to unexpected side reactions and increased fouling	H&S	5	Control logic in place to manipulate flow (PIC-401, PIC-403, PIC-404)	H&S	5	L		
			FIN	3	Pipes are installed with reasonable maximum flow capacity. Control valve installed at the disgester outlet (outside battery limit) to maintain flow.	FIN	5			
			REP	3		REP	5			
			ENV	4		ENV	5			
More Flow [Cooling Water to R-401]	Failure of CV-402 (M) and fluctuation in pressure of CW supply	Reactor can be severely cooled which leads to formation of liquid water in the reactor and pipleines (two phase flow)	H&S	4		H&S	4	L		
			FIN	2	TIC-418 may reduce the CW flow	FIN	4			
			REP	5		REP	5			
			ENV	5	Water is used as cooling agent	ENV	5			
	Failure of valve, CV-403 (M)		H&S	4		H&S	4	L		
			FIN	2	Preventive maintenance and Inspection strategies	FIN	4			
			REP	5		REP	5			
			ENV	5		ENV	5			
Leak/ Rupture in feed line	External corrosion (E) Natural disaster (E) External impact (E) PSV-415 failure (M) Signal transmission failure to TIC-418 (M)	1: CO_2 and/or H_2 can displace the air in the building. Plant personnel could inhale pure released gas 2: Explosion of H_2 or equipment damage, leading to unplanned shutdown	H&S	3		H&S	4	L	Install CO_2 and H_2 detectors Install leak detector Perform regular inspection and maintenance on PSV-407, PSV-411, PSV-412, PSV-414, PSC 422	
			FIN	3	Preventive maintenance and Inspection strategies on TIC-418, TI-405, TT-405, PSV-415	FIN	5			
			REP	3		REP	5			
			ENV	3		ENV	5			
High Temperature	CW loop fouling (M)	Loss of cooling water can cause the reactor to severely heat up since the reaction is exothermic in nature, leading to run-away reactions and changes in product quality	H&S	2	Control logic in place to prevent overheating	H&S	3	M	Ensure calibration of instrument, tuning of control parameters with interlocks in place.	
			FIN	2	CV-403 is fail to open	FIN	4	M		
			REP	4		REP	5	L		
			ENV	5		ENV	5	L		
	E-401 and/or E-402 tube fouling (M) Instrument failure (temperature indicators, temperature controllers)	1: Feed to C-402 might be too hot for C-402 to handle, might cause damage to C-402 **(Note: Should be considered in previous node)** 2: Higher feed teperature can cause reaction rate leading to an increase in pressure and possibly rupture of reactor	H&S	3	TIC-406 may increase flow of cooling water	H&S	4	L		
			FIN	5		FIN	5			
			REP	5		REP	5			
			ENV	4		ENV	4			
Lower Temperature	Lower ambient temperature	Decreased reaction rate, lower single-pass conversion of the reaction	H&S	5	TIC-405 installed to control reactor temperature	H&S	5	L	Ensure proper tuning of controller to account for unexpected temperature drops/increases. Enhanced control strategies can account for most variations in ambient conditions.	
			FIN	2	Downstream feed control to ensure reactants enter at desire temp (TIC 406)	FIN	4	M		
			REP	5		REP	5	L		
			ENV	5		ENV	5	L		

Deviation	Cause (Errors, Failures)	Consequences (without safeguards or operator)	Before Safeguards Category	Before Safeguards Severity	Existing Safeguards (On P&ID or in place at facility)	After Safeguards Category	After Safeguards Freq.	After Safeguards Risk Rank	Recommendations / Comments	Responsibility
Lower Temperature	Fouling in the E--401 and E-402 tubes	Decreased reaction rate, lower single-pass conversion. Decrease in the efficiency of the heat exchanger, leading to an increase in utility cost.	H&S	4	Regular maintenance checks	H&S	4	L	To account for fouling, a preventative approach should be taken. Regular maintenance checks, using clean water is important, also using additives may be required.	
			FIN	2	Ensure water used is clean (from RO system) to prevent any impuritites to build up	FIN	4	M		
			REP	4		REP	4	L		
			ENV	4		ENV	4	L		
Higher Pressure	Malfunction of C-401 and C-402 or increased flow rate	Increase in the pressure of the vessel can cause the reaction to speed up. This can potentially lead to an explosion of the vessel, causing major health and safety concerns.	H&S	1	Upstream and downstream pressure relief valves (PSV-407, PSV411, PSV-412, PSV-414, PSV-415)	H&S	4	M	Important for PSV to be checked and maintaned properly.	
			FIN	1	Preventative maintenance strategies	FIN	4			
			REP	1		REP	4			
			ENV	1		ENV	4			
Lower Pressure	Malfunction of C-401 and C-402 or decreased flow rate	Reaction rate shifts, changes the expected yield. This will decrease the production of biogas.	H&S	4	Downstream pressure control of feed at the compressor stage (PIC-403) may increase the stream pressure	H&S	5	L	Ensure proper tuning of controller to account for unexpected pressure drops/increases.	
			FIN	2		FIN	4	M		
			REP	3		REP	5	L		
			ENV	4		ENV	5	L		
Wrong Composition/Concentration	Valve failure up stream or efficiency noise	Rate of reaction changes, unexpected side reactions leading increased fouling in the system.	H&S	4		H&S	5	M	Ensure proper tuning of the ratio control loop.	
			FIN	2	Ratio control strategy is used to ensure the correct ratio of hydrogen to carbon dioxide is entering the reactor	FIN	4	M		
			REP	3		REP	4	L		
			ENV	5		ENV	5	L		
Wrong Reaction	Incorrect catalyst support (i.e. α-phase alumina rather than g-phase)	Catalyst deactivation, decreased yield, formation of carbonates which can damage the reactor, deactivate the catalyst, and reduce yield.	H&S	5	Setup/maintenance checklist to make sure correct catalyst is being used in the reactor	H&S	5	L	Formal checklist to ensure the reactor is being setup properly (using the appropriate catalyst). Maintaining the temperature under 600°C to prevent potential phase transitions.	
			FIN	1		FIN	4	M		
			REP	2		REP	4	M		
			ENV	5		ENV	5	L		
Maintenance Hazards	Catalyst deactivation	Decreased yield, and material creep (potential for downstream equipment failures)	H&S	2		H&S	4	M	To prevent the reactor from getting damaged (exposure to corrosion) regular preventative maintenance checks must be done. Proper inspection of vessel walls and maintenance of inner glass layer should be performed regularly.	
			FIN	1	Setup/maintenance checklist to make sure correct catalyst is being used in the reactor	FIN	4			
			REP	1		REP	4			
			ENV	2		ENV	4			
	Poor operator training/floor supervision Inadequate equipement inspection	1: Danger to plant personel 2: Unexpected equipment failure and shutdown	H&S	1		H&S	1	H		
			FIN	2	Regular operator trainings and meetings carried out by Safety Department	FIN	2	H		
			REP	2		REP	2	H		
			ENV	3		ENV	3	S		

Deviation	Cause (Errors, Failures)	Consequences (without safeguards or operator)	Before Safeguards		Existing Safeguards (On P&ID or in place at facility)	After Safeguards			Recommendations / Comments	Responsibility
			Category	Severity		Category	Freq.	Risk Rank		
Startup/Shutdown Hazards	Trapped gas (pressurized) in pipes	Burst pipe, and damaged valves can result from the pressure build-up. This can lead to major health and safety concerns as it can lead to severe equipment damage.	**H&S**	1	PSV setup to prevent pressure build-up	**H&S**	4	M	PSV are important to prevent any unwanted pressure build up in the process. Valves and pipes must be maintained to ensure they operate as intended.	
			FIN	1	Regular maintenance to ensure valves/pipes are functioning properly	**FIN**	4			
			REP	1		**REP**	4			
			ENV	1	Preventive maintenance strategies	**ENV**	4			
Workplace Safety Hazards	Compressed hydrogen	Gas leaks, flammable/explosive gas hazard since hydrogen is a flammable gas. Potential for a fire which can be a major health and safety risk as well as damage equipment in the process.	**H&S**	2	Hydrogen sensor set up in the facility to detect any hydrogen leaks	**H&S**	4	M	Hydrogen sensors and alarms should be in place to detect any build-up of hydrogen (eg. from leaks) in the facility.	
			FIN	2	Perform leak checks before actual operation of the system	**FIN**	4			
			REP	2		**REP**	4			
			ENV	3	Preventive maintenance strategies	**ENV**	4			
	High Temperature surfaces	Various parts of the process are performed at high temperatures (>200 C). This can lead to various high temperature pipes and surfaces being exposed, which can lead to major safety issues if touched.	**H&S**	2	Insulate high temperature surfaces and place warning signs	**H&S**	4	M	Insulation and warning signs should be placed to avoid any injuries due to high temperature surfaces.	
			FIN	3		**FIN**	4			
			REP	3	Training performed to teach staff about how to handle high temperature surfaces if needed	**REP**	4			
			ENV	4		**ENV**	4			

			FREQUENCY				
			Frequent – expected to occur	Probable – likely to occur in the next 5 yrs	Occasional – may occur within the life of facility	Rare – not anticipated to occur	Improbable
			1	**2**	**3**	**4**	**5**
CONSEQUENCE	Fatality, Irreversible Env. Damage, $1Million +	**1**	H	H	S	M	L
	Severe Injury, Major Env. Damage $100k-$1Million	**2**	H	S	M	M	L
	Lost time accident, Reportable Env. Event, $10k - $100k	**3**	S	M	M	L	L
	Medical treatment, Onsite release, $1-$10k	**4**	M	M	L	L	L
	Minor exposure, localized spill, <$1k	**5**	M	L	L	L	L

Figure E-1: Risk Matrix used for HAZOP analysis

APPENDIX F

Plant Layout

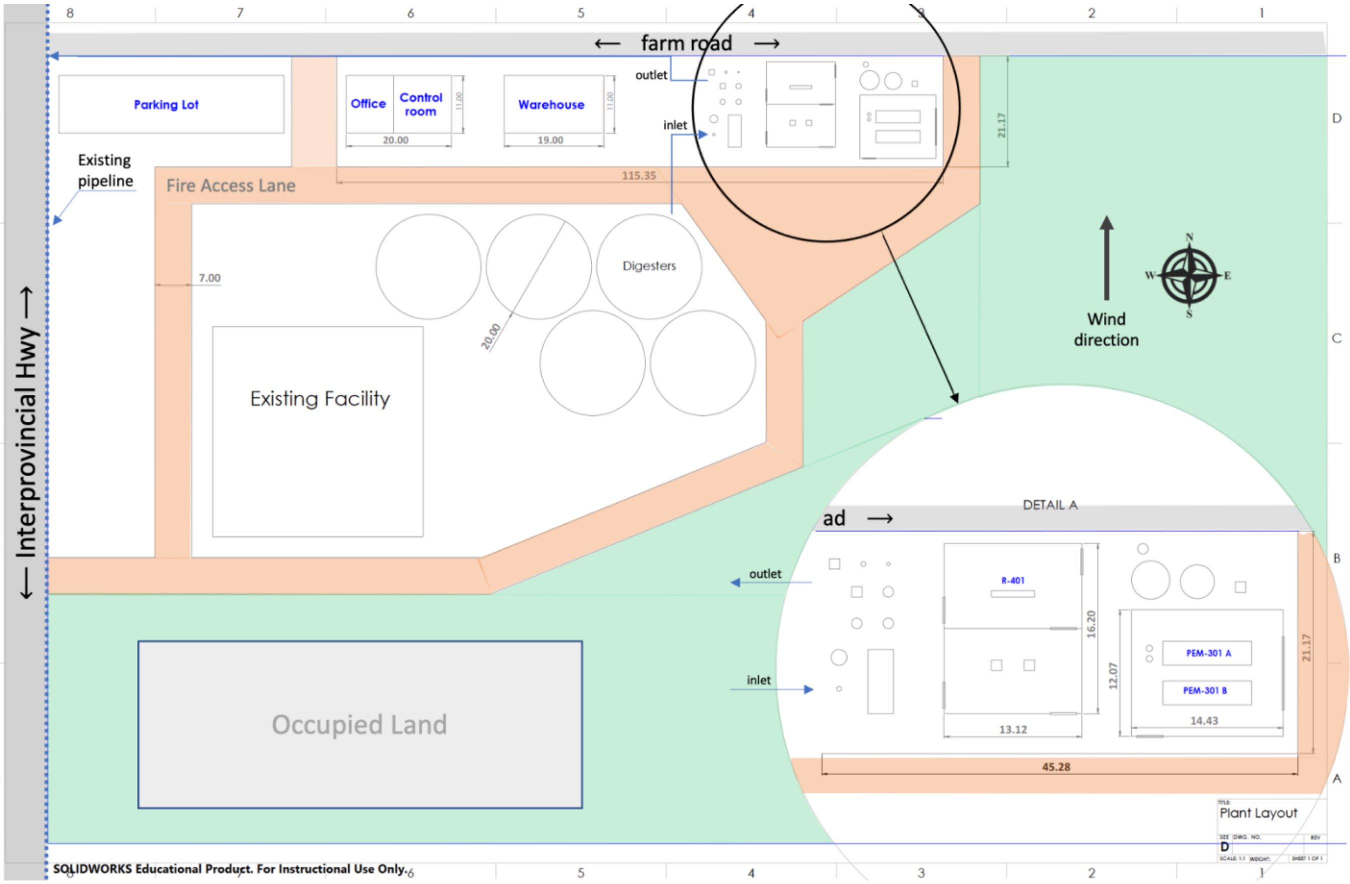


Figure E-1: SOLIDWORKS 2-D drawing of the plant layout. DETAIL A shows the layout of the equipment. Unit of measurement is in meters.

APPENDIX G

Economic Analysis

PFD No.	Equipment Tag Number	Description	Total Direct Cost (CAD/USD)	Equipment Cost (USD)	Equipment Cost (CAD)
100	C-101	Wet Biogas Compressor		930076	$1,190,497.28
	E- 101	Glycol-Glycol Heat Exchanger		205213	$262,672.64
	V-101	Flash Drum		28920	$37,017.60
	T-101	Glycol Contactor		178088	$227,952.64
	E-102	Biogas Cooler		205213	$262,672.64
	T-102	Glycol Regenerator (Stripper+Reboiler)		141645	$181,305.60
	TK-101	Surge Tank		11689	$14,961.92
	P-101	Lean Glycol Pump		5000	$6,400.00
Total - PFD-100			0		$2,183,480.32
200	V-201	Activated Carbon Adsorber			$294,845.00
	V-202	Pressure Swing Adsorber			$1,368,684.21
	V-203	Pressure Swing Stripper			$1,368,684.21
	C-201	Biomethane compressor			$840,900.00
	E-201	Biomethane cooler			$69,300.00
Total - PFD-200			0		$3,942,413.42
300	P-301	Raw Water Pump		2,915	$3,731.20
	V-301	Water Purification System		waiting on quote	$20,000.00
	TK-301	DI Water Storage Tank			$12,000.00
	P-302	DI Water Pump		2,915	$3,731.20
	PEM-301 A	PEM Electrolyzer		2,000,000	$2,560,000.00
	PEM-301 B	PEM Electrolyzer		2,000,000	$2,560,000.00
	C-301	Compressor		$1,257,780.00	$1,609,958.40
	V-302	H2 Storage Vessel			$180,000.00
Total - PFD-300			0		$6,949,420.80
400	C-401	First Compressor Stage			$935,000.00
	C-402	Second Compressor Stage			$935,000.00
	CV-401	Hydorgen Feed Control Valve			$120,000.00
	CV-402	Reactor Jacket Control Valve			$80,000.00
	E-401	Compressor Interstage Cooler			$110,000.00
	E-402	Reactor Heater Exchanger			$100,000.00
	E-403	Furnace			$760,000.00
	R-401	Jacketed Sabatier Reactor			$343,100.00
Total - PFD-400			0		$3,383,100.00
500	C-501	RNG Cooler		100000	$128,000.00
	V-501	Flash Drum #1		13557	$17,352.96
	V-502	Flash Drum #2		28920	$37,017.60
	E-502	Dry RNG Heater		100000	$128,000.00
	X-501	Expander		82556	$105,671.68
Total - PFD-500			0		$416,042.24

BUDGET

Assumptions

No Quotes are available to confirm costs
All site improvements paid for by FortisBC and not supplier
A structure is required for temperature control and snow isolation.
A thermal oxidizer is required to reduce carbon intensity.
Equipment Sizing done using Aspen or Literature values

BUDGET

	Item	Description	Qty	Units	Unit Cost	Subtotal		% of Total
Direct	**1**	**Site Preparation**						
	1.01	Land Survey	1	ls	$ 3,500.00	$ 3,500.00		
	1.02	Geotechnical Analysis	1	ls	$ 15,000.00	$ 15,000.00		
	1.03	Environmental Assessment	1	ls	$ 5,500.00	$ 5,500.00		
	1.04	Civil Engineering	10	day	$ 2,400.00	$ 24,000.00		
	1.05	Fencing	40	m	$ 150.00	$ 6,000.00		
	1.06	Excavation	250	m^2	$ 560.00	$ 140,000.00		
	1.07	Fence Gates	16	m	$ 130.00	$ 2,080.00		
	1.08	Biogas Line Trenching	60	m	$ 300.00	$ 18,000.00		
	1.09	Concrete Slab	50	m^3	$ 1,500.00	$ 75,000.00		
	1.10	Electrical Service						
	1.11	BC Hydro Service - 600 Amp	1	ls	$ 25,000.00	$ 25,000.00		
	1.12	Trenching	35	m	$ 100.00	$ 3,500.00		
	1.13	Environmental Soil Sampling and Testing	1	ls	$ 7,000.00	$ 7,000.00		
	1.14	Environmental Ecological Field Assessment	1	ls	$ 3,000.00	$ 3,000.00		
	1.15	Environmental Management Plan	1	ls	$ 6,000.00	$ 6,000.00		
	1.16	Environmental Site Restoration	1	ls	$ 2,000.00	$ 2,000.00		
	1.17	Archeological Assessment	1	ls	$ 20,000.00	$ 20,000.00	$ 355,580.00	1.7%
	2	**Plant Installation**						
Direct	2.1	**Equipment (Break down in seperate tab)**						
	2.11	PFD-100	-	-	-	$2,183,480.32		
	2.12	PFD-200	-	-	-	$3,942,413.42		
	2.13	PFD-300	-	-	-	$6,949,420.80		
	2.14	PFD-400	-	-	-	$3,383,100.00		
	2.15	PFD-500	-	-	-	$416,042.24	$ 16,874,456.78	80.9%
Direct	2.2	**Mechanical**						
	2.21	Equipment installation	60	day	$ 3,600.00	$ 216,000.00		
	2.22	Interconnection piping between equipment	20	day	$ 2,400.00	$ 48,000.00		
	2.23	Carbon Steel Piping	1000	m	$ 130.00	$ 130,000.00		
	2.24	Stainless Steel Piping	1000	m	$ 210.00	$ 210,000.00		
	2.25	Site Testing	10	day	$ 5,600.00	$ 56,000.00	$ 660,000.00	3.2%
Direct	2.3	**Electrical**						
	2.32	Main PLC						
	2.33	Control Cabinet	1	ls	$ 300,000.00	$ 300,000.00		
	2.34	Installation	500	hr	$ 100.00	$ 50,000.00		
	2.35	Raceway						
	2.36	Material	300	m	$ 150.00	$ 45,000.00		
	2.37	Installation	35	hr	$ 100.00	$ 3,500.00		
	2.38	Cabling						
	2.39	Material	750	m	$ 65.00	$ 48,750.00		
	2.40	Labour	200	hr	$ 80.00	$ 16,000.00		
	2.41	Other Electrical Allowance	-	-	-	$ 50,000.00	$ 513,250.00	2.5%
Direct	2.4	**Building and Supporting Structures**						
	2.41	Steel Insulalted Buidling	400	m^2	$ 1,200.00	$ 480,000.00		
	2.42	Access Platform	1	ls	$ 75,000.00	$ 75,000.00		
	2.43	Overhead Lighting	6	ea	$ 5,000.00	$ 30,000.00		
	2.44	Gas Detection	1	ea	$ 50,000.00	$ 50,000.00		
	2.45	Pipe Bridge and Supports	1000	kg	$ 4.50	$ 4,500.00		
	2.46	Buildings	1000	m2	$ 700.00	$ 700,000.00	$ 1,339,500.00	6.4%
Indirect Cost	**3**	**Construction Expenses**						
	3.01	Contractors Non Destructive Inspection	10	day	$ 2,000.00	$ 20,000.00		
	3.02	Contractors Hydrovac truck	3	ls	$ 1,400.00	$ 4,200.00		
	3.03	Construction Site Security	90	day	$ 1,440.00	$ 129,600.00		
	3.04	Welding Fabrication	20	day	$ 110.00	$ 2,200.00		
	3.05	Field Tie-in Welds	100	ls	$ 100.00	$ 10,000.00	$ 166,000.00	0.8%
Indirect Cost	**4**	**Engineering/PM**						
	4.01	Project Management	80	day	$4,000	$ 320,000.00		
	4.02	Engineering	50	day	$6,000	$ 300,000.00		
	4.03	Drafting	50	day	$2,000	$ 100,000.00		
	4.04	Procurement	10	day	$1,000	$ 10,000.00		
	4.05	Construction Supervision	90	day	$1,200	$ 108,000.00	$ 838,000.00	4.0%
Indirect Cost	**5**	**Regulatory**						
	5.01	Development Permit	1	ls	$ 1,300.00	$ 1,300.00		
	5.02	First Nation Permits	1	ls	$ 3,000.00	$ 3,000.00		
	5.03	Archeological Permits	1	ls	$ 5,000.00	$ 5,000.00		
	5.04	Oil and Gas Commision Permit	1	ls	$ 50,000.00	$ 50,000.00		
	5.05	Environmental Permits and Approvals	1	ls	$ 4,000.00	$ 4,000.00		
	5.06	Facility Permit	1	ls	$ 21,500.00	$ 21,500.00		
	5.07	TSBC Electrical Installation Permit	1	ls	$ 32,500.00	$ 32,500.00		
	5.08	TSBC Gas Design Registration	8	hr	$ 150.00	$ 1,200.00		
	5.09	TSBC Gas Installation Permit	2	ea	$ 700.00	$ 1,400.00		
	5.10	TSBC Gas operating Permit	1	ls	$ 160.00	$ 160.00	$ 120,060.00	0.6%
WC	6	**Taxes**						
	6.01	PST on Equipment	7%	%	$ 17,978,206.78	$ 1,258,474.47		
	6.02	PST on Permits	7%	%	$ 120,060.00	$ 8,404.20		
	6.03	PST on Construction	7%	%	$ 1,161,500.00	$ 81,305.00	$ 1,348,183.67	6.5%

TOTAL:	**$ 20,866,846.78**
Contingency:	30%
FCI	**$ 27,126,900.81**
WC	**$ 4,874,680.78**
TCI	**$ 32,001,581.59**

	Assume Operational Year is 8000 hrs	8000											
				Electricity				Cooling Water/Low Pressure Steam					
PFD No.	Equipment Tag Number	Description	Utility Type	Electricity Cost (CAD/KW*h)	Usage per day (KW*h)	Usage per year (KW*h)	Electricity Cost per Year (CAD)	Cost per m^3 (CAD/m^3)	Cost per kg (CAD/kg)	Usage per Hour (kg/hr)	Hourly Cost (CAD/hr)	Cooling Water Cost per Year (CAD)	Utility Cost per Year (CAD)
	C-101	Wet Biogas Compressor	Electricity	0.0606	3,154.00	1,051,333.33	$63,710.80						$63,710.80
	E-101	Wet Biogas Cooler	Cooling Water			0.00	$0.00	1.17	$0.001174	28,899.55	33.91	$271,313.75	$271,313.75
	V-101	Gravity Separator drum				0.00	$0.00		$0.000000		0.00	$0.00	$0.00
	T-101	Glycol Contactor				0.00	$0.00		$0.000000		0.00	$0.00	$0.00
100	E-102	Heat Exchanger				0.00	$0.00		$0.000000		0.00	$0.00	$0.00
	T-102	Glycol Regenerator				0.00	$0.00		$0.000000		0.00	$0.00	$0.00
	E-103	Reboiler	Electricity	0.0606	49.32	16,440.00	$996.26		$0.000000		0.00	$0.00	$996.26
	TK-101	Surge Tank				0.00	$0.00		$0.000000		0.00	$0.00	$0.00
	P-101	Lean Glycol Pump	Electricity	0.0606	1.32	439.00	$26.60		$0.000000		0.00	$0.00	$26.60
	V-201	Activated Carbon Adsorber	Electricity	0.0606	358.45	119,483.33	$7,240.69		$0.000000		0.00	$0.00	$7,240.69
	V-202	Pressure Swing Adsorber	Electricity	0.0606	3,519.15	1,173,050.00	$71,086.83		$0.000000		0.00	$0.00	$71,086.83
200	V-203	Pressure Swing Stripper	Electricity	0.0606	3,519.15	1,173,050.00	$71,086.83		$0.000000		0.00	$0.00	$71,086.83
	C-201	Biomethane compressor	Electricity	0.0606	25.21	8,403.33	$509.24		$0.000000		0.00	$0.00	$509.24
	E-201	Biomethane cooler	Cooling Water			0.00	$0.00	1.17	$0.001174	4,404.00	5.17	$41,345.48	$41,345.48
	P-301	Raw Water Pump	Electricity	0.0606	54.00	18,000.00	$1,090.80		$0.000000		0.00	$0.00	$1,090.80
	V-301	Water Purification System	Electricity			0.00	$0.00		$0.000000		0.00	$0.00	$0.00
	TK-301	DI Water Storage Tank	-			0.00	$0.00		$0.000000		0.00	$0.00	$0.00
300	P-302	DI Water Pump	Electricity	0.0606	54.00	18,000.00	$1,090.80		$0.000000		0.00	$0.00	$1,090.80
	PEM-301 A/B	PEM Electrolyzer	Electricity	0.0606	10,000.00	3,333,333.33	$202,000.00		$0.000000		0.00	$0.00	$202,000.00
	C-301	Compressor	Electricity	0.0606	58.72	19,573.33	$1,186.14		$0.000000		0.00	$0.00	$1,186.14
	V-302	H2 Storage Vessel	-			0.00	$0.00		$0.000000		0.00	$0.00	$0.00
	C-401	First Compressor Stage	Electricity	0.0606	1,240.00	413,333.33	$25,048.00		$0.000000		0.00	$0.00	$25,048.00
	C-402	Second Compressor Stage	Electricity	0.0606	1,240.00	413,333.33	$25,048.00		$0.000000		0.00	$0.00	$25,048.00
	CV-401	Hydrogen Feed Control Valve	-			0.00	$0.00		$0.000000		0.00	$0.00	$0.00
400	CV-402	Reactor Jacket Control Valve	-			0.00	$0.00		$0.000000		0.00	$0.00	$0.00
	E-401	Compressor Interstage Cooler	Cooling Water			0.00	$0.00	1.17	$0.001174	213.00	0.25	$1,999.68	$1,999.68
	E-402	Reactor Heater Exchanger	-			0.00	$0.00		$0.000000		0.00	$0.00	$0.00
	E-403	Furnace	Electricity	0.0606	4,000.00	1,333,333.33	$80,800.00		$0.000000		0.00	$0.00	$80,800.00
	R-401	Jacketed Sabatier Reactor	Cooling Water			0.00	$0.00	1.17	$0.001174	11,530.00	13.53	$108,245.54	$108,245.54
	E-501	Cooler	Cooling Water	0.0606		0.00	$0.00	1.17	$0.001174	94,176.71	110.52	$884,146.45	$884,146.45
	V-501	Separator drum				0.00	$0.00		$0.000000		0.00	$0.00	$0.00
	K-100	Compressor	Electricity	0.0606	164.50	54,833.33	$3,322.90		$0.000000		0.00	$0.00	$3,322.90
	V-502	Separator drum	-			0.00	$0.00		$0.000000		0.00	$0.00	$0.00
	E-502	RNG Heater	Low Pressure Steam			0.00	$0.00		$0.000000		0.00	$0.00	$0.00
500						0.00	$0.00	1.17	$0.001174		0.00	$0.00	$0.00
						0.00	$0.00		$0.000000		0.00	$0.00	$0.00
						0.00	$0.00		$0.000000		0.00	$0.00	$0.00
						0.00	$0.00		$0.000000		0.00	$0.00	$0.00
						0.00	$0.00		$0.000000		0.00	$0.00	$0.00
						0.00	$0.00		$0.000000		0.00	$0.00	$0.00

PFD No.	Equipment Tag Number	Equipment	Description of Replacement	Cost of Replacement (CAD) Special Maintanace	Lifetime (Years)
100	C-101	Wet Biogas Compressor			
	E-101	Wet Biogas Cooler			
	V-101	Gravity Separator drum			
	T-101	Glycol Contactor			
	E-102	Rich Glycol Heater			
	T-102	Glycol Regenerator			
	E-103	Reboiler			
	TK-101	Surge Tank			
	P-101	Lean Glycol Pump			
	E-104	Lean Glycol Cooler			
200	V-201	Activated Carbon Adsorber	Change of Activated Carbon	$60,000.00	1
	V-202	Pressure Swing Adsorber	Makeup Glycol	$40,000.00	1
	V-203	Pressure Swing Stripper	Makeup Glycol	$40,000.00	1
	C-201	Biomethane compressor			
	E-201	Biomethane cooler			
300	P-301	Raw Water Pump			
	V-301	Water Purification System	Change of Resin	$100,000.00	1
	TK-301	DI Water Storage Tank			
	P-302	DI Water Pump			
	PEM-301 A/B	PEM Electrolyzer	Replacement on the Cell	$200,000.00	2
	C-301	Compressor			
	V-302	H2 Storage Vessel			
400	C-401	First Compressor Stage			
	C-402	Second Compressor Stage			
	CV-401	Hydorgen Feed Control Valve			
	CV-403	Reactor Jacket Control Valve			
	E-401	Compressor Interstage Cooler			
	E-402	Reactor Heater Excahnger			
	E-403	Furnace			
	R-401	Jacketed Sabatier Reactor	Catalyst Replacement	$8,242.37	1
500	E-501	Cooler			
	V-501	Separator drum			
	K-100	Compressor			
	V-502	Separator drum			
	E-502	Rich Glycol Heater			
General Annual Maintenance (Including Supplies)				$500,000.00	

APPENDIX H

Assembly of Database

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

Property	Units	Components					
		CO2	H2	H2O	CH4	H2S	TEG
Formula		-	-	-	-	-	$C_6H_{14}O_4$
Molecular Mass	kg/kmol	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]

$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$ + heat	$\Delta H = -165$ kJ/mol at 298 K
$-r_a = k_a \bullet P^{\alpha}_{H2} \bullet P^{ß}_{CO2} \bullet (1-\frac{P_{CH4} \bullet P^2_{H2O}}{P^4_{H2} \bullet P_{CO2} \bullet K_{Eqlbm}})$	$\alpha = 0.96$ $ß = 0.41$ $k_a = 1.94 \bullet e^{\frac{Ea}{8.314T*10^{-3}}} = 21711$ 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

[H3] Aspen Plus V11

APPENDIX I
Aspen Simulations

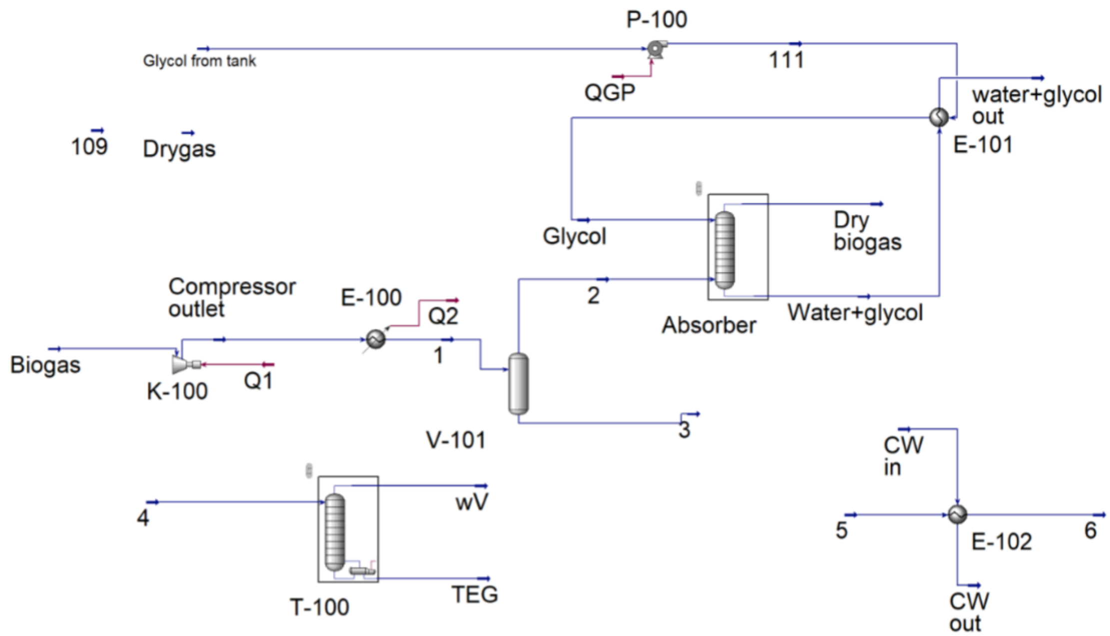


Figure I-1: PFD 100, Biogas pre-treatment HYSYS simulation

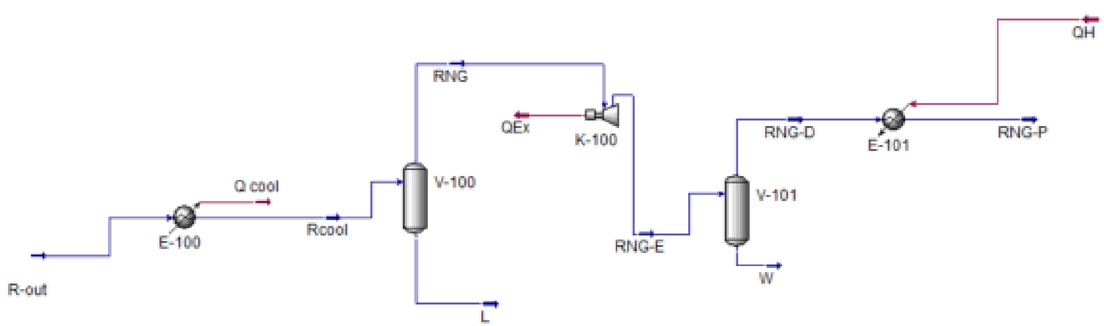


Figure I-2: PFD 500, Product post-treatment HYSYS simulation