Technical Memorandum

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°F	degrees Fahrenheit
APB	acid-producing bacteria
BC	Brown and Caldwell
BTU	British thermal unit
CAPEX	capital expenditures
CH_4	methane
City	City of Bellingham
CNGC	Cascade Natural Gas Corporation
CO_2	carbon dioxide
ft^3	cubic feet
GHG	greenhouse gas
H_2S	hydrogen sulfide
hr	hour(s)
IOB	iron-oxidizing bacteria
kWh	kilowatt-hour(s)
lb/MMscf	pounds per million standard cubic feet
LCC	life-cycle cost
mg/Nm^3	milligrams per normal cubic meter
mg Si/Nm^3	milligrams of silicon per normal cubic meter
MMBTU	million British thermal units
MMBTU/hr	million British thermal units per hour
N_2	nitrogen
NDA	non-disclosure agreement
NOx	nitrogen oxide
NPW	net present worth
O_2	oxygen
O&M	operations and maintenance
OPEX	operating expenditures
ppm_v	parts per million by volume
PSA	Pressure Swing Adsorption
qPCR	Quantitative polymerase chain reaction
RFP	Request for Proposal
RNG	renewable natural gas
scfm	standard cubic feet per minute
SRB	sulfate-reducing bacteria
SRT	solids retention time
TM	technical memorandum
TSA	temperature swing adsorption
VOC	volatile organic compound
VSR	volatile solids reduction
WWTP	wastewater treatment plant

Section 1: Introduction

The City of Bellingham (City) is in the planning stage of evaluating options for long-term biosolids management and beneficial reuse opportunities for the wastewater residual solids and energy recovered from the Post Point Resource Recovery Plant (Post Point). The Post Point Biosolids Project (Project) is being conducted in three phases–from alternative screening and evaluation through design and construction.

Phase 1 of the Project included the initial identification of all potential biosolids and energy alternatives, screening to identify viable alternatives for further evaluation, and the selection of a preferred conceptual alternative. In February 2019, the results of Phase 1 were summarized in *Technical Memorandum (TM) 1–Preferred Conceptual Alternative Selection*. Phase 2 further developed the preferred conceptual alternative and evaluated specific processes for biosolids treatment, biogas end uses, and other processes. In May 2019, *TM 2–Final Alternative Selection* summarized the results of Project planning Phase 2. The Project is currently in Phase 3, which further defines the selected alternative technical requirements and documents the planning effort within the *Biosolids Facility Planning Report*, which is an update to the City's existing, comprehensive *2011 Wastewater Facility Planning Report* (Carollo 2011).

This Phase 3 *TM 6–Biogas Upgrading Technology Alternatives*, summarizes viable biogas upgrading technologies and provides an initial screening and evaluation of alternatives for the City's specific application.

1.1 Background

The City is upgrading biosolids and biogas systems at Post Point to replace existing multiple-hearth incinerators with a new anaerobic digestion process. Biogas produced from the anaerobic decomposition of wastewater sludge within the digesters will be collected and treated to remove carbon dioxide (CO_2), moisture, and gaseous contaminants. The product gas, comprised primarily of methane (CH_4), will be of a quality suitable for injection into the natural gas pipeline.

1.2 Previous Findings

Due to its high CH_4 content, biogas is combustible and suitable for use as fuel (cogeneration and vehicle fuel) and as a natural gas substitute (or supplement). See *TM 2* for BC's earlier evaluation of Post Point's biogas utilization alternatives. TM2 concluded that converting Post Point's biogas to renewable natural gas (RNG) was the most cost-effective and environmentally beneficial solution.

1.3 Document Organization

Development and screening of biogas upgrading technologies are presented in the following sections:

- Section 2: Basis of Analysis: Establishes the criteria used to compare biogas upgrading technologies, including raw biogas quantity and quality assumptions and anticipated RNG quality specification.
- Section 3: Conceptual-Level Technology Screening: Identifies, describes, and screens available biogas upgrading technologies to determine which are suitable to meet City objectives.
- Section 4: Cost Evaluation: Provides preliminary equipment capital and operating costs.
- Section 5: Short-Listed Upgrading Alternatives Development: Compares the two biogas upgrading technologies (membrane and PSA systems) identified as the most likely to meet City requirements.
- Section 6: Biogas Upgrading Alternatives Development: Describes vendor-specific systems representative of the screened technologies and presents potential equipment layouts.
- Section 7: Findings and Recommendations: Summarizes findings presented in the TM and identifies recommended necessary next steps for Project development.

Section 2: Basis of Analysis

This section describes the criteria used to compare biogas upgrading technologies, including Post Point 's projected biogas production, and assumed biogas quality.

2.1 Evaluation Methodology

The applicability of one available biogas upgrading technology over another will depend on the nature of the project. Project characteristics such as size, biogas quality, and RNG end use will have a direct impact on the feasibility of using a specific upgrading technology. Key design criteria for developing the biogas upgrading system alternatives evaluation for the Project include:

- Estimated biogas production
- Assumed raw biogas quality
- Required capacity and turndown of the biogas upgrading system
- RNG quality requirements defined by Cascade Natural Gas Corporation (CNGC)
- CH_4 recovered from the raw biogas for upgrading to RNG (high methane capture rate)
- CH_4 content of the upgraded RNG (high methane content)

Based on these criteria, the following approach for developing and evaluating biogas upgrading technologies was used:

- Develop design requirements for capacity and turndown based on projected biogas production (and quality) during the design period (2025–45).
- Conduct a review of the known companies marketing biogas upgrading systems to screen those technologies that meet the design criteria.
- For each of the screened candidate technologies, select a single system to represent that technology and develop a conceptual system layout so that potential Post Point sites can be identified for locating the biogas upgrading system improvements as part of a separate facilities planning effort.
- Evaluate the selected technologies based on non-economic criteria (an economic analysis is recommended as part of a future and more detailed evaluation).

2.2 Raw Biogas Production

Anticipated biogas production rates from the new Post Point anaerobic digesters were used to develop preliminary sizing of candidate biogas upgrading systems. Biogas production estimates for Post Point were based on a combination of solids production estimates and historical plant operating data. Biogas production estimates are summarized in Table 2-1. (Note: subsequent to preparing this TM, wastewater flows and loads were adjusted by approximately 2 percent (*TM3-Wastewater Flows and Loads*). This was deemed not to be significant for the purpose of selecting biogas upgrading technologies. Therefore, gas production estimates were not updated for this TM, but will be updated for the final *TM 16–Mass Balances, Energy, and GHG Update*.) It is anticipated that the new biogas upgrading system will eventually be expanded to increase capacity by about 50 percent to treat biogas flows that will occur at buildout conditions. Expansion of the biogas upgrading system will be considered as part of the final design.

Table 2-1. Biogas Upgrading System Preliminary Sizing Criteria

Criterion	Biogas Production, scfm	Required System Turndown Ratio
Year 2025, minimum week	175	–
Year 2045		
Average annual	290	1.7:1
Maximum week	350	2.0:1
Maximum month	360	2.1:1
Maximum day	425	2.4:1
Anticipated buildout condition	540	3.1:1

Abbreviations:

scfm = standard cubic feet per minute

Note that the maximum week biogas production is slightly less than the maximum month biogas production. This may seem counterintuitive because maximum week sludge production exceeds maximum month sludge production. However, volatile solids reduction (VSR) is anticipated to be up to 5 percent lower for maximum week sludge production due to the shorter solids retention time (SRT) required to process the greater sludge loading. Conversely, SRT will be extended for the lower sludge loading conditions that represent the maximum month and average annual conditions. Thus, VSR will increase with SRT and biogas production will also increase.

Maximum month biogas production is the recommended design condition as this will capture all biogas produced under most conditions. Sizing for maximum day biogas production would result in underutilized equipment capacity for most of the Project life. Conversely, sizing for average annual biogas production would result in continuously flaring excess biogas during significant portions of the year and reducing the return on the capital investment.

Biogas upgrading systems provided by various manufacturers may not be available with specific capacities and turndown tailored explicitly for Post Point. Some manufacturers have standard product offerings only. Therefore, some flexibility in selecting the final design values is warranted. The preliminary biogas upgrading system criteria presented in Table 2-1 will be referenced throughout this TM and used for initial equipment sizing.

2.3 Raw Biogas Quality

Raw biogas quality will dictate key design criteria for the biogas upgrading system. Most biogas upgrading systems do not remove nitrogen (N_2). Because N_2 and CO_2 are both inert, the quantity of N_2 in the biogas will dictate the degree to which CO_2 must be removed to achieve the required RNG heating value. Biogas quality will also dictate a portion of the operating costs for most biogas upgrading systems. For example, the quantity of hydrogen sulfide (H_2S) and siloxanes in the raw biogas will dictate the type and amount of treatment media needed to comply with the RNG quality requirements described in Section 2.4.

Post Point does not yet operate anaerobic digesters and thus does not produce biogas, therefore anticipated raw biogas quality is based on conservative assumptions. Table 2-2 presents the assumed biogas composition, which is based on typical anaerobic digesters used for municipal wastewater sludge stabilization.

Table 2-2. Assumed Post Point Biogas Composition		
Criteria [a]	Typical	Range
Methane, dry, mole %	60	55-65
CO_2, dry, mole %	39.5	35-45
Nitrogen, dry, mole %	0.5	0.25-0.75
H_2S, ppm_v [b]	600	100-1,000
Total siloxanes, mg Si/Nm^3 [c]	25	5-50

a. Raw biogas, as produced, has a relative humidity of 100%.
b. ppm_v–parts per million by volume
c. mg Si/Nm^3–milligrams silicone per Normal cubic meter.

Once the new anaerobic digesters have been fully commissioned, the City should immediately implement a sampling program to determine the actual biogas composition. Actual biogas composition, as determined by laboratory analysis, is not expected to impact the results of this alternatives analysis but will be important for determining the type of pre- and post-treatment systems needed to remove H_2S and siloxanes, along with the costs associated with these systems.

2.4 RNG Quality Specification

The new biogas upgrading system will be required to produce RNG that meets the gas quality requirements set forth by CNGC. Based on experience with other RNG upgrading projects, a draft agreement with CNGC will likely define specific constituent concentrations as well as monitoring, testing, reporting, and recordkeeping requirements. Anticipated RNG quality requirements per preliminary discussions with CNGC are summarized in Table 2-3.

Table 2-3. CNGC Gas Quality Specification		
Parameter	Minimum Value	Maximum Value
Heating value (BTU/SCF)	985	–[a]
Wobbe number (BTU/SCF)	1,290	–[a]
Temperature (°F)	35	100
Carbon dioxide (%)	–	2
Nitrogen (%)	–	2[a]
Total inerts + oxygen (%)[c]	–	3[b]
Oxygen (%)	–	0.20[d]
Hydrogen sulfide (grain/CCF)	–	0.25
Total sulfur (grain/CCF)	–	5
Moisture (lb/MMSCF)	–	7
Hydrocarbon dew point (°F) at delivery pressure	–	15

a. The Company may establish maximum heating and Wobbe number values if biomethane is enriched with other hydrocarbons.
b. The Company may establish higher nitrogen and/or total inert levels at its discretion.
c. Inerts are defined here as nonhydrocarbon gases including, but not limited to, carbon dioxide, nitrogen, and oxygen.
d. All parties agree to exercise every reasonable effort to keep the gas completely free of oxygen.

Abbreviations:
BTU/SCF = British thermal units–standard cubic feet
CCF = 100 standard cubic feet
MMSCF = One million standard cubic feet

In addition to the RNG quality requirements presented in Table 2-3, periodic sampling will be required to confirm several other gas constituents (see Attachment A) are below specified limits. Siloxanes are common in biogas may not exceed 0.1 milligrams of silicon per cubic meter (mg Si/m^3) in the RNG. A polishing step is recommended for all biogas upgrading alternatives to capture any remaining siloxanes that may have passed through the upgrading process. Using activated carbon, silica gel, and/or other adsorbents for this purpose is considered inexpensive insurance against a siloxane breakthrough.

Section 3: Conceptual-Level Technology Screening

Several biogas upgrading technologies were considered during the conceptual screening phase. This section describes:

- The biogas upgrading technologies reviewed
- The evaluation criteria used to perform an initial screening of technologies
- The results of the criteria comparison

3.1 Request for Quotations

At the time of this evaluation, four biogas upgrading technologies were considered viable for the Project. A total of 16 system manufacturers representing the four biogas upgrading technologies were contacted and asked to provide budgetary proposals. Raw biogas data and CNGC's RNG specifications, as presented in Section 2, were provided and manufacturers were requested to provide a preliminary, wholistic solution for biogas upgrading, including pre- and/or post-treatment and compression to produce RNG in compliance with CNGC's specification.

Table 3-1 lists the manufacturer name, technology offered, and respective proposal status for all 16 firms contacted. The proposals listed as "acceptable" are shown in boldface type and were included in the conceptual level technology screening process described herein. Several manufacturers declined to respond to the request for a quotation and one proposal was considered non-responsive based on the manufacturer's apparent inability to meet the stated RNG quality requirements.

It is worth noting that one manufacturer, Greenlane, provides water scrubbing, membrane, and pressure swing adsorption (PSA) systems. As noted in Table 3-1, Greenlane proposed a PSA system, which it believes is superior to the membrane system and far superior to the water scrubber in terms of their ability to consistently produce RNG in compliance with the RNG quality requirements.

Table 3-1. RNG Upgrading Manufacturers, Technology, and Proposal Status

Manufacturer	Technology[a]	Proposal Status
Clariant	Amine–chemical absorption	Did not provide a proposal
Morrow Energy	**Amine–chemical absorption**	**Acceptable**
Wärtsilä	**Amine–chemical absorption**	**Acceptable**
Dürr MEGTEC	**High-pressure water scrubbing**	**Acceptable**
Malmberg	High-pressure water scrubbing	Did not provide a proposal
Air Liquide	Membrane	Did not provide a proposal
DMT Clear Gas Solutions	**Membrane**	**Acceptable**
Generon	Membrane	Proposal was non-responsive
GraniteFuel Engineering	**Membrane**	**Acceptable**

Table 3-1. RNG Upgrading Manufacturers, Technology, and Proposal Status

Manufacturer	Technology[a]	Proposal Status
Nacelle	Membrane	Did not provide a proposal
Roeslein & Associates	Membrane	Did not provide a proposal
Unison Solutions	**Membrane**	**Acceptable**
Greenlane	**Pressure Swing Adsorption (PSA)**	**Acceptable**
Guild Associates, Inc.	**PSA**	**Acceptable**
Schmack Carbotech	**PSA**	**Acceptable**
Xebec	**PSA**	**Acceptable**

a. The total number of proposals received by technology type are as follows:

Amine–chemical absorption	*2*
Water scrubber	*1*
Membrane	*3*
PSA	*4*

In addition to providing budgetary proposals, manufacturers were requested to complete a brief questionnaire, as replicated in Table 3-2. The purpose of the questionnaire was to quickly determine if the proposed system could meet the RNG quality requirements and to provide the information necessary to assess operating costs, including connected load and heat demand and recovery (for amine systems).

Table 3-2. Biogas Upgrading Questionnaire

Criteria	Value
Methane recovery, %	—[a]
Methane in product gas, %	—[a]
Oxygen in product gas, %	—[a]
System uptime, %	—[a]
Connected load, hp	—[a]
Heat demand, MMBTU/hr (amine systems only)	—[a]
Heat recovery, MMBTU/hr (amine systems only)	—[a]
Upgrading system operating pressure, psig	—[a]
System turndown ratio	—[a]

a. Technology performance values provided by the respective system manufacturer.

3.2 Technology Descriptions

This section describes the biogas upgrading technologies being considered for the Post Point Project. Each manufacturer's approach to biogas upgrading is also described. However, it should be noted that some manufacturers declined to provide detailed technical information and drawings unless a non-disclosure agreement (NDA) was signed. The information provided thus far by the manufacturers described in this TM is sufficient for a conceptual-level technology evaluation. As the City and the BC team move beyond this conceptual-level technology evaluation, it may become necessary to sign an NDA with certain manufacturers that are eventually short-listed as preferred alternatives.

Further, as process calculations were refined, it was determined that initial biogas production rates were overestimated. Biogas projections were subsequently revised, as listed in Table 2-1. Despite the recent revisions to the biogas projections, the technical information presented below remains relevant for this initial screening of alternatives.

3.2.1 Amine System

Amines are nitrogen-bearing compounds that are derived from ammonia. Amine based biogas upgrading systems feature a water-based solvent that chemically and selectively absorbs CO_2 and H_2S from biogas thus producing a CH_4 rich product gas. CH_4 in the RNG routinely exceeds 97.5 percent.

A typical amine-based biogas upgrading system primarily includes a contact tower and a regenerator. The gas separation process takes place in a scrubbing column operated in a counter-flow configuration. Raw biogas enters the base of the contact tower while the amine solution enters near the top of the tower. CO_2 in the raw biogas is chemically absorbed into the amine scrubbing solution while the CH_4 flows up and out of the tower as enriched RNG. The CO_2 laden scrubbing solution is then removed from the contact tower and warmed in a heat exchanger prior to entering the regeneration tower. This regeneration process releases the CO_2 from the amine solution. The CO_2 is then removed from the regeneration tower and the regenerated amine solution is returned to the contact tower to complete a closed loop cycle. The energy efficient regeneration of the scrubbing solution is implemented by a combination of thermal heating and pressure relief. Amine systems use heat to regenerate the amine solution. Figure 3-1 illustrates the process flow diagram for a typical amine-based system.

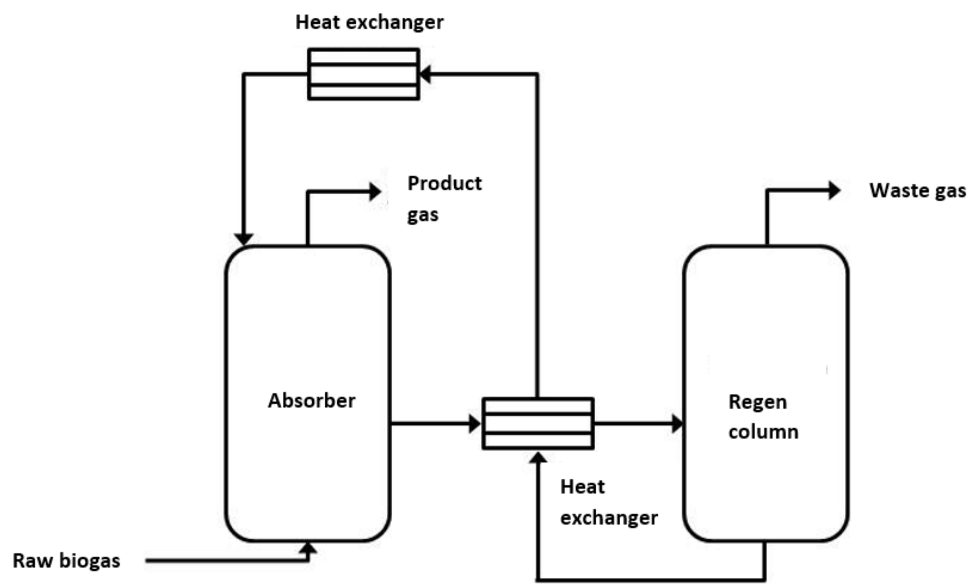

Figure 3-1. Amine system process flow diagram

The amine solution can also absorb and separate H_2S from the biogas. However, the amine solution regeneration process reaches higher temperatures if H_2S is removed. Amine systems typically operate at lower H_2S concentrations than the assumed design criteria (1,000 ppm H_2S) for the Project. Therefore, a pre-treatment step would be required to remove H_2S from the raw biogas.

In general, amine systems are not expandable to accommodate increases in future biogas production. Therefore, a potential amine system should be sized for anticipated biogas production through 2045. If additional capacity is required beyond 2045, a parallel system could be installed.

BC received acceptable proposals from two manufacturers of amine-based systems: Morrow Energy and Wärtsilä. Details on each of the respective systems are presented below, followed by a comparison of the two amine systems based on responses to the manufacturer's questionnaire (Table 5).

3.2.1.1 Morrow Energy

Morrow Energy (Morrow) has 15 operating amine-based biogas upgrading systems in the United States. These facilities range in size from 1,500 to 12,800 scfm. None of these facilities treat biogas produced from the anaerobic digestion of municipal wastewater sludge. Most of Morrow's installed systems treat landfill gas with a few installed at dairies.

Morrow has stated its ability to comply with CNGC's RNG quality requirements. The proposed system has a 99 percent CH_4 recovery rate with 97.5 percent CH_4 RNG. Morrow also claims a system uptime or availability of 99 percent, the highest of all proposers. The Morrow system has a heat demand of approximately 5 MMBTU/hr for regenerating the amine solution. Morrow claims that 4 MMBTU/hr of the heat input can be recovered for use onsite. The Morrow proposal includes a commercial water heater for regenerating the amine solution. Figure 3-2 shows an example of a Morrow amine installation on site.

Figure 3-2. Morrow amine installation treating 12,000 scfm of biogas at a landfill

The Morrow proposal includes an iron chelate system to pretreat raw biogas for H_2S removal. Iron chelate is a water-based system that chemically converts H_2S to sulfur. The system operates in a similar manner to the amine system in that biogas and a water-based solution interact within a contact tower where the H_2S is absorbed into the solution. Solid sulfur is then removed from the solution via a regeneration process. The regenerable H_2S removal system claims to have low operating cost because it does not rely on disposable adsorption media. The iron chelate system can achieve greater than 98 percent removal of H_2S in the raw biogas. Additional H_2S will subsequently be removed in the amine system.

Morrow did not provide any information on its proposed siloxane removal system other than to state that it would be an activated carbon type system and that actual biogas data is needed to properly size and select the system.

3.2.1.2 Wärtsilä

Wärtsilä reportedly has numerous biogas upgrading installations around the world, however, only two are located in the United States, neither of which treat biogas produced from the anaerobic digestion of sewage sludge.

Wärtsilä claims that its amine system has a CH_4 recovery rate of 99.9 percent. This is an important criterion as it is directly related to the volume of RNG produced for sale to CNGC and thus impacts the overall profitability of the Project. The Wärtsilä system has a heat demand of approximately 2.1 MMBTU/hr for regenerating the amine solution, with approximately 1.9 MMBTU/hr recoverable. The Wärtsilä proposal does not include a boiler for regenerating the amine solution. If requested, Wärtsilä could provide this equipment or heat from the Post Point boiler system could be used.

Wärtsilä proposes to pretreat the raw biogas to remove H_2S with a THIOPAQ biological scrubber by Paques Environmental Technologies. The THIOPAQ system features a caustic solution that is continuously regenerated in a bioreactor. The regenerated caustic solution flows counter to the raw biogas in a contact tower and then back to the bioreactor. Elemental sulfur is separated and removed from the process.

Wärtsilä proposes treating the biomethane product gas (approximately 60 percent of the raw biogas flow) with activated carbon to removal siloxanes. The proposed siloxane removal system includes three, 4-feet-diameter by 12-feet-tall vessels to be operated in series. A final particulate filter would be provided to capture carbon dust carryover.

Figure 3-3 shows an example of a Wärtsilä amine-based system installation.

Figure 3-3. Wärtsilä’s CA30LP amine system has a biogas treatment capacity of up to 550 scfm

3.2.1.3 Amine System Performance Summary

Table 3-3 summarizes the amine system performance as indicated by responses to the manufacturer's questionnaire.

Table 3-3. Amine System Technical Comparison

Criteria	Morrow	Wärtsilä
Methane recovery, %	99.0	99.9
Methane in product gas, %	97.5	99
Oxygen in product gas, %	NA	0.09
System uptime, %	99	98
Connected load, hp	366	308
Heat demand, MMBTU/hr	5	2.07
Heat recovery, MMBTU/hr	4	1.93
Upgrading system operating pressure, psig	15	58
System turndown ratio	4:1	3:1

While both manufacturers have indicated their ability to comply with CNGC's gas quality requirements, the Wärtsilä system appears to have slightly better performance in terms of CH_4 recovery, percent CH_4 in the RNG (BTU content), heat demand, and connected load. These key criteria will impact Project revenue, both in terms of quantity of RNG available for sale, and in operating costs.

Amine systems are generally more cost competitive relative to other technologies at high biogas flow rates and do not offer attractive economies of scale at low flows. As evidence of this, Morrow's smallest system to date is designed to treat a biogas flow of 1,500 scfm, which is nearly three times more biogas than is expected for Post Point at Project buildout conditions. Wärtsilä only has two projects in the United States, one at a landfill and one at a dairy. Between the two viable amine system manufacturers, there appears to be little to no experience at low biogas flow rates and within the United States. Aesthetics may also be a concern for some facilities as amine systems include tall vessels, at least 40-feet tall. For these reasons, amine systems do not appear to be appropriate for the Post Point and should be eliminated from further consideration.

3.2.2 Water Scrubber System

Water scrubbing systems used for biogas upgrading operate on the principle of solubility. CO_2 and H_2S are more soluble in water than CH_4. In a water scrubbing system, compressed biogas flows upward through a contact tower while water flows downward in a countercurrent fashion. Water scrubbing systems typically operate at high pressure to take advantage of improved CO_2 and H_2S solubility that increases with higher pressure. Contact towers are typically filled with packing materials to increase the surface area for biogas and water to interact. The compressed biomethane leaves the contact tower water-saturated and with a CH_4 concentration of approximately 98 percent. In addition to CO_2 and H_2S, some volatile organic compounds (VOC) and siloxanes may also be removed. The biomethane is then dried to remove moisture thus completing the conversion to RNG. Figure 3-4 shows a typical flow process diagram for water scrubbing systems.

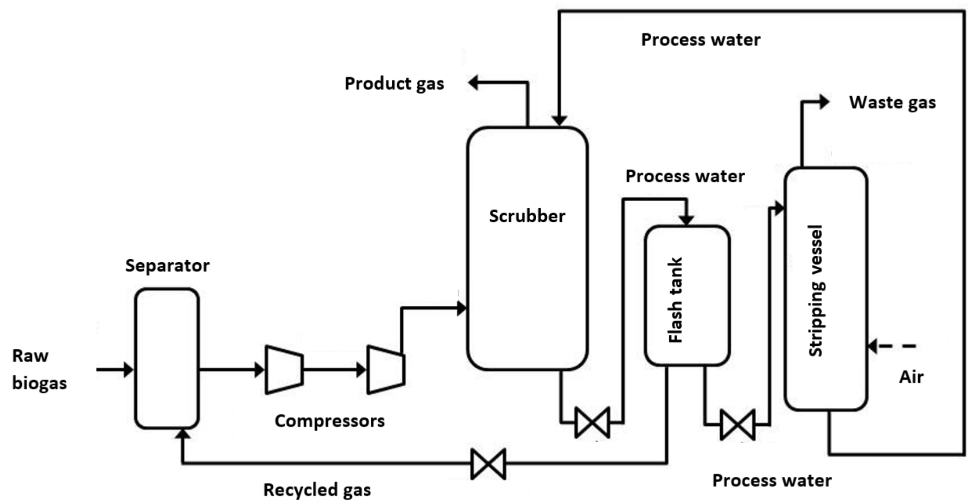

Figure 3-4. Water scrubber system process flow diagram

BC received only one proposal for high-pressure water scrubbing systems and this was from Dürr MEGTEC (Dürr). Details on the Dürr system are presented below, followed by the manufacturer's responses to the questionnaire (Table 5).

3.2.2.1 Dürr MEGTEC

Dürr is based in De Pere, Wisconsin, and has a broad corporate profile in environmental control technologies, including biogas upgrading. The firm offers a two-stage water scrubber. Raw biogas is pressurized to approximately 150 psig prior to entering the contact towers. The biomethane leaving the contact towers then passes through two molecular sieve vessels for desiccant drying. The Dürr water scrubber system operates such that the process water is a closed loop that is regenerated in a two-stage process. The first regeneration step drops the pressure of the process water from the contact tower to a pressure of approximately 30 psig in a flashing vessel. Reducing the pressure of the process water causes some of the dissolved gases to release from the water. The released gases are then recycled to the inlet of the system to increase the overall CH_4 capture rate.

The CH_4 capture rate is reportedly 98.5 percent while the RNG CH_4 concentration is about 97 percent. The second stage of regeneration occurs when the process water pressure is reduced to atmospheric pressure and run downward through a second packed contact tower (known as a stripping vessel) in a counterflow arrangement to incoming compressed air. From within the stripping vessel, the captured CO_2 and H_2S are removed from the process water and the waste gas is typically vented to atmosphere. Figure 3-5 shows a rendering of Dürr's 1,000 scfm capacity water scrubber system.

Dürr proposes to provide scavenger type pre-treatment systems to independently remove H_2S and siloxanes from the raw biogas upstream of the water scrubber system.

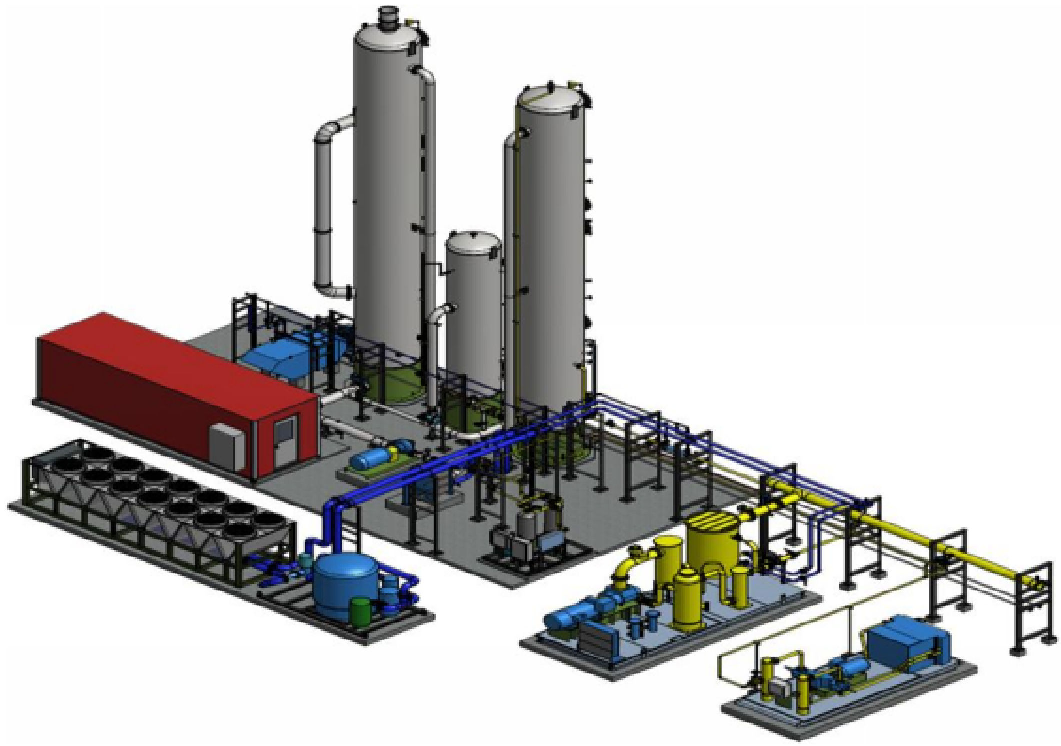

Figure 3-5. Dürr MEGTEC rendering of a 1,000 scfm capacity water scrubber system

3.2.2.2 Water Scrubber System Performance Summary

Table 3-4 summarizes Dürr's response to the manufacturer's questionnaire.

Table 3-4. Water Scrubber System Technical Summary

Criteria	Dürr
Methane recovery, %	98.5
Methane in product gas, %	97
Oxygen in product gas, %	0.2
System uptime, %	95
Connected load, hp	675
Upgrading system operating pressure, psig	150
System turndown ratio	4:1

The primary disadvantage of a two-stage water scrubbing system is the challenge to comply with stringent RNG quality requirements, such as those defined by CNGC. When process water is recycled in a two-stage system, air is used in the stripping vessel to remove any of the remaining gases absorbed into the water. As a result, the process water becomes saturated with O_2 (and N_2) and could result in the RNG exceeding the O_2 limit prescribed by CNGC. RNG with elevated O_2 and N_2 levels may not comply with CNGC's heating value requirement. Excessive amounts of O_2 and N_2 could lower the RNG heating value to such an extent that the required heating value could not be met even at 1 percent CO_2 in the product gas.

Given the challenges in meeting the RNG quality specification and the fact that only one manufacturer (limited competition for competitive pricing) proposed a water scrubber, this type of biogas upgrading system should be eliminated from further consideration.

3.2.3 Membrane Systems

Membranes are thin, semi-permeable barriers that selectively separate molecules of different sizes. Membranes are commonly used to separate CO_2 from biogas. The driving force for the process is differential partial pressures with a high pressure on the process side and low pressure on the waste side. Membranes operate at high pressures, typically from 150 to 220 psig. Figure 3-6 shows a typical flow process diagram for membrane systems.

The CO_2 dissolves and diffuses through the thin, non-porous membranes faster than CH_4. The selectivity for CO_2 is not as high as with adsorbents or solvents and, as a result, a two-stage or three-stage process is usually required to achieve the CH_4 capture efficiency required to comply with CNGC's RNG quality requirements.

Membranes also remove residual water and H_2S (although H_2S can degrade the membrane life) and to a lesser degree, O_2 and N_2, from biogas. Preliminary H_2S treatment is required due to the potential to form a fine powder of elemental sulfur which will eventually clog the membranes if not removed properly. VOCs and siloxanes are known to degrade membranes and must be removed upstream, typically with a scavenging media.

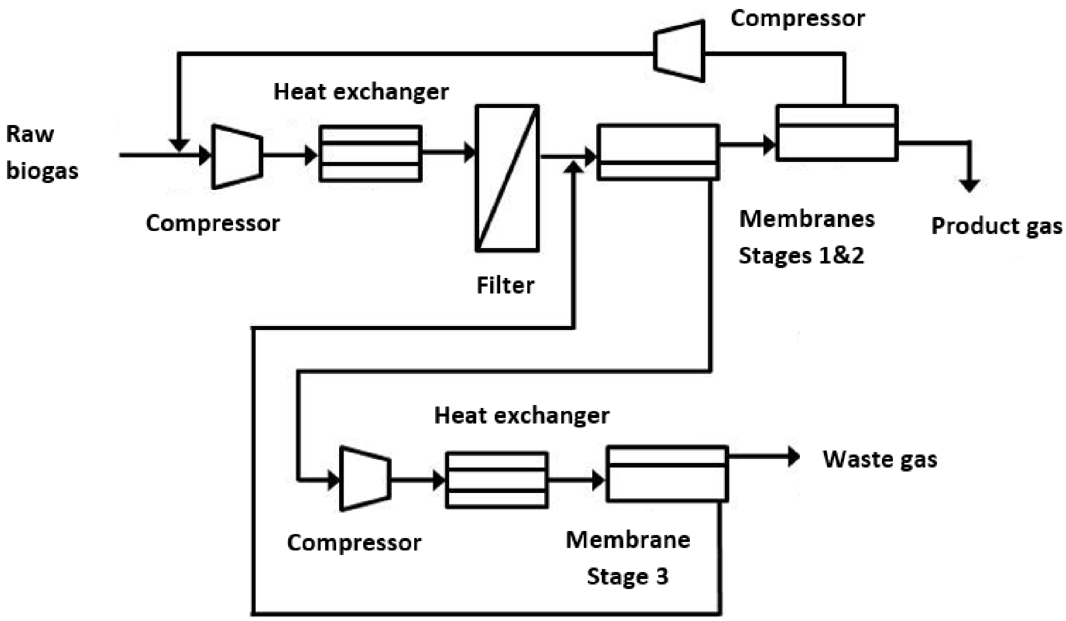

Figure 3-6. Membrane system (three-stage) process flow diagram

BC received responsive proposals from three manufacturers of membrane systems: DMT Clear Gas Solutions, GraniteFuel Engineering, and Unison Solutions. A fourth manufacturer, Air Liquide elected not to submit a proposal, but provided Unison Solutions as an alternate.

Details on each of the respective systems are presented below, followed by a performance comparison of the three membrane systems based on responses to the manufacturer's questionnaire (Table 3-2).

3.2.3.1 DMT Clear Gas Solutions

DMT Clear Gas Solutions (DMT) has installed dozens of membrane systems around the world, a few of which are located at wastewater treatment plants (WWTPs). Twelve of these installations are located in the United States, with at least four of those installations treating biogas produced from the anaerobic digestion of municipal wastewater sludge.

DMT has offered its three-stage membrane system for Post Point's biogas upgrading Project. DMT has stated that its proposed system will meet the specified RNG quality requirements. The three-stage membrane system will reportedly achieve a CH_4 recovery rate of 99.5 percent. DMT acknowledges that membranes degrade over time and that near the end of the membrane life CH_4 recovery rate is expected to drop to approximately 98.5 percent. While DMT claims an exceptional CH_4 recovery rate, the CH_4 concentration in the RNG is amongst the lowest at only 96 percent (see also Unison Solutions, Guild Associates, Inc., and Xebec). Figure 3-7 shows a rendering of the DMT containerized membrane skid unit.

DMT's proposal also includes a pre-treatment system consisting of two vessels packed with granular iron oxide scavenger media for bulk H_2S removal followed by lead-lag activated carbon vessels for siloxane removal.

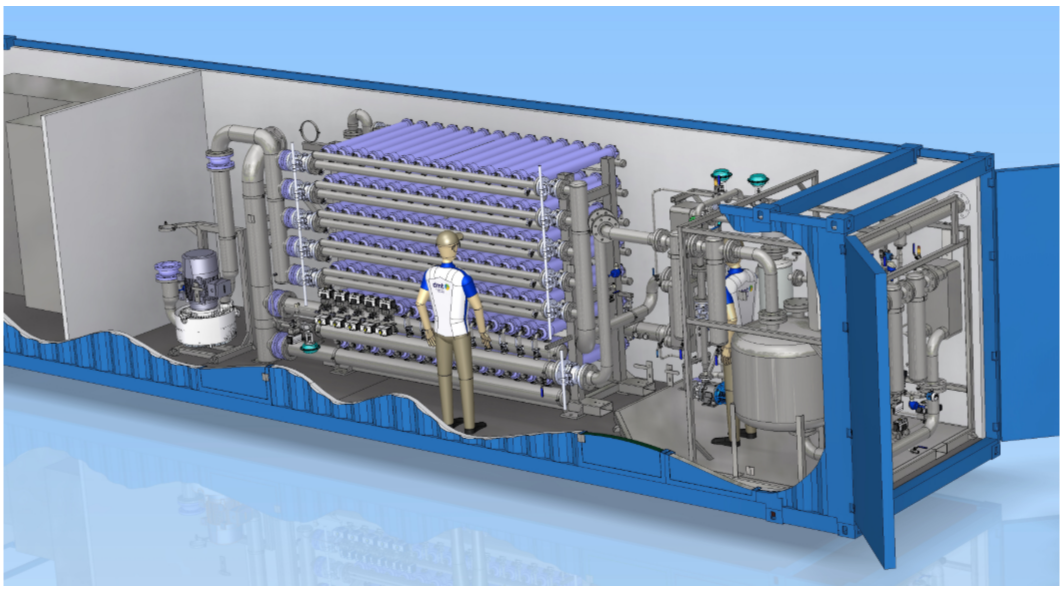

Figure 3-7. DMT containerized membrane skid rendering

3.2.3.2 GraniteFuel Engineering

GraniteFuel Engineering's (GraniteFuel) parent company, DCL, is one of the leading catalyst manufacturers in the world. Because catalysts are highly susceptible to fouling caused by the contaminants found in biogas, DCL entered the biogas treatment market to fabricate equipment designed specifically to protect its catalysts. DCL created GraniteFuel to focus solely on biogas treatment. Over time, GraniteFuel expanded its operations to include biogas upgrading systems.

The GraniteFuel proposal includes a three-stage membrane system. GraniteFuel claims a 99.5 percent CH_4 recovery rate and the highest RNG CH_4 concentration amongst all manufacturers considered for this evaluation. Additionally, GraniteFuel claims the lowest connected electrical load of all membrane system suppliers. Figure 3-8 shows illustrations of the GraniteFuel pre-treatment and membrane systems.

GraniteFuel's proposal includes a pre-treatment system consisting of two H_2S scavenging vessels followed by gas dehydration and compression equipment. The final phase of the pre-treatment system is GraniteFuel's proprietary temperature swing adsorption (TSA) system for siloxane and VOC removal.

The TSA system consists of two vessels filled with a proprietary polymer media. The media is loaded into several trays that are stacked in the vessels. This configuration allows for simple expansion of the TSA system by adding additional trays as needed. The polymer media is continuously regenerated and has a lifespan of at least 10 years. While one vessel is operating to treat the biogas, the other vessel is isolated from the biogas and regenerated. Heated air is forced through the regenerating vessel. The elevated temperature breaks the adsorption bonds and causes the captured siloxanes and VOCs to release from the media. In this manner the two vessels alternate between treating the biogas and regenerating the media.

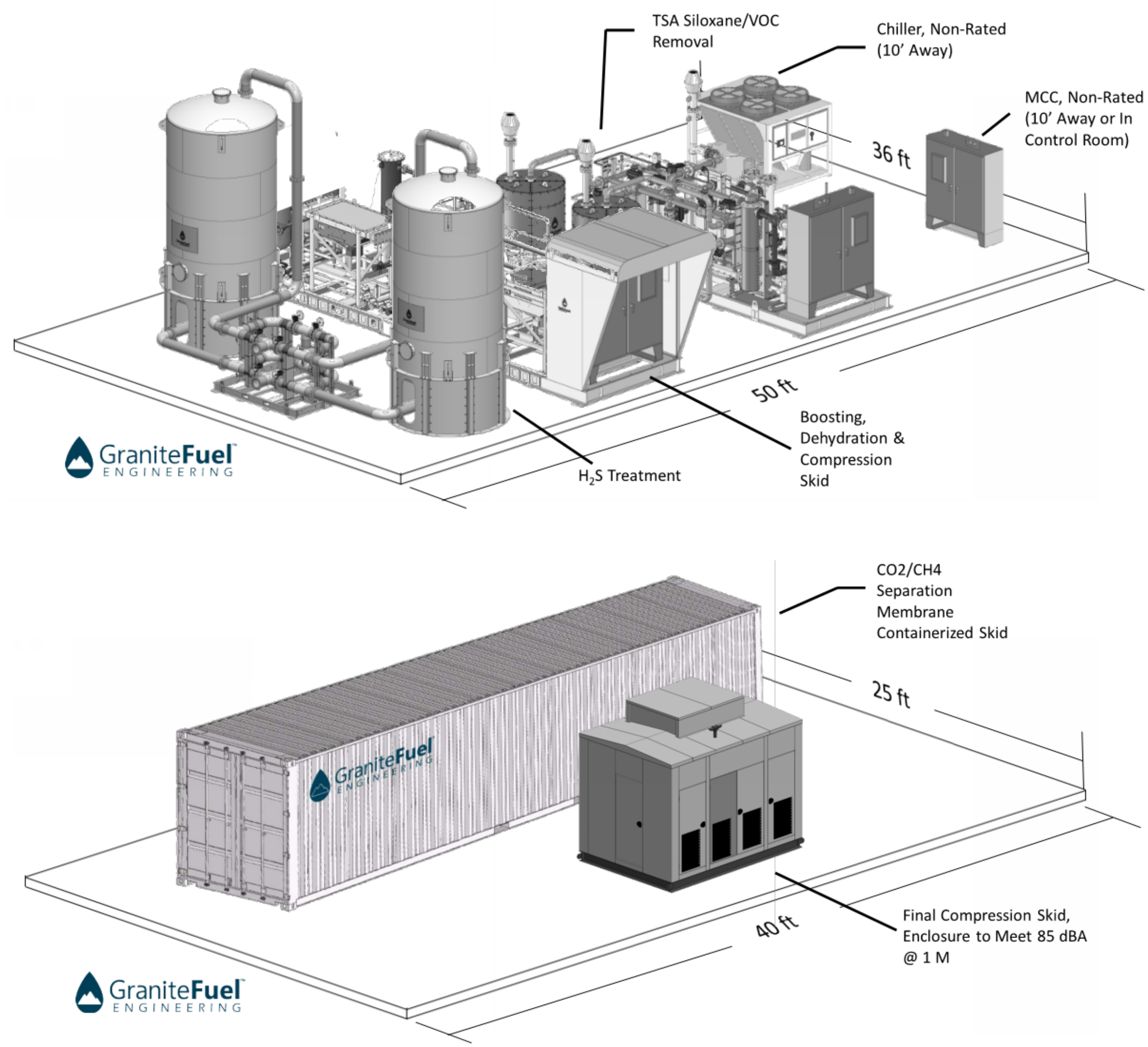

Figure 3-8. GraniteFuel pre-treatment and membrane systems

3.2.3.3 Unison Solutions

Unison Solutions (Unison) has a long and successful history of supplying biogas pre-treatment equipment with a few biogas upgrading systems. As noted above, Unison was recommended by Air Liquide, who opted not to provide a proposal for the Project. Unison subsequently provided a proposal based on a three-stage Air Liquide membrane system. The proposed system includes two vessels loaded with granular iron oxide media for H_2S removal and five vessels filled with activated carbon for siloxane and VOC removal.

The Unison proposal indicates that it will comply with the minimum heating value (985 BTU/ft^3) requirement per CNGC. However, the proposal does not explicitly state the anticipated CH_4 concentration in the RNG. A 985 BTU/ft^3 heating value corresponds to an RNG CH_4 concentration of approximately 97.5 percent.

Figure 3-9 shows a Unison membrane system.

Figure 3-9. Unison membrane system treating 400 scfm of biogas at a WWTP

3.2.3.4 Membrane System Performance Summary

Each of the three candidate membrane system manufacturers proposed a three-stage membrane system with pre-treatment systems to protect the membranes from H_2S, siloxanes, and VOCs. Three-stage membrane systems have high CH_4 recovery rates, with two of the manufacturers claiming 99.5 percent. Membrane systems typically have high electric power demands due to the biogas compression required to meet the membrane's optimal operating pressure. Table 3-5 provides a comparison of the three systems.

Table 3-5. Membrane System Technical Comparison

Criteria	DMT	GraniteFuel	Unison
Methane recovery, %	99.5	99.5	99
Methane in product gas, %	96	99.5	97.5
Oxygen in product gas, %	0.05	0.3	0.2
System uptime, %	98	98	98
Connected load, hp	650	553	835
Upgrading system operating pressure, psig	210	180	150
System turndown ratio	3:1	3:1	4:1

3.2.4 Pressure Swing Adsorption Systems

PSA systems use adsorbent media to separate CO_2 from biogas according to its molecular characteristics and affinity for the adsorption material. PSA systems take advantage of the difference in equilibrium capacities of adsorbents for CO_2 at high and low pressures. Special adsorption materials are used as a molecular sieve, preferentially adsorbing the CO_2 at high pressure. Adsorbents are highly porous materials with extremely large surface areas. Adsorbents with pore sizes selective for CO_2 (and other gas species) include activated carbon, silica gel, alumina, and zeolite. The capacity of an adsorbent for CO_2 is the amount of CO_2 that can be adsorbed at an equilibrium condition. The capacities at high pressure are greater than those at low pressure. Figure 3-10 shows a typical process flow diagram for PSA systems.

PSA systems feature multiple vessels filled with the adsorbent media. The systems operate such that at least one vessel is actively treating the biogas at high pressure while at least one other vessel is regenerating its media at low pressure. Undesirable gaseous molecules are adsorbed at high pressure and desorbed at low pressure, hence the term pressure swing adsorption.

During normal operation, each vessel operates in an alternating cycle of adsorption/regeneration. During the adsorption phase, biogas enters from the bottom into one of the vessels adsorbing CO_2 onto the media surface. The purified RNG can contain up to 99 percent CH_4. As the media in the vessel becomes saturated with adsorbed compounds, the flow is directed to the following vessel where the media has been previously regenerated thus providing continuous operation. The vessel with now saturated media is then depressurized to regenerate the adsorbent media. The regeneration process creates a waste stream of the collected impurities.

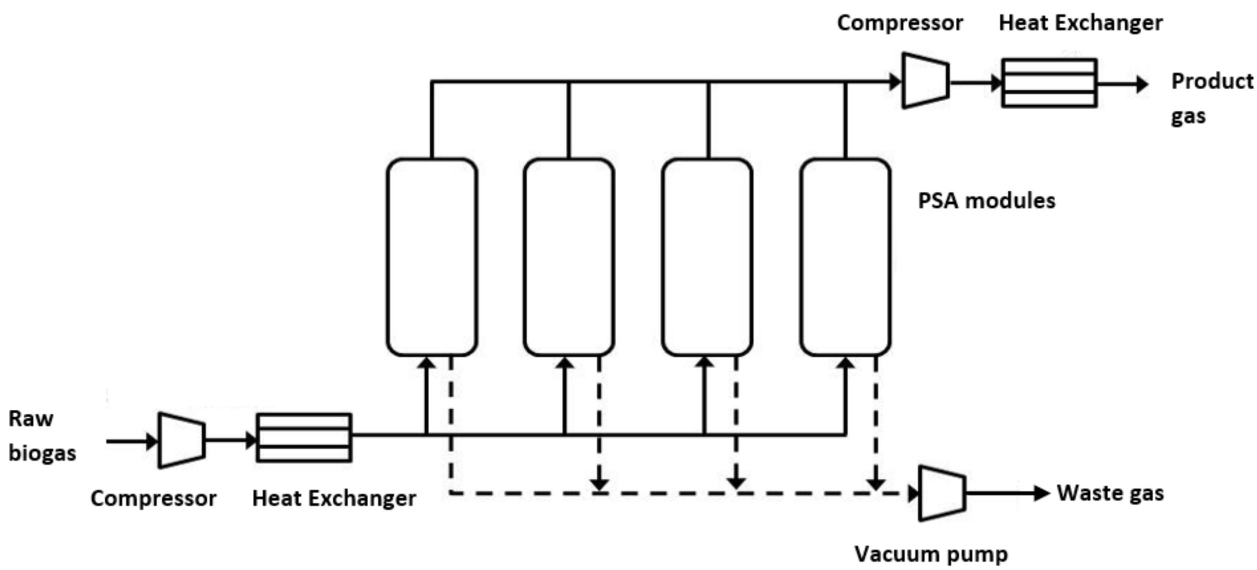

Figure 3-10. Pressure swing adsorption system process flow diagram

BC received acceptable proposals from four PSA systems manufacturers: Greenlane, Guild Associates, Inc., Schmack Carbotech, and Xebec. Details on each of the respective PSA systems are presented below, followed by a performance comparison of the four PSA systems based on responses to the manufacturer's questionnaire (Table 3-2).

3.2.4.1 Greenlane

Greenlane has been providing biogas upgrading systems for over 30 years and has over 110 installations throughout the world. It also claims to have provided the largest biogas upgrading system in the world. Greenlane claims to be the only manufacturer to offer three types of biogas upgrading systems: PSA, membrane, and water scrubber. Based on the design criteria for the Project, Greenlane elected to propose on a PSA system since it provides the highest likelihood of meeting the RNG quality requirements. According to Greenlane, a membrane can also meet the RNG quality requirements, but not as easily as the PSA system can. Also, its PSA system can remove N_2 while its membrane system cannot. Thus, the Greenlane PSA system provides a higher quality RNG than its membrane system. Further, Greenlane does not recommend its water scrubber system since that type of system would be challenged to meet the RNG quality requirements.

The proposed Greenlane system includes 12 PSA vessels arranged in two banks of six vessels, each. The 12 vessels are operated in a cycle of four phases: pressure build-up, adsorption, depressurization, and regeneration. The phased operation of all 12 vessels is controlled by a single rotary valve. One of the unique features of the Greenlane system is achieving pressure build-up in the first phase vessels by equalizing them with vessels that are in the depressurization phase. Figure 3-11 shows a Greenlane PSA system on site at a dairy.

In addition to removing CO_2, the system is also designed to remove O_2 and N_2. The ability to remove some O_2 and N_2 is expected to help achieve compliance with the RNG quality requirements. Greenlane's proposed PSA has a 98 percent CH_4 recovery rate and RNG CH_4 concentration of over 98 percent.

Greenlane's proposal includes a single iron sponge vessel for H_2S removal. Siloxanes and VOCs will be removed by activated carbon adsorption in two vessels.

Figure 3-11. Greenlane PSA system treating 800 scfm of biogas at a dairy

3.2.4.2 Guild Associates, Inc.

Guild Associates, Inc. (Guild) has extensive experience with biogas upgrading. Guild systems have been installed with at least 23 digesters (breakdown of WWTPs and dairy digesters is not known) and 9 landfills. Guild currently has three systems in various stages of installation and startup. Figure 3-12 shows a Guild PSA system on site at a WWTP.

The Guild system uses proprietary molecular sieve adsorbent that can be used to remove CO_2, H_2S, VOCs, siloxanes, and moisture in a single step. Gas pre-treatment is not required.

The RNG and waste gas from a Guild system have CH_4 concentrations of 96 percent and 9 percent, respectively. Along with DMT, Unison, and Xebec, the Guild system has the lowest RNG CH_4 concentration.

Figure 3-12. Guild PSA system treating 700 scfm of biogas at a WWTP

3.2.4.3 Schmack Carbotech

Schmack Carbotech (Carbotech) is one of Europe's leading biogas upgrading system manufacturers and has been active in the business for over 30 years. Carbotech is based in Germany and is represented in the United States by BIOFerm.

Carbotech offers one and two-stage PSA systems. The first-stage PSA removes CO_2, H_2O, and some O_2 and N_2. If needed, a second-stage PSA can be provided to remove nearly all the remaining O_2 and N_2. BIOFerm selected the singe-stage system for the Post Point due to the low O_2 concentration expected in the raw biogas. The singe-stage system can apparently achieve up to 99 percent CH_4 recovery and 98 percent CH_4 in the RNG.

H_2S, siloxanes, and VOCs will be removed from the biogas in upstream pre-treatment systems. A biological desulphurization system is proposed for H_2S removal while a regenerative TSA system would be used for siloxane and VOC removal.

Figure 3-13 shows a photo of the Carbotech PSA on site at a meat processing facility.

Figure 3-13. Carbotech PSA system treating 1,200 scfm of biogas

3.2.4.4 Xebec

Xebec was established in Canada in 1967 and has supplied over 250 PSA systems around the world. While Xebec did provide budgetary pricing for a PSA system, it refused to provide any level of detail until an NDA is in place. The following information is from a Xebec sales brochure. Figure 3-14 provides an illustration of a typical Xebec PSA system configuration. The six numbered items are identified follows:

1. H_2S Scavenger–Lead-lag vessels with activated carbon
2. Compressor Room–Feed gas blowers, compressors, and regeneration vacuum pumps
3. Buffer Tanks–PSA system inlet, recycle, RNG and waste gas buffer tanks
4. PSA System–Nine PSA vessels with regenerative adsorbent
5. Control Room–Automated control of biogas flow and RNG flow/composition
6. Water Chiller Package–Dehydration system with chiller and heat exchanger

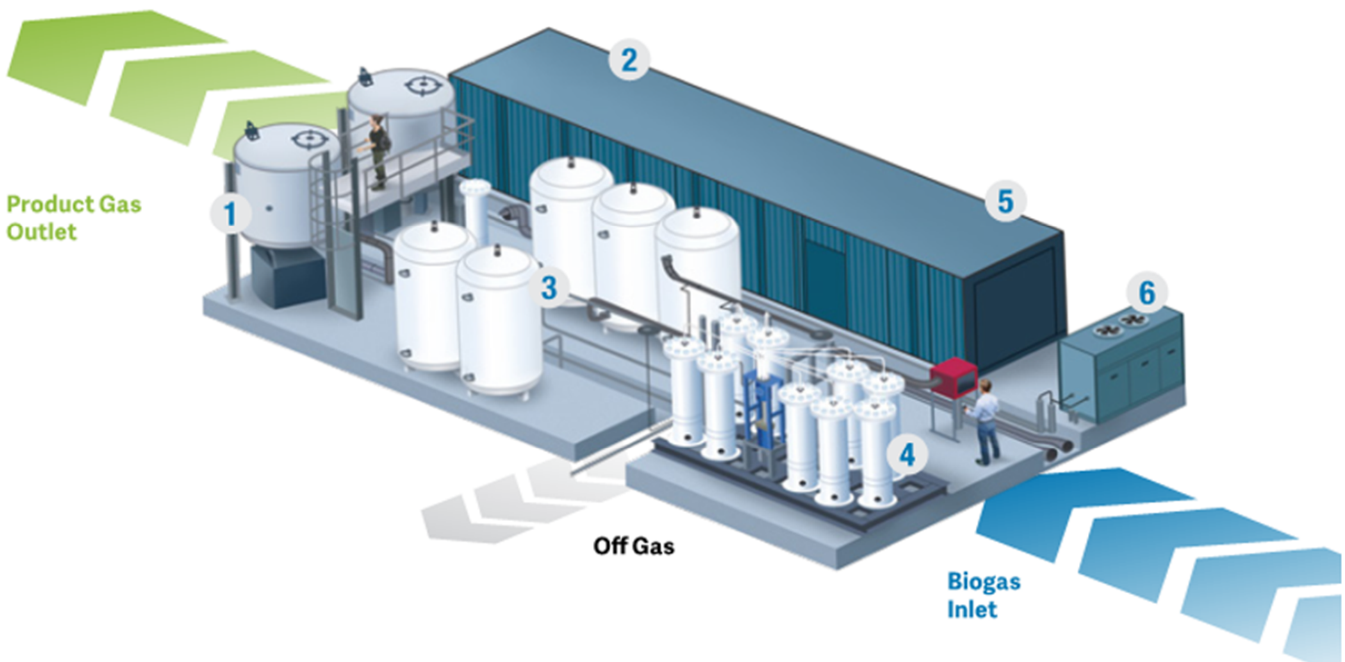

Figure 3-14. Typical Xebec PSA system configuration

While not identified in the figure above, it is expected that the Xebec PSA system will require additional pre-treatment equipment to remove siloxanes and VOCs. Based on review of a Xebec sales brochure, expected CH_4 recovery is 98.5 percent.

3.2.4.5 PSA System Performance Summary

Four manufacturers provided proposals for PSA systems. As mentioned above, Greenlane offers three different types of biogas upgrading systems and elected to propose a PSA system due to its ability to most easily meet the RNG quality requirements. Xebec provided a budgetary cost quotation but did not provide any detailed information about the equipment sizing and performance. The information presented in Table 3-6 was reproduced from a Xebec sales brochure. The Guild system has a very low CH_4 recovery rate and the waste gas therefore has a high CH_4 concentration.

Table 3-6. Pressure Swing Adsorption System Technical Comparison				
Criteria	Greenlane	Guild	Carbotech	Xebec
Methane recovery, %	98	92	99	98.5
Methane in product gas, %	98	96	98	98
Oxygen in product gas, %	0.05	0.1	0.04	NA
System uptime, %	97	98	96	98
Connected load, hp	295	553	525	400
Upgrading system operating pressure, psig	130	150	150	NA
System turndown ratio	5:1	4:1	3.3:1	2.5:1

3.3 Thermal Oxidizers

RNG will be continuously monitored for compliance with CNGC's specified quality requirements. If the RNG is out of compliance it will be rejected by the automatic closing of a "purity" valve. This prevents off-spec gas from entering the CNGC pipeline. In such a situation it would be necessary to dispose of the off spec RNG in a waste gas burner. Waste gas burners are the appropriate combustion technology for eliminating waste gas streams with approximately 25 percent or more CH_4. Once the RNG is confirmed to meet the quality requirements, the purity valve would automatically open and allow RNG into the CNGC pipeline.

By virtue of their ability to separate CO_2 (and other gases) from CH_4, biogas upgrading systems produce a waste gas stream consisting primarily of CO_2, but also small amounts of CH_4. Depending on the biogas upgrading system's CH_4 recovery rate and CH_4 concentration in the waste gas, the waste gas stream may need to be combusted. Waste gas streams with low CH_4 concentrations below approximately 25 percent are difficult to combust in standard waste gas burners and would require an assist gas (natural gas, biomethane, or raw biogas) to enrich that waste gas stream and sustain combustion.

A thermal oxidizer allows oxidation or combustion of gases containing low amounts of combustible fuel. Thermal oxidizers have a ceramic-insulated section where the waste gas is held at a high temperature to ensure oxidation of the CH_4 (and other combustible gases) in the waste gas stream. This insulated section along with a pilot flame and support burner enable the thermal oxidizer to achieve destruction efficiencies of 98 percent or higher at an operating temperature of approximately 1,600°F. This configuration allows for combustion without a support gas at CH_4 concentrations as low as 7 to 8 percent. A recuperative heat exchanger for combustion air preheating can accommodate waste gas with even lower CH_4 concentrations, but at additional capital cost, complexity, and technical risk.

As an alternative to gas-assisted waste gas burners and thermal oxidizers, some utilities that operate biogas upgrading systems with CH_4 recovery rates of approximately 98 percent or more allow the waste gas to be vented to atmosphere. The venting of waste gas results in higher greenhouse gas (GHG) emissions due to CH_4 release. Although many air permitting authorities allow venting of gas streams with small amounts of CH_4, this approach is likely not acceptable to the City.

It is important to note that CH_4 has a global warming potential of 34 (100-year time horizon) relative to CO_2. Combustion oxidizes each mole of CH_4 to one mole of CO_2 (and two moles of water vapor), thus significantly reducing GHG emissions in comparison to venting raw CH_4 to atmosphere. In most jurisdictions, CH_4 is not a regulated pollutant. However, when CH_4 is combusted it creates nitrogen oxide (NOx), which is a criteria air pollutant as defined and regulated by the United States Environmental Protection Agency.

Section 4: Cost Evaluation

As described in Section 3, water scrubber and amine systems have been eliminated from further consideration. This section provides a summary of budgetary costs for the biogas upgrading system alternatives representing the short-listed technologies: membrane and PSA.

4.1 Capital Cost

A project's capital cost is typically a one-time expense that occurs at the beginning of the project and primarily consists of:

- Construction costs including contractor overhead and profit
- Capital expenditure (CAPEX), i.e., the cost to purchase or upgrade an asset
- Engineering fees
- Administrative and legal fees
- Contingency

Only CAPEX costs are presented in this TM. The CAPEX costs listed in Table 4-1 are the budgetary purchase prices quoted by these biogas upgrading system manufacturers and include all compression and pre- and post-treatment equipment.

Table 4-1. Biogas Upgrading System CAPEX

Manufacturer	Technology	CAPEX
Guild	PSA	$2,274,000
Greenlane	PSA	$2,285,000
Xebec	PSA	$2,594,000
DMT	Membrane	$3,640,000
GraniteFuel	Membrane	$3,784,000
Carbotech	PSA	$5,265,000
Unison	Membrane	$5,595,000

4.2 Operation and Maintenance Costs

Operation and maintenance (O&M) costs are the sum of the cost to operate and maintain each piece of equipment that is part of the overall system. O&M costs recur, typically at regular intervals, throughout the life of the system and include:

- Electric power
- Fuel
- Chemicals and other consumables, including shipping and disposal
- Labor

Operating expenditures (OPEX) are related solely to the operation of the individual equipment items that make up a system. As part of their proposals, manufacturers were asked to provide OPEX costs based on an assumed $0.08/kWh cost of electricity. OPEX costs also include the cost of disposable media used in pre- and post-treatment systems. Table 4-2 lists OPEX costs provided by the proposers. Note that OPEX costs do not include City labor rates.

Table 4-2. Biogas Upgrading System OPEX		
Manufacturer	Technology	OPEX/yr
Greenlane	PSA	$154,200
Carbotech	PSA	$334,000
Guild	PSA	$338,700
GraniteFuel	Membrane	$345,600
DMT	Membrane	$519,700
Xebec	PSA	$544,500
Unison	Membrane	$990,900

Section 5: Short-Listed Biogas Upgrading Technologies

Membrane and PSA systems have been identified as the biogas upgrading technologies most likely to meet the City's biogas upgrading needs. This section compares membrane and PSA systems.

5.1 Criteria Comparison

The conceptual-level technology screening presented in this TM is focused on capital and operating costs and the ability of the proposed systems to meet the RNG quality requirements. The criteria were weighted based on perceived importance. The key performance criteria evaluated in this exercise are easily quantifiable and include:

1. **CAPEX:** High score for low cost
2. **OPEX:** High score for low cost
3. **Methane recovery:** High score for high CH_4 recovery
4. **Methane in product gas:** High score for high RNG CH_4 concentration
5. **System availability:** High score for high percentage of time the system is fully operational

Table 5-1 summarizes preliminary evaluation criteria and the assumed importance weights. Justification for the selected weight is included in the last column.

Table 5-1. Sample Criteria Weighting		
Criteria	Weight	Reason for Weight
CAPEX	15	Impacts initial capital outlays
OPEX	25	Impacts annual revenue
Methane recovery	25	Impacts available volume of RNG for sale
Methane in product gas	30	Key indicator of RNG quality compliance
Availability	5	Impacts annual revenue

The conceptual-level technology screening has been limited to membrane and PSA systems. As previously described, amine (lack of experience with low biogas flows and within the United States) and water scrubber systems (difficulty in meeting the RNG quality requirements) were eliminated from further evaluation.

Table 5-2 presents a preliminary, weighted criteria scoring on the two remaining technologies.

Table 5-2. Preliminary Weighted Criteria Scoring with OPEX

Criteria	Weight	Membrane			PSA			
		DMT	GraniteFuel	Unison	Greenlane	Guild	Carbotech	Xebec
CAPEX	15	52	48	22	135	133	25	102
OPEX	25	67	100	35	225	102	104	64
Methane recovery	25	221	221	217	208	162	217	213
Methane in product gas	30	234	270	249	246	234	254	234
Availability	5	43	43	43	41	43	40	43
Manufacturer Score		617	683	566	856	675	640	656
Manufacturer Rank		6	2	7	1	3	5	4
Technology Average Score		622			707			
Technology Rank		2			1			

Per the preliminary scoring presented above, it appears that PSA systems are the highest-ranking technology based on the design criteria and assumed scoring criteria and weighted importance factors.

5.2 Technology Screening Summary and Conclusions

The purpose of the scoring exercise presented above is to identify gas upgrading technologies that are appropriate for Post Point's design conditions and that comply with the RNG requirements established by CNGC. Given the complex nature of biogas upgrading systems and the degree of variability amongst systems proposed by the candidate manufacturers, even within the same technology category, the City should consider procuring the biogas upgrading system as a complete package with all necessary pre- and post-treatment equipment and compression equipment under a single scope of supply.

Section 6: Biogas Upgrading Alternatives Development

This section presents a preliminary layout for each of the two short-listed biogas upgrading technologies. The preliminary layouts do not include RNG odorizing and quality monitoring equipment. These items will be coordinated with CNGC during design. The systems represented in the preliminary layouts are expected to require a thermal oxidizer for eliminating waste gas. However, thermal oxidizers are not shown in the layouts presented below.

The highest ranked biogas upgrading systems, according to the preliminary screening (see Section 5) are as follows:

1. Greenlane–PSA
2. GraniteFuel–membrane

Equipment dimensions provided in the Greenlane and GraniteFuel proposals were used to develop preliminary layouts for the membrane and PSA systems presented below.

6.1 GraniteFuel–Membrane

The GraniteFuel system is easily expandable to accommodate increased future flows. This can be accomplished by leaving space for and adding membrane modules to the system when needed. Also, GraniteFuel's proprietary TSA system for siloxane removal is easily expandable by simply adding more cartridges to the treatment vessels. Figure 6-1 shows a potential layout for the GraniteFuel membrane system.

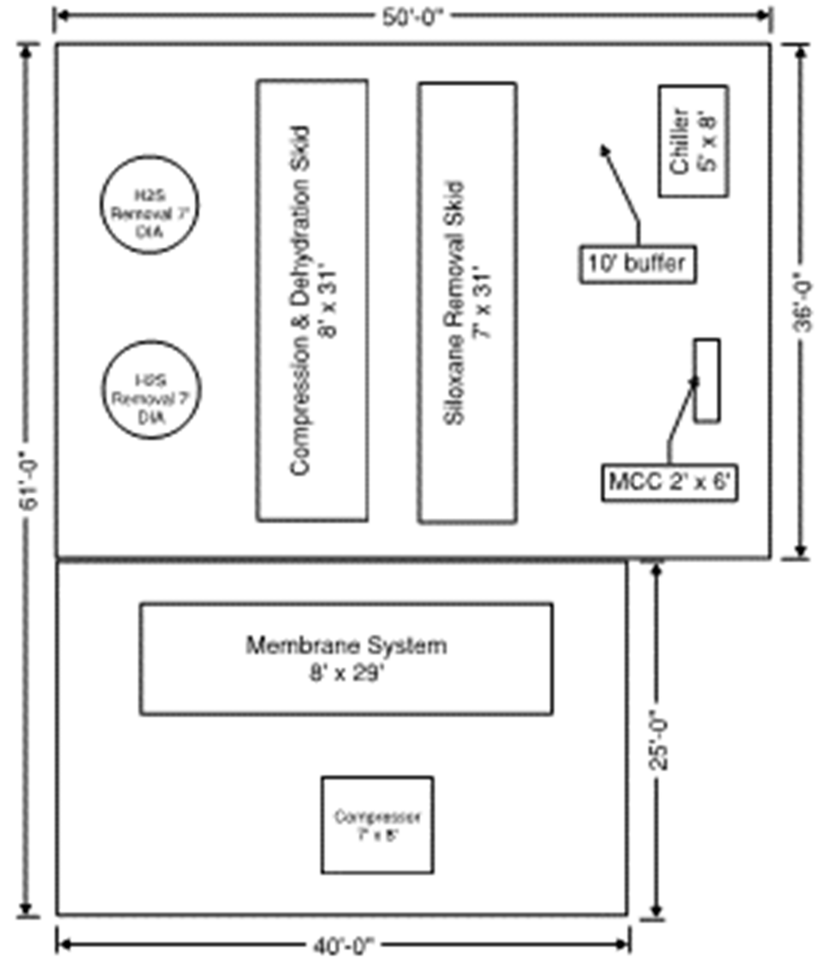

Figure 6-1. Potential layout for the GraniteFuel biogas upgrading system

6.2 Greenlane–PSA

The Greenlane proposal included detailed drawings of each sub system that form a complete biogas upgrading system. The layout shown in Figure 6-2 represents a potential Greenlane PSA configuration.

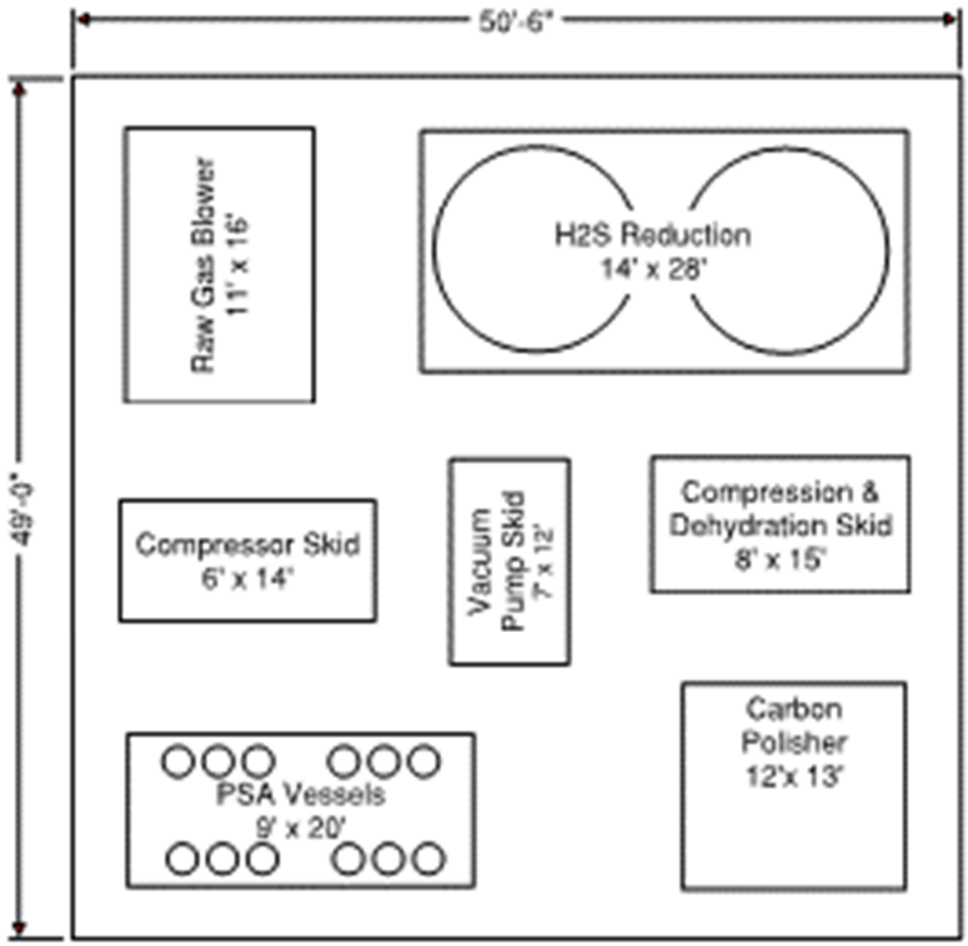

Figure 6-2. Potential layout for the Greenlane biogas upgrading system

The overall footprint of the proposed Greenlane system, as shown above, may change depending on the City's desire for redundancy at the various compressors.

Section 7: Findings and Recommendations

To perform the conceptual-level technology evaluation described in this TM, BC contacted and requested proposals from 16 biogas upgrading system manufacturers. Four biogas upgrading technologies were represented amongst the ten budgetary proposals that were received. The amine and water scrubbing technologies have been eliminated from further consideration, primarily due to lack of experience in the United States and challenges related to meeting the RNG quality requirement for O_2, respectively.

Based on the technical information provided by the respondents, it appears that two of the technologies considered can meet the stringent RNG quality requirements. The short-listed technologies that warrant further evaluation are membrane and PSA. Subsequent conversations with membrane and PSA system suppliers revealed that several suppliers offer both membrane and PSA systems. All suppliers that offer both membrane and PSA systems recommended PSA systems for the Project, primarily for the following reasons:

- PSA systems remove N_2 and some O_2 which results in greater flexibility in complying with RNG requirements as specified by CNGC. These systems can more easily comply with the Total Inerts + Oxygen requirements. Additionally, the removal of N_2 and O_2 produces a gas product that more easily complies with the high Heating Value and Wobbe Number requirements (see Table 2-3). Conversely, membrane systems do not remove N_2 and O_2, which results in these constituents becoming more concentrated in the RNG.
- PSA systems have lower OPEX costs due to having a much lower operating pressure and lower pressure loss through the system. PSA systems operate at approximately 150 psig, whereas membrane systems operate at about 250 psig. Pressure loss through a PSA system is about 15 psig compared to 50 psig for membrane systems.
- While a degree of moisture removal is required for all technologies, PSA systems are more tolerant of small amounts of moisture due to their ability to continuously regenerate their media and thus reject some moisture trapped in the media.
- PSA media can be tailored to specific raw gas constituents.

The feedback from suppliers that offer both technologies is consistent with the findings from BC's preliminary evaluation, which resulted in PSA being the top scored technology. Therefore, BC recommends the selection of the PSA technology for biogas upgrading at Post Point.

Attachment A: Constituents for Periodic Sampling

Table A-1. Constituents for Periodic Sampling

Constituent	Allowable Level mg/m^3 (ppm_v)
Health Protective Constituents–Carcinogenic	
p-Dichlorobenzene	140 (24)
Ethylbenzene	650 (150)
Vinyl chloride	21 (8.3)
Health Protective Constituents–Non-Carcinogenic	
Mercaptans (Alkyl Thiols)	N/A (610)
Toluene	45,000 (12,000)
Pipeline Integrity Constituents	
Ammonia	5 grains/CCF (10)
Biologicals[b]	4×10^4/scf
Hydrogen	0.10%
Mercury	0.08 ug/m^3
Siloxanes	0.1 mg Si/m^3

a. The first number is in milligrams per cubic meter of air (mg/m^3), while the second number in parenthesis is in parts per million volume (ppm_v), unless otherwise specified

b. qPCR per Acid-producing Bacteria (APB), Sulfate-reducing Bacteria (SRB), Iron-oxidizing Bacteria (IOB), group and commercially free of bacteria > 0.2 microns