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LOW-CARBON RENEWABLE NATURAL GAS (RNG) FROM WOOD WASTES

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SoCalGas
A Sempra Energy utility

PG&E Pacific Gas and Electric Company

SMUD

NW Natural

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Abstract

The state of California needs facilities that can dramatically reduce GHG emissions and black carbon production by using wood waste. The closing of biomass power plants is leading to open burning of the excess of these wastes. GTI led a team in performing a site-specific engineering design study focused on how an existing woody biomass power plant can be converted into a renewable natural gas (RNG) facility producing approximately 3 billion cubic feet of RNG annually. RNG is a low-carbon fuel that can be used in transportation, industrial, commercial, and residential sectors of the economy. The team relied on commercially available process equipment for this design, so that project development could proceed upon completion of this work. The engineering study provides detailed information about site-specific equipment layouts and connections for RNG production, detailed cost estimates for integration of the RNG producing equipment, capital expenses (CAPEX)(± 30%), operating expenses (OPEX), and life-cycle analysis (LCA) quantifying the carbon intensity of the product. The engineering design was performed by GTI, Black & Veatch, Andritz, and Haldor Topsoe. These companies are world experts in gasification, gas clean-up, and conversion technologies. The LCA was performed by Argonne National Laboratory, the developer of the GREET® model.

Executive Summary

BACKGROUND

California air quality continues to be exacerbated by black carbon and conventional air pollutants produced from the open burning of agricultural wastes and from devastating forest fires. Expanding opportunities for the processing of agricultural, forest, and urban wood wastes provides a means to reduce black carbon, which is one of the most potent climate change pollutants, and to reduce conventional air pollutants that can lead to increased incidences of asthma and other breathing disorders. Additionally, with the continued closing of biomass power plants that processed wood wastes to produce electricity, there are now not enough facilities to process all the wood waste being produced. This is leading to open burning of agricultural wastes throughout the state, including in the San Joaquin Valley, and contributing to devastating forest fires throughout the state every year. This project provides much needed design and engineering information to transform existing biomass power plants into RNG producing facilities. RNG production facilities for wood waste conversion will create a means to process these waste streams and virtually eliminate all criteria pollutants associated with existing biomass electricity production facilities. Additionally, a replacement for natural gas will be produced that has a very low carbon intensity, providing opportunities for carbon emission reductions in the transportation, industrial, commercial, and residential energy sectors.

METHODS

GTI led a team of engineers and scientists to produce an engineering design that provides a blueprint to transform an existing biomass power plant into an RNG producing facility utilizing some of the existing infrastructure and all the wood waste feedstock. The DTE biomass power plant in Stockton was the host site for the engineering design.

GTI began with a regional resource analysis and reviewed the site layout and operations at the Stockton, CA biomass-to-power facility. A process concept and preliminary layout specific to the Stockton Biomass Power Plant site was developed. The team prepared a complete set of process flow diagrams (PFD's) to show the process flow through the facility including the required auxiliary systems. Preliminary equipment specifications for the major equipment were compiled. Electrical loads were estimated and an electrical load list for all new equipment was created. A preliminary layout of major vessels, equipment and a set of preliminary general arrangement drawings were prepared. The existing GTI gasification simulation model based on the latest pilot-plant and commercial wood gasification data from GTI and other sources was reviewed. The gasification model, addressing input parameters such as temperature, pressure, fluidized bed material, velocities, residence time, char recycle, and feedstock moisture was refined. A cost estimate for the engineering, procurement, installation, and integration of the new equipment needed for RNG production was developed. Based on the engineering work performed, resource assessment, and pipeline interconnection, an estimate for the cost of producing RNG was created, including a sensitivity analysis. A summary of the project scope, engineering documents, costs estimates, execution approach, and

schedule was compiled into a scope book. A lifecycle analysis (LCA) was performed to evaluate the environmental impacts of the gasification pathway to produce RNG based on the engineering study at the Stockton site.

RESULTS

The following table shows a summary of results for the Stockton site-specific RNG study:

Biomass Input Annually, tons/yr (17% moisture)		310,000
Plant Capacity (base case), MMm^3/yr (BCF/yr)		82 (2.9)
All-in capital cost, $MM		340 (± 30%)
Annual OPEX, $MM/yr		39.3
Cost of RNG Production, cents/MJ ($/MMBTU)		1.2-1.4 (13-15)
GREET® Life cycle carbon intensity (CI), gCO_2e/MJ		16.8*
Criteria Pollutant Emissions, g/MJ (lb/MMBTU)	PM	0 (0)
	VOC	0.002 (0.005)
	SO_2	0.0001 (0.0003)
	NOx	0.0009 (0.002)

*California GREET® 3.0 CI = 17 gCO_2e/MJ

CONCLUSION

Wood Waste to RNG: reducing criteria pollutants by approximately 99% and producing a very low carbon fuel.

The engineering design study provides an understanding of the costs and issues surrounding the conversion of an existing biomass power plant into an RNG producing facility utilizing commercial technologies. The deployment of the RNG process provides substantial environmental benefits, reducing criteria pollutants by approximately 99% and producing a very low carbon fuel in the base case and below zero in the case including carbon sequestration technologies. The study quantifies the large greenhouse gas (GHG) benefits achieved by RNG produced from wood wastes from a product standpoint, as well as from the reduced potential for forest fires and open burning of agricultural wastes in the San Joaquin Valley and other areas in California by cleanly processing forest, urban and agricultural wastes. Additionally, the design study confirms the ability to produce large amounts of high quality, low carbon RNG for use in all energy sectors. The cost of integration of these technologies into an existing facility was influenced by specific attributes of the site itself. The learnings will help identify the most advantageous sites in California, and elsewhere, for conversion from biomass power to RNG production.

1. Introduction

The state of California has a well-earned reputation for its focus on substantial reductions of conventional air emissions within California to achieve federal ozone standards and other state and federal regulations. Reducing criteria pollutants including NOx and VOCs are critical to achieving future federal ozone standards.

California has also set aggressive targets for greenhouse gas (GHG) reductions. Achieving these targets will require reductions by all sectors of the state's economy. Specifically, deployment of fuels having a lower carbon intensity can help the state reach its goals.

One pathway to substantially reduce GHG and criteria pollutant emissions is by expanded use of RNG. RNG can be produced from a number of sources, such as digesters, wastewater treatment facilities, landfills and from thermal conversion of renewable carbonaceous materials like woody biomass. RNG is distinguished from biogas by its quality. RNG can be produced by upgrading biogas or syngas to be of an appropriate quality and make-up to supplement or replace natural gas. Most RNG being used in California and throughout the rest of the United States is produced from landfills. Methane (CH_4)-containing gas is collected from the landfill, cleaned and processed, and then compressed as required to enter into a natural gas pipeline.

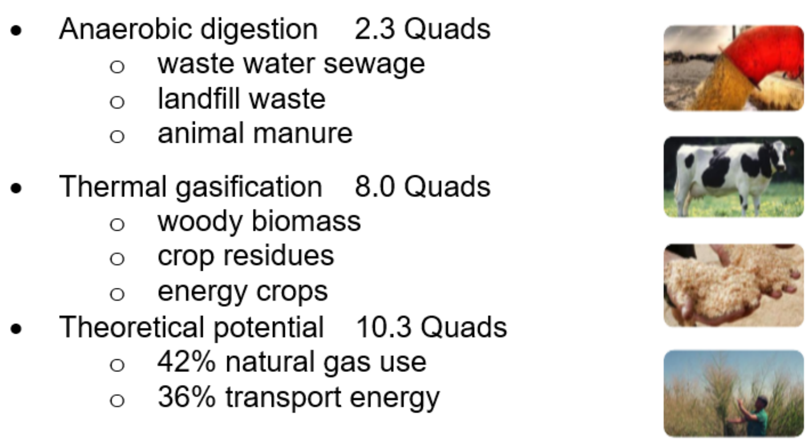

Figure 1. Background on the Potential for RNG Production from Different US Sources[1]

While there are still many sources of landfill gas yet to be treated to produce RNG, there is a limit of how many landfills can gain access to pipeline infrastructure. Biogas at landfills can alternatively be utilized to produce electric power on site, most often using internal combustion

[1] The Potential for Renewable Gas: Biogas Derived from Biomass Feedstocks and Upgraded to Pipeline Quality. Gas Technology Institute. Sep 2011

engines. It can also be used on site for vehicle fuel but needs to be upgraded to about the same quality as for pipeline injection and a compression station or liquefied natural gas facility needs to be built so the vehicles can be fueled. Wastewater treatment facilities and manure or food-waste digesters can also be sources of methane to produce RNG but have some of the same issues connecting to pipeline infrastructure. To produce large amounts of very low carbon RNG, thermal conversion of wood waste is key. For RNG's value to be easily realized by consumers, connection to pipeline infrastructure is critical.

RNG: Using the existing energy infrastructure to produce and move low carbon energy can enable a lower cost pathway to reduced carbon dioxide (CO_2) emissions in a shorter time.

Using the existing energy infrastructure to produce and move low carbon energy can enable a lower cost pathway to reduced carbon dioxide (CO_2) emissions in a shorter time. One means to use existing energy infrastructure is to develop low carbon "drop in" fuels that can be used in vehicles, power plants and for other residential, commercial, and industrial applications. RNG is one fuel that can be readily transported through the existing pipeline infrastructure. In California today, RNG is used by many compressed natural gas (CNG) vehicles to lower GHG emissions. RNG as a transportation fuel has one of the lowest carbon intensities of available drop-in fuels, based on lifecycle analysis (LCA). Over the last decade, California has focused a portion of its R&D funding for the development of low NOx engine technology for transportation and stationary use. Much of this technology is fueled by natural gas. These engines will go a long way to help meet current and future NOx emission goals.

The proposed RNG plant for Stockton could fuel approximately 50,000 light-duty vehicles or about 2,200 heavy-duty vehicles each year. This assumes 3 BCF/yr RNG production, which equates to 25 million gge/yr, where each car consumes about 500 gge/yr[2]. This plant alone could displace approximately 170,000 tons of CO_2 vehicle emissions each year, given a reduction of about 60 gCO_2/MJ between gasoline and the RNG being produced here.

This plant alone could displace approximately 170,000 tons of CO_2 vehicle emissions each year.

Electric power plants in California are also using RNG to produce lower carbon electricity. Looking to the future, RNG can play a key role in California's energy future by providing a low carbon fuel that can be used in many transportation, power, and thermal applications.

GTI, in collaboration with Andritz (gasifier technology), Haldor Topsoe A/S (HTAS, synthesis gas, or syngas cleaning and methanation technology supplier), and Black & Veatch (B&V engineering services and balance of plant), investigated the potential to convert an existing biomass power station (DTE Energy Stockton) into a facility that produces RNG via the gasification of woody biomass.

The specific scope and purpose of the project were to complete a site-specific engineering study for converting an existing woody biomass power plant to a plant that produces pipeline-ready RNG (see Table 7 for details on the expected composition of RNG). The current annual feedstock consumption was assumed constant for the repurposed plant. The engineering design focused on a facility of approximately 82 million cubic meters (2900 million cubic feet) of RNG

[2] *Transportation Energy Data Book*. Oak Ridge National Lab. https://cta.ornl.gov/data/index.shtml

production annually. The design includes a connection to the natural gas pipeline system and the production of RNG that meets the existing utility requirements for pipeline quality. A lifecycle analysis (LCA) quantifying the environmental benefits of the RNG produced is one of the key study results.

Thermochemical conversion of biomass technologies has a number of advantages over biological or biochemical conversion technologies. For example, thermochemical conversion technologies tend to be more feedstock flexible. Feedstocks may include agricultural wastes, forestry wastes, organic municipal wastes, and byproducts from a variety of industries.

The main commercially available thermochemical conversion technologies include direct combustion and gasification. Direct combustion is technologically the simplest approach, however, inefficiencies make combustion less than ideal. Common issues include relatively low thermodynamic efficiency in power applications, incomplete combustion, requirements for excess air, excessive temperatures which lead to higher NO_X and other emissions, sensitivity to contaminants, etc. [3,4].

Gasification has many advantages over direct combustion, including the ability to generate liquid and gaseous drop-in fuels compatible with existing infrastructure. Another alternative would be to generate electricity from the synthesis gas, which would address some of the environmental issues with direct combustion. However; the fuels generated by combining gasification and synthesis, unlike heat or electricity, can be easily stored for on-demand uses. Gasification is a process that operates at relatively high temperatures in the presence of an oxidant that makes the conversion of the biomass particles quite fast. The gases produced from biomass can be cleaned and upgraded in catalytic reactors on site, making the entire conversion process, from biomass particle to finished product, happen in the order of minutes, not days, as would be the case for biochemical conversions. The process eliminates roughly 99% of criteria pollutants that combustion would typically generate (see Section 1.2.1 for details). Direct gasification, in particular the processes based on fluid beds, is the most intense biomass-to-gas conversion technology, providing the highest possible carbon conversions to fuel. Gasification-based processes can also be scaled-up appropriately to accommodate any optimum, biomass collection radius.

1.1. Background

California air quality continues to be exacerbated by black carbon and conventional air pollutants produced from the open burning of agricultural wastes and from devastating forest fires. Expanding opportunities for the processing of agricultural, forest and urban wood wastes provides a means to reduce black carbon, which is one of the most potent climate change pollutants and to reduce conventional air pollutants that can lead to increased incidences of

[3] Brown, Robert C.; Biorenewable Resources: Engineering New Products from Agriculture, 1st Ed, 2003 Iowa State Press

[4] Kumar, Ajay et al. Thermochemical Biomass Gasification: A Review of the Current Status of the Technology. Energies 2009, 2, 556-581

asthma and other breathing disorders[5,6]. Additionally, with the continued closing of biomass power plants that processed wood wastes to produce electricity, there is now not enough facilities to process all the wood waste being produced. This is leading to open burning of agricultural wastes in the San Joaquin Valley[7] and rampant forest fires throughout the state every year[8] . This project provides the much-needed design and engineering information to transform existing biomass power plants into RNG-producing facilities. RNG production facilities for wood waste conversion will create a means to process these waste streams and virtually eliminate all criteria pollutants associated with existing biomass electricity production facilities. Additionally, an almost zero carbon replacement for natural gas will be produced, providing opportunities for carbon emission reductions in the transportation, industrial, commercial, and residential energy sectors.

1.2. Opportunities

Over the past several decades, California has sent much of its woody biomass wastes to existing biomass power plants for processing to produce electricity[9]. These wood streams include urban or demolition wood waste, agriculture and forest wastes. While biomass power plants have provided an outlet to turn wood into electricity, these plants produce criteria air pollutants like NOx and particulate matter that can lead to local air quality issues. When biomass power plants are not available for processing, these wood wastes often sit in rotting piles, are burned, or enhance the potential for forest fires. This lack of opportunity to process woody biomass can lead to increased methane or black carbon emissions that are considered serious short-lived climate pollutants by California air agencies.

For many years, there have been discussions about producing RNG from woody biomass, but with the price of natural gas low, it has not made economic sense. Recently, however, with the substantive goals and mandates regarding CO_2 emissions in California and elsewhere, and the understanding of utilities that their electricity and natural gas will need to have a much lower carbon footprint, a new market demand for RNG has emerged. Still, the prospect of building a new greenfield site to produce RNG from woody biomass is challenging, in part, because of land acquisition costs and technology readiness. Commercially available technologies have been available to gasify wood for many years; however, no commercial technology had been available to condition the syngas to a clean enough state to be used in a commercial methanation unit. That has changed over the last number of years, and it makes possible a commercial scale woody biomass to RNG facility. In summary, the unit operations and hardware required for the entire facility are all based on commercially available components, minimizing the technology risk.

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[5] *Black Carbon Factsheet.* Center for Climate and Energy Solutions. https://www.c2es.org/site/assets/uploads/2010/04/what-is-black-carbon.pdf

[6] Ramanathan, V. and G. Carmichael. 2008. Nature Geoscience, 1:221-227

[7] *Despite Tight Restrictions, Open Ag Burning Increases in the Valley*. Valley Public Radio. http://www.kvpr.org/post/despite-tight-restrictions-open-ag-burning-increases-valley

[8] *California Wildfires and Acres for all Jurisdictions*. http://cdfdata.fire.ca.gov/pub/cdf/images/incidentstatsevents_269.pdf

[9] *Biomass: Essential for California.* California Biomass Energy Alliance. http://www.calbiomass.org/general-statement/

Increased air regulations, renewable fuel incentives, new commercial technologies, and the prospect of integration with existing woody biomass power plants has renewed the prospect of producing RNG profitably from woody biomass. Equipment needed to handle wood feedstocks, as well as utilities, water supply, power production, wood storage and other equipment and resources needed for an RNG producing facility already exists on biomass power plant sites. Integrating existing equipment and systems into a repurposed biomass power facility will likely improve the feasibility and, in many cases, reduce the costs. Equally or more importantly, an existing biomass power plant has relationships and contracts with companies and individuals that provide various wood wastes to the facility. Integration, into an existing facility, can take advantage of these existing partnerships compared to starting anew with a greenfield site.

Infrastructure at existing biomass power plants that can improve the feasibility and help mitigate risks when compared to greenfield development of RNG producing facilities include:

- Feedstock supply chain
- Feedstock handling and storage
- Water supply
- Thermal and electric energy
- Other utilities
- O&M expertise
- Natural gas delivery (often)

Many of the biomass power facilities in California are also having difficulty competing in the renewable electricity market due to growing competition from other renewable sources. The opportunities for RNG in California are growing and all appropriate sources will be needed to address this new market. Therefore, there are prospects for existing biomass energy sites to be revamped to provide this beneficial product.

On top of the next page is a graphic that describes the potential for RNG production from the existing biomass power facilities in California.

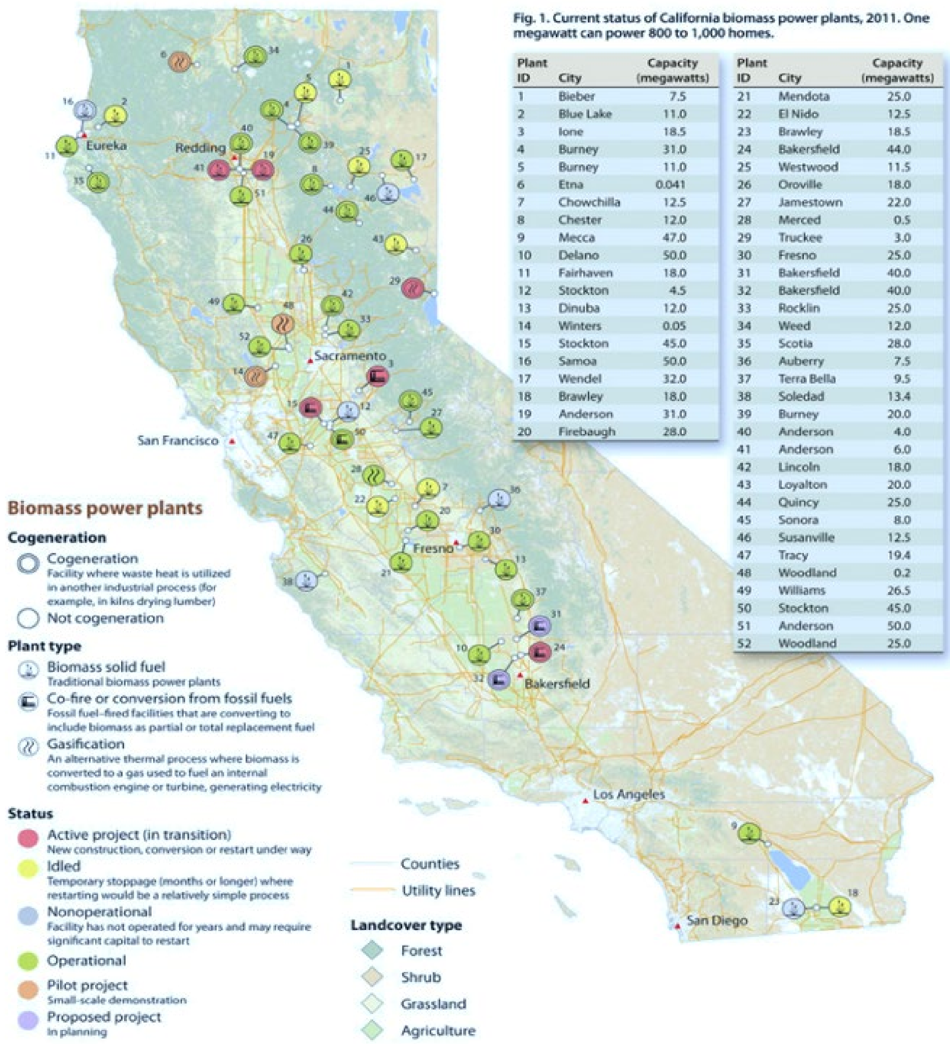

Fig. 1. Current status of California biomass power plants, 2011. One megawatt can power 800 to 1,000 homes.

Plant ID	City	Capacity (megawatts)	Plant ID	City	Capacity (megawatts)
1	Bieber	7.5	21	Mendota	25.0
2	Blue Lake	11.0	22	El Nido	12.5
3	Ione	18.5	23	Brawley	18.5
4	Burney	31.0	24	Bakersfield	44.0
5	Burney	11.0	25	Westwood	11.5
6	Etna	0.041	26	Oroville	18.0
7	Chowchilla	12.5	27	Jamestown	22.0
8	Chester	12.0	28	Merced	0.5
9	Mecca	47.0	29	Truckee	3.0
10	Delano	50.0	30	Fresno	25.0
11	Fairhaven	18.0	31	Bakersfield	40.0
12	Stockton	4.5	32	Bakersfield	40.0
13	Dinuba	12.0	33	Rocklin	25.0
14	Winters	0.05	34	Weed	12.0
15	Stockton	45.0	35	Scotia	28.0
16	Samoa	50.0	36	Auberry	7.5
17	Wendel	32.0	37	Terra Bella	9.5
18	Brawley	18.0	38	Soledad	13.4
19	Anderson	31.0	39	Burney	20.0
20	Firebaugh	28.0	40	Anderson	4.0
			41	Anderson	6.0
			42	Lincoln	18.0
			43	Loyalton	20.0
			44	Quincy	25.0
			45	Sonora	8.0
			46	Susanville	12.5
			47	Tracy	19.4
			48	Woodland	0.2
			49	Williams	26.5
			50	Stockton	45.0
			51	Anderson	50.0
			52	Woodland	25.0

Problem
California biomass power plants are closing leading to more unprocessed wood wastes which can increase methane and black carbon emissions

California
52 existing biomass power plants
= 1,075 MW_e total capacity
= 65 BCF annually
= 4x NGV use in 2012
= 5% non-power use in 2012

Opportunity
Transform existing biomass power plants to RNG production facilities

Figure 2. California's Biomass Power Plant (Bio-power) Landscape[10]

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[10] Assessment of the Emissions and Energy Impacts of Biomass and Biogas Use in California, Provided to the California Air Resources Board by Marc Carreras-Sospedra, Professor Donald Dabdub University of California, Irvine; in collaboration with Robert Williams California Biomass Collaborative, January 14, 2015.

1.2.1. Emission Reduction Opportunity

Repurposing biomass power plants with technologies that can turn woody biomass into RNG will eliminate almost all criteria air emissions and provide a concentrated CO_2 stream that can be utilized to create more RNG or other by-products. Such a facility would provide a closed loop production system with very low net emissions while creating a storable renewable energy product that can be used as natural gas, delivered through the pipeline, with a small carbon footprint. Figure 3 compares the emissions profile between a biomass power plant and a RNG producing facility.

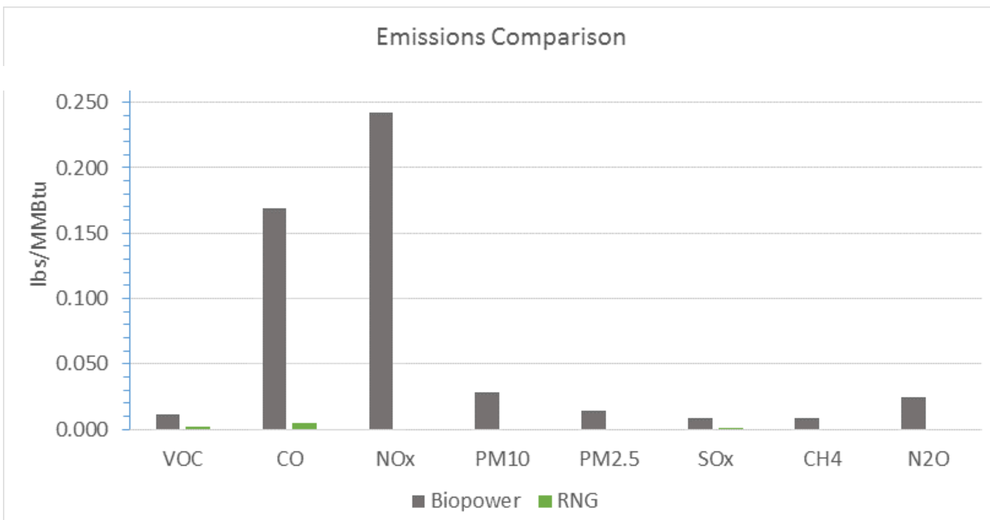

Figure 3. California's Bio-power Emission Profile[10]

1.2.2. Products Produced at a Wood Waste Biomass RNG Facility

- Pipeline-quality renewable natural gas
    - Fungible product for transportation or other natural gas applications
- Concentrated CO_2 stream
- Steam
    - Waste heat boiler(s) to raise steam for the gasifier, shift reactor, glycol stripping, etc.
    - High-grade steam for electric power production
- Waste heat
    - Feedstock drying

The potential for producing co-products coupled with integration into an existing biomass power site could reduce RNG production costs.

1.2.3. Site Specific Engineering Design

To develop the capital and operating costs fully for an RNG facility integrated with an existing biomass to electricity plant, a site-specific engineering study was performed at Front End Loading (FEL)-2 (± 30%)[11] level of fidelity using commercially available process equipment. The study determined RNG production cost and quantified the value of integration with the host site. Engineering design and costs will easily translate to other bio-power sites.

The information gained from this site-specific engineering design study creates the knowledge and framework needed to help policymakers, regulators, elected officials, utilities and potential RNG facility developers more clearly understand the requirements, costs and potential benefits of repurposing California biomass power plants into RNG producing facilities. The project team believes this will lead to accelerated investment in the development of RNG production facilities throughout California.

The study team led by GTI included B&V, Andritz, and Haldor Topsoe. These companies are world experts in gasification, gas cleanup, and biomass conversion plant design and integration. This project leveraged millions of dollars of previous pilot-scale testing (United States (US)) and commercial design work performed (Europe).

Synergies and economies of using a biomass power facility as a host site are beginning to be more clear, a few of them listed here:

- Wood supply access
- Fuel processing and handling
- Availability of installed power islands
- Natural gas pipeline injection options
- Utilization of site acreage
- Local support

The completed study will be paramount for securing commitments of financiers and California government agencies and utilities to better understand the opportunity for expanded RNG production in California.

1.2.4. RNG Production Process

The thermochemical approach for wood waste conversion to RNG involves several process steps as shown in the RNG process illustration in Figure 4 and the Stockton site block diagram in Figure 5 on the next page.

[11] Defined similarly to: KBR, Front End Loading Process https://www.kbr.com/Documents/Onshore%20Refining%20Handouts/FrontEndLoadingProcessAndDeliverables_final.pdf

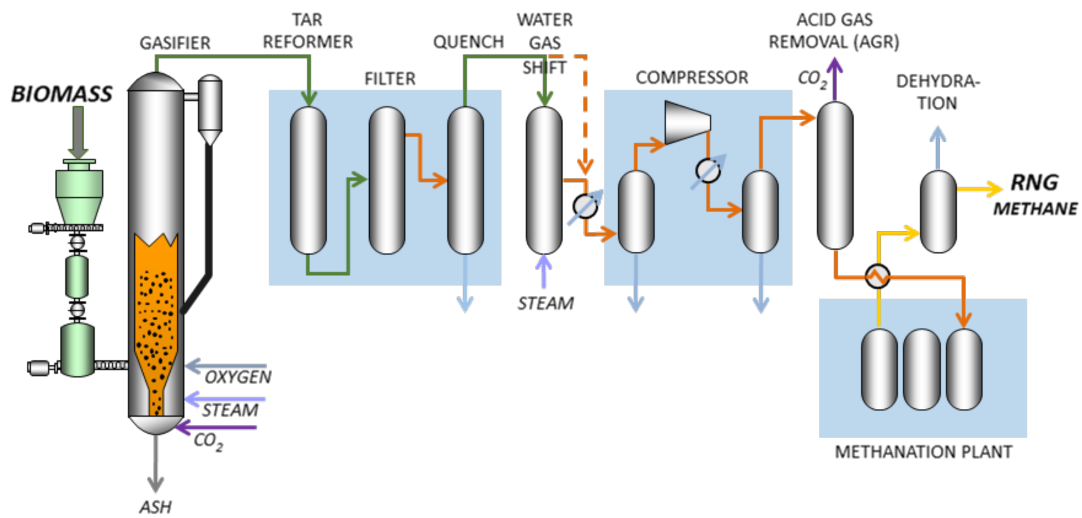

Figure 4: The Gasification-powered RNG Process

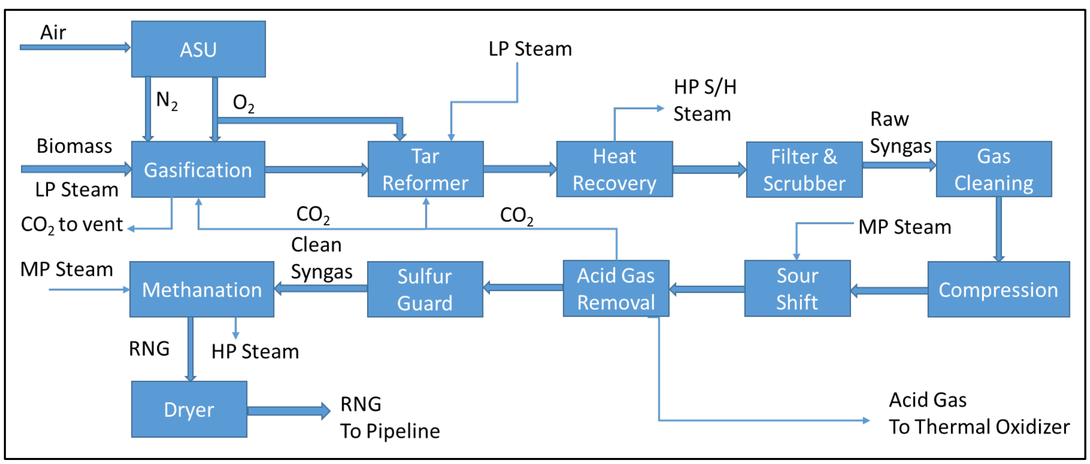

Figure 5. Block Diagram of Wood Waste Conversion at Stockton Site

The gasification process converts wood waste to synthesis gas (or syngas) which is composed of hydrogen (H_2) and carbon monoxide (CO) in a steam–oxygen atmosphere. An air separation unit (ASU) supplies oxygen (O_2) and nitrogen (N_2) to the gasification process. The dusty gas from the gasifier is sent to a tar destruction step carried out by a tar steam reformer where high-molecular-weight hydrocarbons are catalytically reformed into CO and H_2 components, increasing the syngas quantity. The removal of the heavy tar component is required to avoid physical fouling of downstream equipment and catalysts that operate at low temperatures.

The hot, reformed syngas is cooled in gas coolers (heat recovery) generating superheated steam. The remaining dust in the syngas is removed in a filter unit. A water scrubber is utilized to further cool the syngas as well as remove the remaining contaminants in the gas stream. The raw syngas is slightly heated after scrubbing to reduce relative humidity before compression.

The compressed syngas is sent to Sour Shift where CO conversion into H_2 and CO_2 occurs in the presence of steam over sulfur-resistant Cobalt/Molybdenum catalyst. After the shift reactor, hydrogen sulfide (H_2S) in the syngas is removed in the Acid Gas Removal (AGR) unit to produce a less than 1 ppm H_2S-syngas stream. The presence of H_2S can cause poisoning and deactivation of the methanation catalyst. Therefore, H_2S removal is required upstream of the methanation unit. CO_2 is also removed from the syngas in the AGR unit to meet the RNG quality specification after methanation. The concentrated stream of acid gases will be sent to a thermal oxidizer for complete conversion of hazardous components. The syngas leaving the AGR will pass through a Sulfur Guard, which removes the remaining H_2S in the gas.

The CO, CO_2, and H_2 in the clean syngas are converted into CH_4 in a 2-pass methanation reactor. The exothermic heat generated during the reaction is used to produce high-pressure (HP) steam. This will be combined with the high-pressure steam from heat recovery and will be sent to a steam turbine for power generation. RNG leaving the methanation unit will be dried in molecular sieve and silica gel beds prior to entering the pipeline.

1.2.5. Benefits and Outcomes

With the goal of achieving the 2023 and 2031 federal ozone standard deadlines while substantially lowering GHG emissions, understanding the potential for locally produced low carbon energy sources will be critical for emission reduction planning purposes.

Considering the potential outlined earlier in the report, producing more RNG from additional sources in California can save existing and create new jobs while providing a fuel that can be used in existing and future low NOx CNG engines and other current natural gas applications.

RNG can play a major role in helping to meet the ambitious emission reduction goals of the state and air regulators and knowing the cost of building a wood waste to RNG facility and the production cost of the fuel will be useful for policy making.

Another benefit is that most of the knowledge learned through this site-specific engineering study can be transferred to other locations, thus assisting in the development of other potential RNG producing facilities that can yield RNG for use throughout the state.

Local Community Benefits:

- Eliminating almost all levels of criteria pollutants will provide an immediate benefit to local communities.
- More benefits can accrue by converting the wood chipping equipment at the site to run on RNG and from the development of programs that support the conversion of trucks that transport the woody biomass to operate on RNG.

    - This will further reduce local emissions as well as noise because trucks and equipment that operate on RNG are much quieter and cleaner than their diesel counterparts.

- The retention of jobs in wood waste collection and delivery, which would be lost upon the shutdown of biomass combustion facilities, and the creation of new jobs to support the new RNG operations. Each RNG facility will employ approximately 50 full-time staff and support another 100 jobs indirectly in the fuel supply and services sectors.

2. Materials and Methods

2.1. Resources Analysis

The project team developed an estimated biomass supply cost and resource data. The supply analysis was constrained to the current actuals used at the Stockton site. The team gained a better understanding of the value of the relationships with the feedstock suppliers, which have been developed over the years. In addition, there is a better understanding of the sensitivities of feedstock price based on fluctuations in supply and demand, considering the presence of other buyers of the feedstock in the area.

Analysis of biomass feedstock at Stockton was provided by DTE Stockton. The biomass characterization covers ultimate and proximate analysis as well as calorific value.

2.2. Site Evaluation

The methods for site evaluation included a review of plant engineering design documents and on-site discussions with the Stockton Biomass Power Plant's (operated by DTE) operators. These activities were primarily done to gather information on which pieces of equipment could be repurposed in the retrofit and which systems or structures will need to be either abandoned or demolished to make room for new equipment. The site evaluation covered various factors that have a significant influence on the site layout and development costs:

- Size and topographical layout of the site
- Site accessibility and transportation options
- Proximity to the fuel supply (DTE Energy Services provided analysis of regional biomass resources)
- Evaluation of existing biomass handling equipment
- Availability of water, electricity, and other utilities
- Ash and other waste disposal
- Gas transmission access and capacity

In addition, separate tasks were also performed to provide the groundwork in developing site general arrangement and layout drawings, and integrating equipment to the project site. These tasks included identifying potential locations for specific equipment, evaluating interconnection for utilities and biomass handling equipment, and assessing any site issues related to plant conversion.

2.3. Engineering Study

The tasks, listed on the next page, were done as part of the FEL-2 engineering study to support a preliminary cost estimate of the project. The project team assembled a summary of the project scope, engineering documents, costs estimates, execution approach, and schedule into a scope book. The project scope book (Appendix 9, not included in this version of the report) provides details of the study, including the assumptions and findings used, and provides conclusions with respect to the efficacy of the approach used in the study.

The project team:

- Developed a conceptual design basis document of the project, which covers site- and discipline-specific engineering design criteria and input information used in the preparation of the design.
- Developed an integrated process model for the RNG plant. Aspen HYSYS v.9 was used to simulate an integrated RNG plant from raw syngas from gasification to RNG production in the Methanation Reactor, as well as the balance of plant (BoP) equipment. This simulation was built based on the latest pilot-plant and commercial wood gasification data from GTI, PFDs and heat and material balance and process studies from both Andritz and HTAS.
- Developed a complete set of PFDs to show the sequence of operations and the relationship between unit operations of the facility. The diagrams for the overall process displayed nineteen unit operations within the RNG plant, equipment designation and number, simplified control instrumentation and stream number. A mass balance table containing stream numbers tied to the PFDs and stream flow and properties was developed separately. The steam system was shown on the PFD with mass flow rates, temperatures, pressures, enthalpies, and power production generated by the steam turbine. A steam balance was developed based on information provided in the PFD.
- Developed general arrangement and layout drawings based on information gathered during the site evaluation. The drawings consisted of overall site layout and equipment layout plan that showed how equipment would be placed across the site.
- Developed preliminary equipment specifications for the major equipment. These specifications were utilized to obtain budgetary quotes for the major equipment packages. Other equipment costs were determined from in-house resources. An equipment list was developed to provide a summary of the major equipment, equipment capacity, size, design conditions, and materials of construction.
- Developed electrical loads and created an electrical load list for all new equipment as well as a preliminary one-line diagram that showed the tie to the existing auxiliary electrical system. Provided a list of major equipment specifications, such as motors, transformers and determined the margins on the existing electrical system and its ability to support the additional loads of the new equipment.
- Developed control architecture of the facility. Provided a review of the existing system and outlined how the new gasification plant will be controlled and integrated into the existing plant control system.
- Prepared a summary of site-specific issues.

2.4. Process Model and Capital Cost Estimate

2.4.1. Capital Cost Estimate

Based on the engineering work performed, the project team developed a cost estimate for the engineering, procurement, installation, and integration of the new equipment needed for RNG production.

The capital cost estimate was based on information developed in this project for the major equipment needed for the planned facility. Andritz and Haldor Topsoe provided design and economic inputs for the gasification and methanation packages respectively, as commercial equipment providers. B&V's current in-house proprietary database of market pricing for the balance of plant equipment and commodities was used to supplement the overall cost estimate. This approach used cost data for similar facilities and factored in adjustments for scope differences between the reference plants.

Construction specialists performed a local wage rate analysis and productivity factor study to refine the estimate. B&V provided input into the project team's cost estimate and RNG production cost estimate based on the engineering work performed.

The project team developed the project pro-forma economic model and estimate of production costs based on project cost estimates and financial parameters (i.e., expected plant capacity factor, forced outage frequency, planned maintenance frequency and costs, plant insurance, property tax, income tax, construction interest, project financing costs, escalation rates for operating and maintenance (O&M) costs, product price, feedstock, and other O&M costs).

A preliminary project economic analysis was developed, taking the perspective of a stand-alone project development entity, which develops, executes, and operates the project. The purpose of this analysis was to provide an understanding of the overall financial performance of the project using the results from the project and to understand key techno-economic sensitivities. It was not to develop an investment prospectus. Thus, a straightforward real dollar, levelized cost approach was used. Furthermore, 100% cash-financed was assumed. The various possible project financing approaches, sensitivities to financial terms, and the effect of potential financial incentives were not explored. A forecasting tool called Crystal Ball was used for the sensitivity analysis. Crystal Ball is a tool used to perform Monte Carlo simulations.

2.5. Life-Cycle Analysis (LCA)

An LCA was performed by Argonne National Laboratory (ANL) to evaluate the environmental impacts of the gasification-based pathway to produce RNG based on the engineering study at the Stockton site. Since 2010, ANL, which developed the Greenhouse gases, Regulated Emissions and Energy use in Transportation (GREET®) model, has investigated various RNG production pathways from waste feedstocks (landfill gas, animal waste, wastewater sludge, and municipal solid waste), conducted the LCA of these pathways, and published technical reports and journal articles. As an expert in LCA for RNG production pathways, ANL was best positioned to perform the LCA of the GTI's RNG production pathway. Argonne built a GREET® 2017 model based on site-specific engineering design inputs. It was this version of the model that was used in this study.

The goal of the LCA was to validate the CO_2-equivalent emissions (carbon footprint) per unit of RNG product and per dry ton of feedstock, up to and including the point of delivery. The project team also analyzed the economic, social, and environmental impact of the proposed conversion facility, including a carbon life cycle (carbon neutrality, comparison with alternative approaches, and economic impact of carbon credits). The scope of this analysis was from the source (field or forest) to pipeline (plant gate).

One of the key tasks in this project was to explore the carbon intensity of the pathway with site-specific design conditions to see if the produced RNG would meet the California Air Resources Board's (CARB's) Tier 2 Low Carbon Fuel Standard (LCFS). This LCA is based on the fuel being used in a transportation application as a vehicle fuel. See Figure 6 containing the carbon intensities of the currently certified pathways.

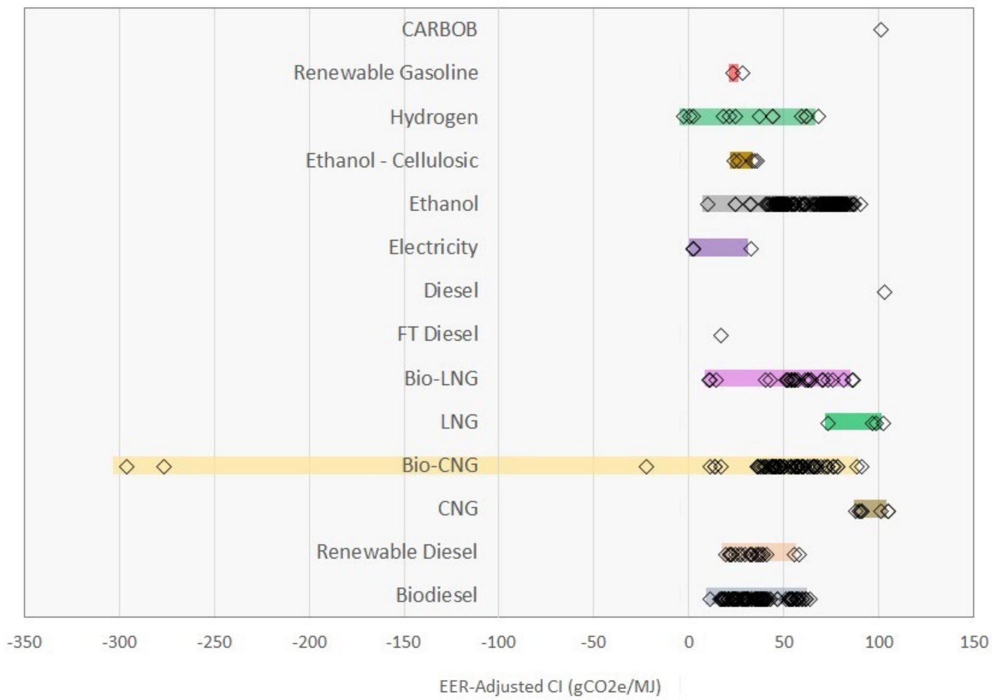

Figure 6. Carbon Intensity Values for Current LCFS Certified Pathways (2018)[12]

[*From the CARB website: The carbon intensities shown above represent the emissions which occur from the use of alternative fuel per MJ of conventional fuel displaced. Each marker represents an individual certified fuel pathway carbon intensity (CI), adjusted by the Energy Economy Ratio (EER). The length of each bar indicates the range of carbon intensity that may be achieved by a fuel pathway. The wide range of carbon intensities is due to the lifecycle emissions methodology of the LCFS, variations in feedstock types, origin, raw material production processing efficiencies, and transportation all contribute to an individual producer's fuel pathway CI. All valid CI values shown here are certified including the legacy, Tier 1, Tier 2, and the Lookup Table*.]

[12]LCFS Pathway Certified Carbon Intensities
https://www.arb.ca.gov/fuels/lcfs/fuelpathways/pathwaytable.htm

An EER adjustment based on engine efficiency with each fuel is needed to be able to compare pathways per the LCFS. In the case of light/medium-duty vehicles, the CNG ratio relative to gasoline has been established as 1.0[13]. RNG and CNG will perform identically in an internal combustion engine, hence no adjustment is needed in the case of RNG to obtain the EER adjusted CI.

The team at ANL performed an LCA for the cases described in Table 1.

Table 1. Cases Considered for Life-cycle Analysis

Cases	**Description**
Base	Design case of GTI's RNG production
Case 1	Base case with carbon capture and sequestration

The base case was developed using the rigorous engineering study with all the inputs and outputs including the transportation of the feedstock and through the end use of the gas fuel. The system boundary for the study is described in the Results section. Case 1 describes a scenario where the concentrated CO_2 stream coming from the acid gas removal step is sent to a dedicated pipeline on its way to a carbon capture and storage facility after reclaiming a portion of it that is needed within the process. The purpose of this Case 1 is to determine what would be the maximum environmental benefit of the process. The effect of Case 1 is strictly on the carbon intensity, since the modifications would be minimal, only affecting a single stream which is already relatively clean, and it will not require a large enough relative increase in equipment or operating cost to be measurable.

The LCA findings and discussion are summarized in the Section 3.6. The full LCA technical report from ANL can be found in the Appendix (not included in this version of the report).

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[13] *California Code of Regulation Title 17, §95485, Table 5*
https://www.arb.ca.gov/fuels/lcfs/CleanFinalRegOrder_02012011.pdf

3. Results

3.1. Resource Analysis

Table 2 and Table 3 contain the wood waste feedstock analysis used by Andritz and Haldor Topsoe in their proprietary performance models to develop material and energy balances for the RNG process. These are properties of the feedstock available at the DTE Stockton site as well as the expected analysis of the processed (sized and dried) feedstock.

Table 2. Feedstock Analysis and Component Ratio for Material and Energy Balances

Parameter	**Unit**	**Forest Waste**	**Demolition Wood Waste**	**Orchard Waste (Weighted Mean)**	**Mix**
As received basis (AR)	Wt.%	40	40	20	100
As fed basis (AF)	Wt.%	40	40	20	100
Dry basis (DB)	Wt.%	42.2	37.3	20.5	100
Proximate Analysis:					
Moisture AR	Wt.%	N/A	N/A	N/A	35.87
Moisture AF	Wt.%	12.7	22.83	14.93	17.2
Volatile	db%	76.16	78.2	75.49	76.78
Ash (550ºC)	db%	3	1.81	6.15	
Fixed Carbon	db%	20.83	19.99	18.36	20.01
Ultimate Analysis:					
Carbon	db%	49.39	49.82	47.51	49.16
Hydrogen	db%	6	5.83	5.86	5.91
Nitrogen	db%	1.07	0.65	0.81	0.86
Oxygen	db%	40.46	41.86	39.56	40.8
Sulfur	db%	0.07	0.05	0.1	0.07
Chlorine	db%	0	0	0	0
Bromide	db%	0	0	0	0
Ash	db%	3	1.81	6.15	3.2
Moisture	db%	0	0	0	0
Heating Values:					
HHV, db	MJ/kg (BTU/lb)	19.8 (8,495)	20.4 (8,783)	19.3 (8,298)	19.9 (8,564)
LHV, db	MJ/kg (BTU/lb)	18.6 (8,010)	19.3 (8,319)	17.9 (7,709)	18.7 (8,061)
Mass Flow	Kg/hr (lb/hr)				35,741 (78,795)

Table 3. DTE Stockton Feedstock Analysis

Parameter	Unit	As Received Feedstock	Processed Feedstock
Size	Inches	≤3	≤1.5
Moisture	Wt.%	37	17
Ash (dry)	Wt.%	3.71	
Carbon (dry)	Wt.%	49.75	
HHV (daf)	MJ/kg (Btu/lb)	21 (8,873)	

3.2. Site Evaluation

The conversion of the existing facility into an RNG production facility will include the installation of three main new process islands including an ASU, Gasification, and HTAS Gas Clean-up and Methanation. In addition to these new systems, the RNG facility will require fuel and ash handling, the balance of plant utilities, and a power generation island.

B&V developed a preliminary layout of the site and new equipment using input from DTE and the various technology providers. Table 4 shows the footprint requirement for each process island and the balance of plant.

Table 4. Estimated Size of the RNG Process Islands

RNG Plant Island	Footprint
Gasification Island	132 ft. x 55 ft.
Methanation Island	250 ft. x 148 ft.
Air Separation Unit	120 ft. x 120 ft.
Radiation Sphere to Flare	50 ft. radius for 100 ft. tall flare
Biomass Drying	100 ft. x 145 ft.
Three Day Dry Biomass Storage	100 ft. x 175 ft.
Process Waste Water Treatment	Undefined at this time

B&V adjusted the equipment arrangement with input from DTE plant operations and site constraints. For the final arrangement for the process at the Stockton Biomass Power Plant site, B &V determined how these new process islands could be located to provide sufficient space for operations and maintenance, and produce minimal impact to existing plant systems.

The RNG Plant arrangement, with the new process islands along with the existing plant equipment and boundaries, is shown roughly in Figure 7 and in detail in Appendix 3 (not included in this version of the report). The new ASU and gasification islands, with the associated flare, will be located where the current boiler and flue gas clean-up equipment resides. The Gas Cleaning and Methanation Island will be located on the vacant lot south of the existing facility.

A majority of the existing fuel handling equipment will be reused; however, the new drying equipment and storage will be located where the West Fuel Pile is currently located.

The various balance of plant systems were reviewed during a site visit and will be reused as applicable, as described further in this section. The existing plant electrical distribution and control systems are expected to have sufficient capacity and space to serve the new equipment. Further evaluation of the electrical and control system capacity will be done as equipment location and sizing are defined in the next phase of the study.

3.2.1. Site Access and Transportation

The DTE Energy Stockton site is located in an industrial area near the intersection of Washington St. and Road 23 in Stockton, CA. The plant is bounded on the west side by the existing Beltline Railroad. The facility is located 0.5 miles south of the port of Stockton and accessible by road via United States (US) Interstate I-5 / US Highway US-4.

3.2.2. Site Layout

The preliminary layout had all of the new equipment associated with the RNG plant sited on a vacant lot to the south of the existing power plant, which would have caused less disturbance to existing systems and minimized plant downtime during construction. However, during the site visit, it was determined that this approach was not feasible due to site constraints (e.g., installation of new conveyors, potential obstructions, etc.). In light of these on-site discussions, the approach was adjusted to site the ASU and Gasification Process Island within the existing power block area and the HTAS Gas Cleaning and Methanation Process Island on the vacant South Lot. Figure 7 shows the location of the new process islands.

Figure 7. Layout of the New Process Islands and Biomass Drying/Storage

3.2.3. Proximity to Existing Fuel Storage and Handling

The fuel handling area is north of Washington St. and is bounded by adjacent industrial properties leased by the Port of Stockton. Discussions with plant personnel indicated that the existing West Fuel Pile was used to ensure good mixing of the material for the boiler feed system, which will no longer be needed for an RNG operation. Therefore, the West Fuel Pile and associated handling equipment could be demolished during the conversion of the plant to an RNG facility (Figure 7 and Figure 8).

For these reasons, the new biomass feedstock drying and three-day storage area will be located where the West Fuel Pile currently sits and not on the vacant South Lot (Figure 8). A new conveyor will be added to cross Washington St. and to deliver the dried biomass feedstock from the three-day storage to the Gasification Process Island.

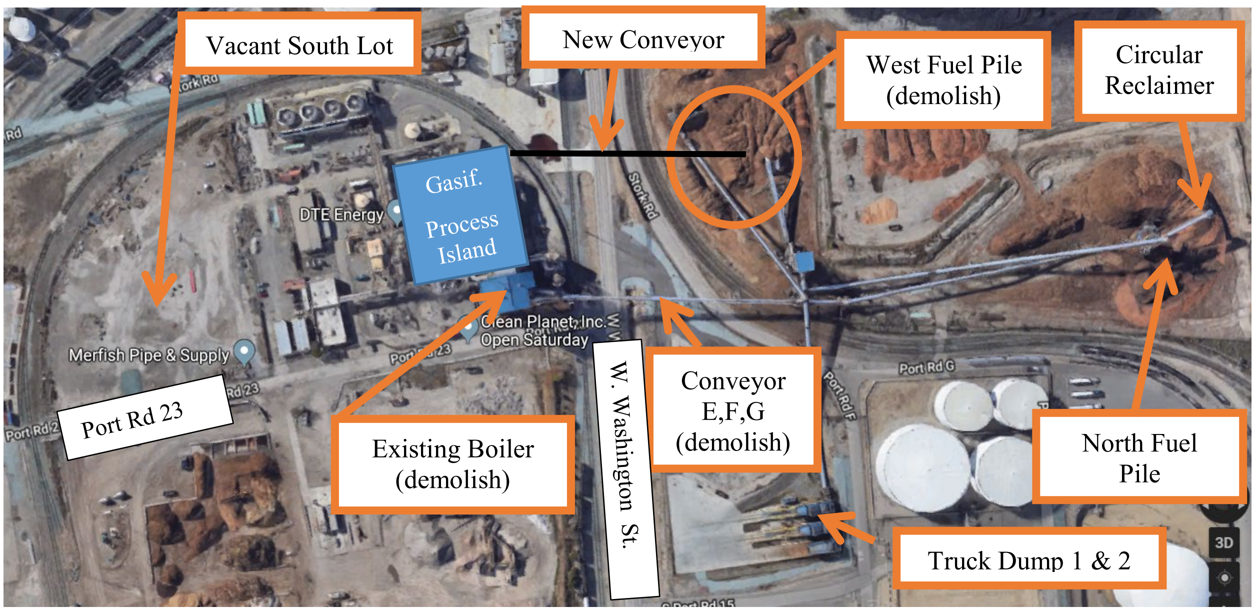

Figure 8. Layout of Existing Fuel Storage and Handling

3.2.4. Evaluation of Biomass Handling Equipment

The existing biomass fuel handling system consists of the “Receiving and Stockout” and the “Reclaim and Boiler Hopper Fill” subsystems. As part of the “Receiving and Stockout” subsystem, incoming delivery trucks pass over a scale to record gross weight and are then unloaded either by tipper-type dumpers or into a pile reclaimer, depending on their self-unloading capabilities. Outgoing trucks then pass over a scale to record tare weight.

Total unloading time based on information from site operators is typically around 30 minutes with approximately 60 to 90 trucks per day, which is conducted six full days per week, 24 hours/day. The reclaimers from tippers and self-unloaded piles then feed a conveyor.

The rated capacity of the equipment that constitutes the “Receiving and Stockout” system is 248 tonnes/hour (273 tons/hour or tph). A series of diverter gates, conveyors, magnetic separators, and disc screens clean the incoming biomass of tramp and oversized material with the former collected for recycling and the latter diverted for size reduction via a hogger (sized for 125 tonnes/hour or 137 tph). Properly sized biomass then goes either to the circular stacker in the North Fuel Pile or to the radial stacker in the West Fuel Pile for stockout.

The "Reclaim and Boiler Hopper Fill" subsystem is sized for 82 tonnes/hour (90 tph) and includes conveyors, discharge gates, and augers to reclaim wood waste from either the North or West Fuel Piles. The North Fuel Pile includes a circular reclaimer and feeds the boiler hoppers directly. The West Fuel Pile uses mobile equipment for reclamation and feeds either a disc screen / hogger or the North Fuel Pile. The West Fuel Pile includes both a pile reclaimer as well as an emergency loader.

The components that constitute the biomass handling and receiving system appear to be in good condition. As mentioned, the handling equipment associated with the West Fuel Pile is recommended for demolition or abandonment due to site arrangement issues and the new requirements for biomass drying and grinding needed in the gasification process.

3.2.5. Availability of Utilities and Structures

Cooling Water

Rebuilt in 2014, the existing cooling tower is an evaporative, mechanical draft type system with four cells, and sized for a duty of 272,204 MJ/hr (258 MMBtu/hr). The rated cooling water flow rate is 162,773 liter per minute (lpm) (43,000 gpm) and the system is designed for a return of 32ºC (90°F) and supply of 26ºC (78°F). The circulation system has three 81,765 lpm (21,600 gpm) pumps, each sized for 50 percent of load (two in operation and one spare) at 21 m (68 ft) of developed head. Cooling requirements for the RNG production facility would be 147,708 MJ/hr (140 MMBtu/hr), which means the existing system is adequate. A booster system takes suction from the cooling water supply to the condenser and returns the pump discharge into the circulating water piping leading to the cooling tower. This system consists of two 100 percent pumps that provide circulating cooling water to various heat exchangers around the power block.

Demineralized Water

The existing demineralized (demin) water system receives water from the city that is treated via reverse osmosis and deionization systems prior to being stored in a 379 m^3 (100,000-gallon) tank. The product water that is then supplied as makeup to the steam system via the steam turbine condenser using three pumps (two in operation and one spare) each rated at 462 lpm (122 gpm) at 43 m (141 ft) of head. The plant consumption is about 757 lpm (200 gpm). Demin water requirements are 644 lpm (170 gpm) for an RNG operation, which means the existing system should be adequate from a capacity perspective.

Compressed Air

The existing compressed air system has three 21 standard cubic meter per minute (Sm^3/min) or 750 standard cubic feet per minute (SCFM) air compressors, each sized for 50 percent of load (two in operation and one spare) at 862 kPag (125 psig) of pressure. After passing through the plant air receiver (sized at 3.5 m^3, or 314 ft^3), instrument air is filtered and dried before distribution to a variety of users. The estimate of existing plant usage is roughly 28 Sm^3/min (1,000 SCFM). Instrument air requirements are about 18 Sm^3/min (650 SCFM) for the RNG conversion, thus the existing system is adequate for the new application. Even though the existing compressed air has enough capacity to supply the plant conversion, instrument air for the RNG plant will be supplied by the new ASU (see Section 3.3.3).

Fire Water

The existing fire water system consists of a 5.7 m^3 (1,500-gallon) tank and electrically-driven, 1,893 lpm (500 gpm) at 95 m (312 ft) of head fire water pump, which are located at the north end of the plant near Washington St. and sourced from the city water supply. An existing underground eight-inch header on the north side of the administration building indicating the fire loop could be continued from this location to the vacant South Lot, as needed.

Air Quality Control

The existing air quality control system (AQCS) includes a wet scrubber for flue gas desulfurization, a series of catalytic converters for control of CO, volatile organic compound, and nitrogen oxide emissions, and a dry sorbent (Trona) injection system for control of sulfur oxide species. The existing AQCS equipment is not required for the RNG conversion; however, the existing Trona system was evaluated for re-use.

The existing Trona system has two 72.6-tonnes (80-ton) storage silos and supplies Trona to a pulverizer via a series of screw conveyors with rotary valves and hoppers, which is then pneumatically conveyed to the flue gas ductwork for injection via two transport blowers. The wet scrubber and catalyst systems are oversized for the RNG operation and cannot be utilized. The Trona system was investigated for reuse to store and deliver bed material to the gasification process via weight / surge hoppers and pressurized CO_2 injection system. However, it was ultimately decided that the Gasification Process Island would include dedicated bed material handling systems and the existing Trona equipment would not be reused.

Natural Gas Supply

The existing natural gas system includes a 379-kPag (55-psig), four-inch supply line downstream of the flow meter, a boundary limit dual pressure regulator, and a one-inch connection from the boundary limit used for building services. In discussions with the local gas utility, PG&E, it was determined that while the existing inside battery limits piping network is sufficient to supply the needs of the RNG production process, it will not be adequate to accept RNG that is produced from the process.

Condensate and Boiler Feedwater (BFW)

The new steam turbine that recovers excess heat from the RNG production process to produce on-site power is expected to be a fraction of the size of the existing steam turbine. This indicates that existing condensate and BFW systems, including piping, pumps, feedwater heaters, and deaerator, will all be oversized for the new application and thus cannot be reused.

Pipe Rack

The existing pipe rack system was evaluated for its ability to carry new interconnecting piping and cable trays for the RNG production operation. A new layer on top of the existing rack is expected, and a new rack is needed for the HTAS Process Island; however, reuse of the existing rack for the Gasification Process Island was deemed feasible.

Foundations

The existing foundations around the current boiler island are planned for reuse to support the Gasification Process Island.

Electrical Distribution

The existing electrical distribution system accommodates a capacity of 50 MW and should therefore be sufficiently sized for reuse in an RNG plant. Physical locations, physical space, capacity, and age of existing equipment were all evaluated as part of the site assessment to determine the extent to which certain equipment could be reused. The existing 58.8-megavolt-ampere (MVA) generator feeds a lineup of 13.8-kilovolt (kV) switchgear, which exports power and feeds plant auxiliary loads. Five feeder breakers provide power to the various plant users including fuel handling, boiler, steam turbine, and BoP loads. The electrical distribution equipment is located in three main areas including the administrative control / electrical building (original from 1989), the boiler electrical room (from 2014), and the fuel handling electrical room (from 2014).

The administration and electrical building consists of switchgear, motor control centers (MCCs), and panels including some spares that could be used / expanded as part of the conversion to RNG. An emergency generator is also available nearby for backup power, but was reported to be unreliable by DTE Energy personnel and is to be replaced in the RNG conversion. The existing main plant protective relaying consists of electromechanical and solid-state relays, which are not modern, but do not appear to hinder operation for RNG production.

The boiler and fuel handling electrical buildings consists of mostly Eaton MCCs and panels with sufficient space to expand in both instances. The existing raceway system consists mainly of aboveground tray and conduit. The main plant corridors include tray on utility racks between areas as mentioned previously; however, the main generator feed to the 13.8-kV switchgear is underground.

3.2.6. Plant Control System

The existing plant primary control system is an Allen-Bradley ControlLogix programmable logic controller (PLC) based system that has limited installed spare capacity and limited physical space for new capacity. The control network is Ethernet type in a star configuration with Wi-Fi system serving as backup with PLC system equipment located in the same areas as the electrical distribution equipment. Each area contains input / output (I/O) cabinets and the administration and electrical building also includes the primary server cabinet and human machine interfaces (HMIs).

The existing PLC equipment (cabinetry, I/O and processors) will be reused and expanded to accommodate the new equipment for the RNG conversion. New PLC equipment (cabinetry, I/O and processors) will be installed in the new electrical enclosures. The existing HMIs will be used to control the new equipment for the RNG conversion.

3.2.7. Ash Disposal

Bottom Ash

The existing bottom ash system uses a drag chain conveyor to remove bottom ash from a quench pool and deposit it in a concrete load-out bin, which is then disposed off-site via truck.

Because the RNG plant will produce vastly different bottom ash quantities and the ash will be produced in a different location within the facility, this system cannot be reused.

Fly Ash

The existing fly ash system uses a drag chain conveyor to remove ash from the electrostatic precipitator and into a bucket elevator, which is then deposited in ash storage silos.

The fly ash is treated with calcium chloride and disposed as non-hazardous waste at a rate of 120 tons per day via truck. Since the RNG plant will produce different fly ash quantities and characteristics, this system will not be reused.

3.2.8. Gas Transmission Access

Discussions with Pacific Gas and Electric (PG&E) indicated that it was not feasible to inject the new RNG production into the local distribution system at the pressure and flow rate required. For the purposes of this project, it was assumed that a six-inch gas transmission pipeline located just outside of battery limit of the facility is available to accommodate the injection of product RNG at 2,103 kPag (305 psig).

3.2.9. Site Evaluation Conclusions and Recommendations

Based on the information gathered and collected from the site, the Stockton, CA facility is a candidate for an RNG generation facility conversion. The existing facility is well maintained, and all equipment observed is in good working order. Preliminary assessment shows that many of the BoP utility systems are adequately sized for the new RNG facility requirements. The site is space constrained, and this has affected the layout of RNG process equipment. There are areas where demolition of existing equipment makes room for new equipment. From equipment proximity and site footprint perspectives the layout developed based on site constraints is not optimal, though it is functional and does not compromise process performance.

The following systems could be reused upon conversion to an RNG production facility:

- Cooling tower and cooling water
- Demin water
- Instrument air
- Natural gas supply
- Fire water
- Biomass handling
- Electrical distribution
- Plant control system

3.3. Engineering

3.3.1. Design Basis Summary

The following section summarizes the basis used in engineering / design activities for FEL-2.

Site Conditions and Effluents

Table 5 shows the criteria used in engineering/design activities for the Stockton RNG production facility conversion.

Table 5. Site-Specific Design Criteria

Design barometric pressure	101.353 kPa (14.7 psia)
Elevation	4 m (13 ft)
Design minimum ambient temperature	-29ºC (-20ºF)
Design maximum ambient temperature (dry bulb)	34ºC (94ºF)
Design maximum ambient temperature (wet bulb)	20ºC (68ºF)
Fuel gas	Pipeline quality natural gas, 379 kPag (55 psig) @ existing meter
Plant cooling	From existing cooling water booster system
Cooling water make-up supply	City water
Fire water sources	City water
Potable water source	City water

The new equipment generates a process condensate stream that will be treated to be recycled for use as BFW make-up. This process condensate must be treated to 8,274 kPag (1,200 psig) BFW quality.

The RNG facility is expected to meet, at a minimum the existing facility air permit requirements and California Ambient Air Quality Standards. The primary air emissions for the RNG plant are from a thermal oxidizer. The liquid wastes are anticipated to include waste oil from the wastewater treatment, and blowdown from the steam plant and hot process water system. It is possible that blowdown streams could be sent to the process condensate treatment unit. A final decision on disposal of blowdown awaits the next phase of design to determine if the discharge permit would allow disposal via municipal drain. Finally, the solid wastes expected from the process will be residual ash from the gasification process, wastewater sludge, and ammonium sulfate solution from process condensate treatment. These solid wastes are trucked-out for disposal.

Utility

Utility requirements and supply information for the RNG facility are shown in Table 6 on the top of the next page.

Table 6. Utility Quantities and Supply Information

Utility	Supply Information
Oxygen (99% purity)	10,917 kg/hr (24,068 lb/hr), 1,400 kPag (203 psig) at (20ºC) 68ºF
Steam	Four steam headers operating at: 8,301 kPag (1,200 psig) and 300ºC (572ºF) 4,144 kPag (600 psig) and 266ºC (510ºF) 1,400 kPag (200 psig) and 290ºC (554ºF) 345 kPag (50 psig)
Nitrogen	1,581 lb/hr, 1,400 kPag (203 psig) at 77ºF
Instrument air	703 kPag (102 psig) 211 Sm^3/hr (7,465 SCFH) for Methanation 893 Sm^3/hr (31,535 SCFH) for Gasification and BoP
Hot process water (demineralized water)	73 psig and 60ºC (140ºF)
Cooling water	Supply temperature: 25ºC (77ºF) Max return temperature: 40ºC (104ºF) Supply pressure: 496 kPag (72 psig)
Dolomite (bed material)	Supply temperature: 25ºC (77ºF) Supply pressure: ambient Specification: 54% $CaCO_3$, 43% $MgCO_3$
Natural gas (auxiliary fuel)	Fuel gas supplied from existing 379 kPag (55 psig) supply header and downstream regulating station

Biomass Feedstock and RNG Product

The biomass feedstock consists of 40% forest waste, 40% demolition wood waste, and 20% orchard waste. The detailed characteristic of the feedstock can be seen in Section 3.1. The moisture content of the as-received feedstock is estimated to be 37%. The feedstock preparation process includes crushing, screening, and drying. The moisture content of the feedstock post preparation is reduced to 17%.

Discussions with Pacific Gas and Electric (PG&E) indicated that it was not feasible to inject the new RNG production into the local distribution system at the pressure and flow rate required. For the purposes of this project, it was assumed that a six-inch gas transmission pipeline located just outside of battery limit of the facility is available to accommodate the injection of product RNG at 2,103 kPag (305 psig). RNG will be delivered at a temperature of (35ºC) 95ºF and a flowrate of 2.5×10^5 Sm^3/d (8.7 MMSCFD) or 82 million Sm^3/year (2.9 Billion Standard Cubic Feet or

BSCF/year) based on 7,884 hours of operation per year. Table 7 shows the expected gas composition and heating values of the RNG.

Table 7. RNG Product Composition and Heating Values

Components	Mol %
Methane	96.50
Nitrogen	1.34
Hydrogen	1.17
Argon	0.78
Carbon Dioxide	0.20
Carbon Monoxide	22 ppm
Water	17 ppm
LHV	33 MJ/m^3 (881 Btu/SCF)
HHV	36 MJ/m^3 (978 Btu/SCF)
Flow based on LHV (total)	337,196 MJ/hr (320 MMBtu/hr)

3.3.2. Material Balance

Table 8 shows the summary of the feedstock, product, and by-products flow rates. Appendix 5 (not included in this version of the report) provides detailed heat and material balances of the RNG production.

Table 8. Feedstock and Product Flow Rates

Parameter	Unit	Value
Inlet		
Biomass	kg/hr (lb/hr)	35,741 (78,795)
O_2	kg/hr (lb/hr)	10,917 (24,068)
N_2	kg/hr (lb/hr)	717 (1,581)
CO_2	kg/hr (lb/hr)	5,071 (11,179)
Dolomite	kg/hr (lb/hr)	407 (897)
Outlet		
RNG Production	kg/hr (lb/hr)	7,086 (15,621)
CO_2	kg/hr (lb/hr)	(28,150) 62,059
Ammonium Sulfate	kg/hr (lb/hr)	0.9 (2)
Bottom Ash	kg/hr (lb/hr)	744 (1,640)
Fly Ash	kg/hr (lb/hr)	1,294 (2,853)

CO_2 from the thermal oxidizer is a byproduct of the RNG production. Other byproducts include ashes from the Gasification Island and ammonium sulfate from the process condensate treatment plant.

3.3.3. Process and Equipment Descriptions

A simplified version of the PFD is shown in Figure 9. The more detailed PFD can be seen in Appendix 4 (not included in this version of the report). The following section explains the process shown in the PFD and summarizes associated equipment. The Andritz scope of supply for the Stockton RNG plant conversion includes all Gasification Process Island equipment and ancillaries. The HTAS scope of supply includes all Syngas Cleaning and Methanation Process Island equipment and ancillaries. The B&V scope primarily includes system integration and all BoP equipment in the equipment list for the RNG production plant.

Biomass Preparation and Storage

The main purpose of the biomass preparation equipment is to dry and size the incoming biomass from the as-received feedstock to the required characteristic as shown on Table 3 (Section 3.1). Two hoggers (~600 kW each) and screens (one existing and one new) will be used to process the incoming biomass feedstock into the required sizes. The dried biomass is stored in a 3,648 m^3 (128,830 ft^3) silo prior to being sent to the Gasifier. Heat requirement for fuel dryers is estimated to be 36 MMBTU/h. The fuel drying will be done by indirectly heating the fuel on belt dryer via fans with hot water/glycol mix. The hot water is tentatively obtained from the Gasification Island waste heat recovery.

Some existing equipment will be retained for the RNG plant conversion (see Section 2.2). New equipment to be installed includes Conveyors E/F/G/H/J (010-U-0001,-0005, -0010, -0012, -0014), Hogger B (010-U-0004), Disc Screens B/C (010-U-0003, -0011), Live Bottom Bin (010-U-0006), Screw Feeders (010-U-0007A/B, -0009A/B) Dryers (010-U-0008A/B) and Storage Silo.

Air Separation Unit

The ASU will be a package unit from a vendor, and will provide 10,917 kg/hr (24,068 lb/hr) of gaseous O_2 and 717 kg/hr (1,581 lb/hr) gaseous N_2 to the gasification process via cryogenic distillation at about 20ºC (70ºF) and 1,380 kPag (200 psig). In addition, the ASU will supply dried instrument air for the entire plant and will replace the existing instrument air unit. The current instrument air system would need to be demolished due to space constraints in siting the wastewater treatment facility.

Biomass Feeding System

The biomass feeding system of the Gasification Plant includes three parallel lock-hopper-based feeding lines. Biomass is fed into the intermediate storage silos (030-U-0001A/B/C) at the top of the feeding lines. The storage silos is purged with nitrogen from the ASU to avoid dust explosion or self-ignition of the dried fuel. From the storage silos, the fuel is moved through slewing screw dischargers, silo screw conveyors (030-A-0006A/B/C), storage transfer screw conveyor (030-A-0007A/B/C) into two lock hoppers per feeding line (030-U-0002A/B/C/D/E/F), where the biomass is pressurized using CO_2. From the lock hoppers, the biomass is fed to surge hoppers (030-U-0003A/B/C) and surge screw conveyors (030-A-0009A/B/C) that mix the feedstock with the bed material (dolomite) prior to entering the gasifier.

The bed material is stored in the bed material silos (030-U-0006). The bed material feeding system is a lock-hopper system, which includes an atmospheric weigh hopper (030-U-0007) where the bed material is fed into the lock- / surge-hopper (030-U-0010) in which it is pressurized to system pressure. The bed material screw conveyor (030-A-0010) at the bottom of the surge hopper moves the bed material to the fuel feeding screw conveyors (030-A-002A/B/C) and feeds it into the gasifier.

Gasifier, Start-up Burner, Ash Handling and Storage

The biomass is gasified in the Gasifier reactor (030-R-0001) in the presence of O_2 and superheated steam at 1,380 kPag (200 psig) and 815ºC (1,500ºF). The gasifier is a pressurized bubbling fluidized bed type gasifier. Both O_2 and steam are introduced through a valve system to the gas distributor grid at the bottom of the gasifier. O_2 is distributed inside the gasification plant from an O_2 tank (030-TK-0003) and distribution header. O_2 is preheated with LP steam via heat exchangers (030-E-0001A/B) to avoid condensation of steam during mixing with O_2. The biomass-derived syngas at 55,319 kg/hr (121,958 lb/hr) exits the gasifier at the top of the reactor. The entrained dust is partly removed from the hot gas in the first gasifier cyclone 030-CY-0001 and returned to the fluidized bed via the cyclone return pipe (dipleg). The raw syngas leaving the first cyclone passes through a second cyclone (030-CY-0002) where the bulk removal of the dust occurs.

Bed material and fuel ash (together referred to as bottom ash) are removed through the bottom of the gasifier using a water-cooled cooling screw to a CO_2-pressurized lock hopper (030-U-0013). The bottom ash at 744 kg/hr (1,640 lb/hr) is conveyed pneumatically through an ash removal hopper (030-U-0014) to the gasifier ash silo (030-TK-0009) by using N_2. Similar to bottom ash, fly ash passes through a lock hopper (030-U-0015) and conveyor hopper (030-U-0015), and it is loaded into a fly ash storage silo (030-TK-0010) at 1,294 kg/hr (2,853 lb/hr).

A natural gas-fueled start-up burner (030-F-0001) located at the bottom part of the gasifier is used to heat the reactor during start-up. In this mode, air for biomass combustion is supplied by a start-up air system consisting of an air compressor (030-C-0002) and an air receiver (030-TK-0004).

Syngas Reformer, Start-up Heater

The dusty syngas enters the syngas reformer (030-R-0002A/B) containing nickel-impregnated monolith catalyst. In the reformer, the tar and other unsaturated hydrocarbon compounds are reformed into H_2 and CO. Reaction temperature is achieved by injecting O_2 and 1,380 kPag (200 psig)-steam through burners at the inlet of the top stages. At start-up, the reformer system is heated by a dedicated Tar Reformer start-up heater.

O_2 and Recycled CO_2 Tanks and Buffers

O_2 from ASU is stored in the O_2 buffer tank (030-TK-0003), heated via O_2 preheaters (030-E-0001A/B) is delivered to the Gasifier and Reformer from the ASU at about 1,379 kPag (200 psig).

A slipstream of recovered CO_2 from the desulfurizer is sent to LP and HP CO_2 compressors (030-C-0003A/B, 030-C-0004A/B), is fed to buffer tanks (030-TK0001/0002) and is used in the biomass/bed material feeding operations. Intercoolers (030-E-0010A) and aftercoolers (030-E-0011A/B) cool the gas stream at the discharge of the compressor.

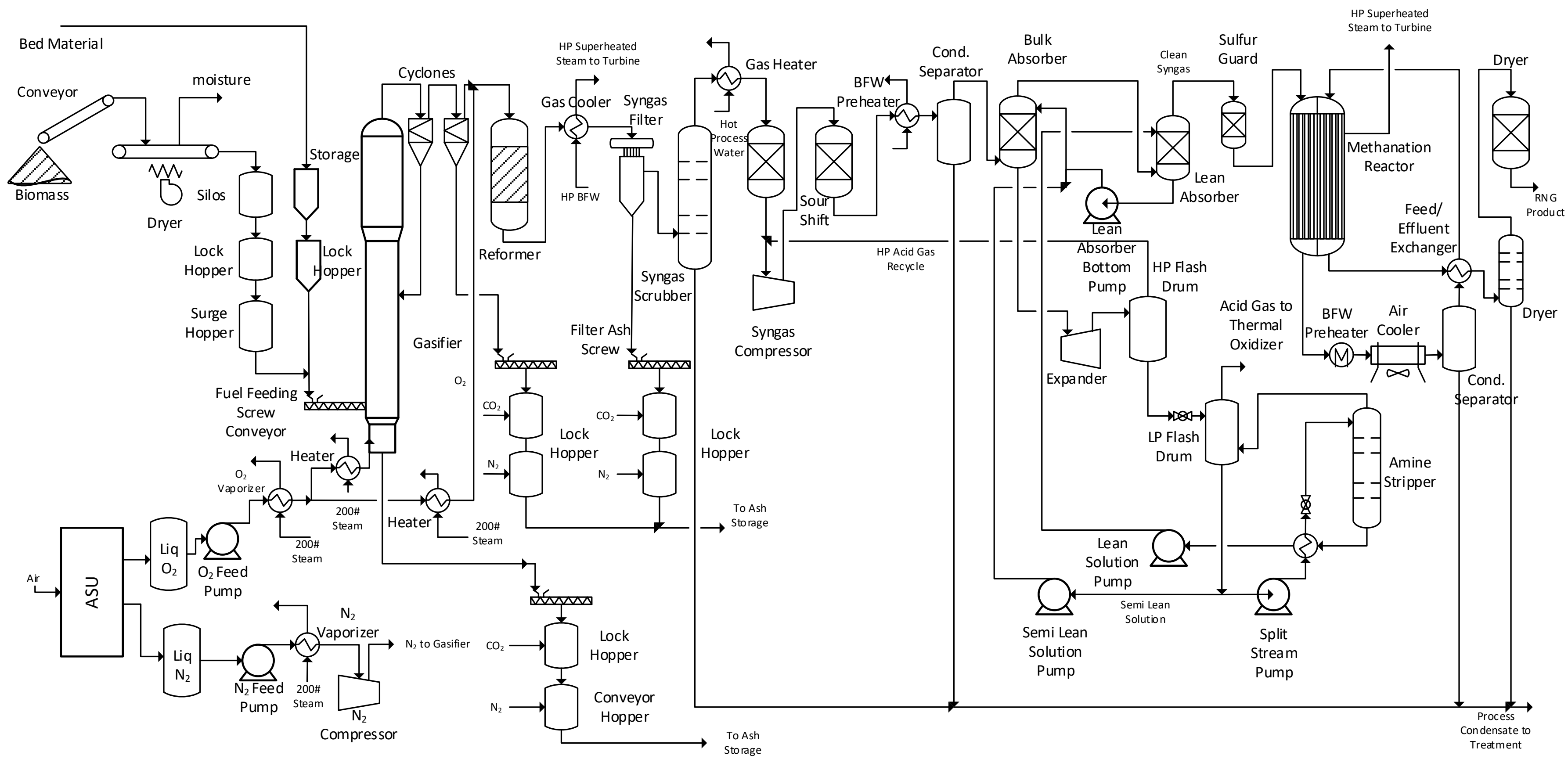

Figure 9. Simplified Process Flow Diagram

Gas Cooler/Heat Recovery Steam Generator, Syngas Filter and Scrubber

From the reformer, syngas at 59,069 kg/hr (130,224 lb/hr) and 910 ºC (1,668 ºF) is cooled in a water tube type gas cooler (030-E-0004A), which includes an evaporator section (030-E-0004B), superheater (030-E-0004A) and steam drum (030-V-0001). The superheater also superheats steam generated from the methanation plant. The steam from the gas cooler is at 8,273 kPag-(1,200-psig) superheated steam, which will be sent to a steam turbine in the steam plant. Preheated BFW is fed to the steam drum of the gas cooler. The gas cooler uses LP steam for soot blowing to remove depositions from the evaporator tubes. The steam drum associated with syngas cooling has blowdown, the disposal for which will be determined in the next design phase.

The syngas leaving the Gas Cooler at 310 ºC (590 ºF) passes a quench cooler (030-E-0005) and enters a syngas filter 030-FL-0001. The quench cooler adjusts the gas temperature in case of a capacity decrease of the gas cooler or replaces the gas cooler in an emergency case to protect the filter unit.

The syngas filter is a candle filter unit consisting of metal candle filter elements arranged in clusters and installed into a tube sheet. The filter candles are cleaned by CO_2 back pulsing from the pulsing gas tank 030-TK-0008. The filter unit is operated at system pressure and the pulsing gas is injected at ambient temperature. Ash is removed from the filter by way of a similar process as the bottom and fly ash (lock hopper and conveyor system), and is transferred to ash storage.

The cooled and filtered gas is further cooled in a two-stage syngas scrubber (030-T-0001) to about 38 ºC (100 ºF). The scrubber removes part of the water vapor and remaining contaminants from the gas and protects the syngas compression system and the chemical process in case of reformer or filter malfunction. The scrubber has an inlet quench system where water is pumped by cooling pumps (030-P-0003A/B) through nozzles into the syngas flow. The gas is then cooled further through the first stage bed. The scrubber water is circulated by circulation pumps (030-P-0004A/B) through a heat recovery heat exchanger (030-E-0006) to the top of the first stage bed. In the second stage, the gas is cooled through the second stage bed by recirculated water (030-P-0005A/B and 030-E-0007). The condensate generated from heat exchangers is delivered to the process condensate treatment per section 4.2.5.

The cooled, saturated syngas from the scrubber is heated up to 49 ºC (120 ºF) in a gas heater heat exchanger (030-E-0008) to reduce the gas relative humidity prior to entering a syngas compressor.

Emergency Flare

A flare (030-F-0002) is included in the gasification plant to burn the syngas safely during start-up / shut-down of the gasifier, in an emergency, during times of off-spec syngas and when the methanation plant is down. The flare is a smokeless-natural draft system utilizing natural gas as a fuel. During heat-up, the flare serves as a stack where the flue gases of the start-up burner(s) and the flue gases from biomass combustion in the gasifier are released.

Tar Adsorbers and Regenerators

Syngas leaving the syngas scrubber is sent to a tar adsorber (030-R-0003A/B/C) where any residual tar compounds are removed with activated carbon adsorbants. The adsorber consists of three vessels, with two vessels in series in operation while the third vessel is regenerated. The first adsorber serves as a pre-adsorber for heavy tar compounds, whereas the second and third are bulk adsorbers used for adsorption of light tar compounds (i.e. benzene, toluene). Superheated steam at 1,380 kPag (200 psig) is used to strip the tar compounds from the second and third adsorbers during regeneration. The heavy tar compounds in the first adsorber cannot be stripped-off, and the activated carbon in this vessel is replaced by one of the bulk adsorbers when saturated.

The off-gas from the tar adsorber is sent to the thermal oxidizer for complete destruction of benzene and toluene. The adsorber cooler (030-E-0009) is used to cool the activated bed after regeneration before it is reset to operation. The process condensate generated from cooling is separated in a knock-out drum (030-V-0002) and is then sent to the process condensate treatment.

Syngas Compressor

The tar-free syngas from the tar adsorber is combined with high-pressure acid gas recycle from Acid Gas Removal unit and is compressed from 690 kPag (100 psig) to 2,896 kPag (420 psig) by a two-stage 3,200 kW (4,291 hp) syngas compressor (030-C-0001).

Sour Water Gas Shift

Compressed syngas at 44,451 kg/hr (97,997 lb/hr) is heated in a feed/effluent exchanger (040-E-0001) and mixed with 4,137 kPag (600 psig) -superheated steam. The mixture is then sent to the sour shift reactor (040-R-0001) where the reaction is controlled by the exit temperature. The reactions in the shift reactors are the water gas shift and the hydrolysis reactions:

Shift reaction: $CO + H_2O \leftrightarrow H_2 + CO_2$ + heat

Hydrolysis reaction: $COS + H_2O \leftrightarrow H_2S + CO_2$

The optimum production of RNG in the methanation reactor downstream of the shift reactor depends on the ratio of H_2, CO, and CO_2 in the methanation feed, which is determined by both water gas shift and acid gas removal operation. Water gas shift facilitates the conversion of CO into H_2, while the acid gas removal system controls the removal of CO_2. About 61% of the CO is converted to H_2 in the shift reactor.

The shifted gas is then cooled-down to 60 ºC (140 ºF) in the feed effluent exchanger, second BFW preheater (040-E-0002), amine stripper reboiler (040-E-0003) and first water cooler (040-E-0004). The condensate generated during the cooling is removed in the first process condensate separator (040-V-0001) before entering the acid gas removal unit.

Acid Gas Removal

The AGR uses activated Mono-diethanol Amine (MDEA) to absorb both H_2S and CO_2 from the syngas. The syngas entering the AGR contains approximately 38 mole% CO_2 and 200 ppm H_2S.

The syngas enters a bulk absorber (040-T-0001) at 2,648 kPag (384 psig). The bulk absorber uses semi-lean MDEA solution, which is pumped by semi-lean solution pumps (040-P-0002A/B) to the top of the absorber to remove the majority of the acid gas. The gas exiting the top of the bulk absorber is sent to the lean absorber (040-T-0002), which removes the remainder of the acid gas. The purified syngas leaving the top of the lean absorber contains approximately 6.7 mole% CO_2 and 1 ppm H_2S.

Rich amine from the bottom of the bulk absorber is expanded via an expander (040-EX-0002) and is then sent to HP flash drum (040-V-0002) and LP flash drum (040-V-0003). This configuration helps save power for 040-P-0002A/B. In the HP flash drum, most of the dissolved inert components are released. The majority of acid gas is released from the solution in the LP flash drum.

The flashed gas from the HP flash drum, which has a high H_2 content, is recycled and mixed with syngas upstream of syngas compression.

The acid gas stream from the LP flash drum is cooled in the acid gas cooler (040-E-0007). The condensate is separated in the product separator (040-V-0004) and is pumped back to LP flash drum via H_2S overhead condensate pump (040-P-0005A/B). The off-gas from the LP flash is sent to the thermal oxidizer.

The condensate from the bottom of the LP flash drum is mostly sent to the semi-lean solution pump, and the rest is sent to the stripper (040-T-0003) via the split stream pump (040-P-0004A/B). The rich amine is heated in the stripper feed/effluent exchanger (040-E-0005), by the lean amine from the bottom of the stripper.

In the stripper, a part of the semi-lean amine is regenerated by stripping the H_2S/CO_2 gases from the solution. The heat to the stripper is supplied by the amine stripper reboiler (040-E-0003). The hot-and-water-saturated acid gas from the stripper overhead is routed to LP flash drum. The lean amine from the bottom of the stripper is cooled by the stripper feed/effluent exchanger and the lean solution cooler (040-E-0006) before pumping back to the lean absorber to restart the process.

Methanation Reactor, Dryer, Waste Heat Recovery Steam Generator

Syngas leaving the AGR is preheated in the feed/effluent heat exchanger (040-E-0008) to 250 ^oC (482 ^oF) and is fed to a sulfur guard (040-R-0002). The sulfur guard bed consists of activated zinc oxide to ensure there is no residual H_2S in the syngas stream that would poison the methanation catalyst.

The effluent from the sulfur guard mixes with recycle gas and enters the methanation reactor (040-R-0003). The production of RNG occurs in the methanation reactor according to the following reactions:

$$CO + 3H_2 \leftrightarrow CH_4 + H_2O + heat$$

$$CO_2 + 4H_2 \leftrightarrow CH_4 + 2H_2O + heat$$

Both reactions are highly exothermic and result in a large increase of temperature. Thermodynamically, these reactions are favored at low temperatures; therefore, a two-pass cooled reactor is used. The methanation reactor consists of tubes immersed in boiling water (boiling water reactor, or BWR) and an inter-stage cooling. Additional steam is required to avoid carbon formation and injecting the required amount of steam through an ejector (040-J-0001) provides a free recycle (without compressor) to the first pass.

Most of the CO and some CO_2 are converted to CH_4 in the first pass. High conversion is achieved by removing water from the process gas through a series of heat exchangers: i.e., methanation first pass feed/effluent exchanger, first BFW preheater (040-E-0009), demin water preheater (040E-0010), RNG air cooler (040-E-0011), and circulate the effluent back to the second pass of the BWR. The condensate is separated in a K.O. drum (040-B-0005), whose temperature is controlled by the air cooler to about 60 ^oC (284 ^oF). The K.O. temperature can be adjusted to control the amount of water in the process gas, which is necessary to avoid carbon formation.

The gas leaving the K.O. drum is preheated in the methanation second pass feed/effluent exchanger (040-E-0012) before being fed to the second pass of the BWR, where the remaining CO_2 will be converted.

The gas leaving the second pass of the BWR is cooled down in the second pass feed/effluent exchanger, and further cooled in the second water cooler (040-E-0013). The RNG product is washed with demineralized water, which is pumped via the wash water pump (040-P-006A/B) into the third process condensate separator (040-V-0006) to eliminate traces of ammonia that may be formed in the methanator.

The RNG product is dried in the mol sieve and silica bed dryers (040-R-0004A/B) to meet the moisture content requirements of the pipeline. The RNG production to the pipeline is 2.5×10^5 Sm^3/d (8.7 MMSCFD).

The BFW used in the cooling of the BWR is converted to steam in the reactor itself. The preheated BFW from the second BFW preheater is routed to a steam drum (040-V-0007). The steam drum is operated at 8,494 kPag (1,232 psig). A continuous blowdown is maintained to ensure the boiler's water quality. (The disposal of the blowdown from the drum will be determined in the next engineering phase).

Part of the steam from the steam drum is depressurized and is superheated in the steam drum before being used as a motive stream for the ejector.

Process Condensate and Sour Water

All condensate coming from compressor scrubbers, syngas scrubbers, and first, second, and third condensate separators of 644 lpm (170 gpm) are sent to an oil separator (050-V-0001). Both water and vapor from the condensate separator are sent to a condensate tank (050-TK-0001). Water is pumped via a condensate tank transfer pump (050-P-0001A/B) to the condensate tank, while the oil is transferred to a slop tank and disposed off-site using the current site disposal procedure.

Off-gas from the condensate tank is sent to the thermal oxidizer via a condensate off-gas blower (050-B-0001). The liquid is transferred to a condensate stripper (050-T-0001) where it is stripped using air from a blower (050-B-0002). The stripped condensate from the bottom of the stripper is sent to a clean condensate tank (050-TK-0002) and is transferred to process condensate water treatment via clean condensate pumps (050-P-0003A/B).

The ammonia-containing off-gas from the condensate stripper is sent to an ammonia absorber (050-T-0002), where it is contacted with a sulfuric acid solution to produce ammonium sulfate. (The disposal of the ammonium sulfate will be determined in the next design phase).

Thermal Oxidizer

The thermal oxidizer (060-F-0002) receives off-gas streams from tar adsorber off-gas, acid gas from acid gas removal, and condensate off-gas from the process condensate tank. Both acid gas and off-gas from process condensate are sent to an acid gas desulfurizer (060-R-0001A/B). The sulfur-free highly concentrated CO_2 stream is then combined with the tar adsorber off-gas.

A slipstream of the combined gas of approximately 5,071 kg/hr (11,179 lb/hr) is routed to the gasification plant, where it is compressed and reused in the biomass feeding process. The remainder of the off-gas stream is sent to the thermal oxidizer, which ensures the complete combustion of hazardous compounds.

The thermal oxidizer is a 38,000 MJ/hr (36 MMBtu/hr)-natural-gas fueled unit equipped with a burner (060-F-0001), an air blower (060-B-0001), an air filter (060-FL-0001), and a stack (060-F-0003).

Steam Plant

HP BFW preheated in the heat exchangers from the RNG plant supplies BFW to both the methanation steam drum (040-V-0007) and the gasification steam drum (030-V-0001). Steam flow from both steam generators of approximately 49,787 kg/hr (109,762 lb/hr) is sent to a superheater (030-E-0004) and is then sent to a steam turbine (070-D-0001) and associated power generation block (surface condenser, 070-E-0001 and vacuum system) to generate 8.1 MW power.

Four steam headers operate as part of the steam plant and serve as the main headers for 8,274, 4,137, 1,380 and 345 kPag (1,200, 600, 200 and 50 psig) steam users throughout the plant.

Both vacuum condensate and clean-condensed steam are sent to the existing deaerator and recycled for BFW.

Water Treatment Plant

The water treatment (070-PK-0001) plant receives cooled process condensate from the process condensate stripper. The water treatment unit is a vendor package consisting of biological treatment, sludge handling, media filters, reverse osmosis (RO), and ion exchange unit operations.

Discharges from RO and filters are disposed to an existing waste collection sump, while the sludge is disposed off-site. Water loss in the treatment is estimated to be 27%. The recovered water is combined with a make-up water from the city water to an existing 100,000-gallon tank (670-701). The water is then transferred by existing pumps (670-700/702/703) to a demin water preheater (040-E-0010) and to an existing deaerator (170-170). The clean condensate leaving the deaerator is pumped by BFW pumps (070-P-0001A/B) to first and second BFW preheaters (040-E-0009 and 040-E-0002) and is sent back to steam boilers.

Cooling Water System

Cooling water system consists of cooling water supply and return headers, and ten heat exchangers used throughout the RNG plant. The cooled water at about 25 ^{o}C (78 ^{o}F) from an existing mechanical-draft cooling tower is sent to the supply header via existing cooling water pumps. The water from heat exchangers at 32 ^{o}C (90 ^{o}F) is sent to the cooling water return and is sent back to the cooling tower.

Hot Process Cooling Water

The hot process water is a closed-loop system that supplies hot water to three heat exchangers in the gasification island. The unit consists of a hot water suction tank (080-TK-0002), circulation pumps (080-P-0002A/B), and a cooler (080-E-0001).

A separate loop of HP cooling water supplies cooling water to the biomass feeding and solid handling screws. The HP cooling water supply is heated by way of heat exchanged with the conveyor and screws. The HP cooling water loop consists of a suction tank (080-TK-0001) and circulation pumps (080-P-0001A/B). Both expansion tanks are equipped with make-up water lines and blowdowns. (Blowdown disposal will be determined in the next engineering phase.)

3.3.4. Power Requirement

Table 9 shows the steady-state power requirements of the RNG production process for major equipment and utilities. The overall gross electrical load is expected to be a maximum of 27 MW. The gross normal load of the facility is 18.1 MW. The net power import for normal operating condition is approximately 9,974 kW or 10 MW.

Table 9. Power Requirement of the RNG Plant at Normal Operations

Equipment	Unit	Total Power
Biomass preparation and handling	kW	3,273.29
Air Separation unit	kW	6,595
Biomass feeding system and gasifier	kW	728
Acid gas removal	kW	5,461
Methanation	kW	31
Utilities		
- Water treatment & steam plant	kW	468
- Process condensate & sour water stripper	kW	50
- Cooling water system	kW	1,154
- Hot process cooling water	kW	398
- Thermal oxidizer & flare	kW	65
- Subtotal	*kW*	*1,985.39*
Total	kW	**18,074**
On-site power generation from steam turbine	kW	(8,100)
Net power import	kW	**9,974**

A summary of the electrical load list is shown in Table 10 below.

Table 10. Summary of Electrical Load List

Major Equipment Name	Total Power kVA	Total Amperage Amps
Existing Main 13.8 kV Switchgear	32,036	1,340
RNG 13.8 kV Switchgear	16,185	677
Existing 4.16 kV MCC A	2,171	301
Existing 4.16 kV MCC B	1,631	226
4.16 kV MCC C	2,991	415
4.16 kV MCC D	1,590	221
Existing 480 V MCC BH-1	480	577
Existing 480 V MCC BH-2	265	318
Existing 480 V MCC FH-1	400	481
Existing 480 V MCC FH-2	400	481
Existing 480 V MCC EM	30	36
480 V Syngas Cleaning MCC A	225	270
480 V Syngas Cleaning MCC B	43	52
480 V BOP MCC A	682	821
480 V BOP MCC B	569	684
480 V Gasifier MCC A	297	357
480 V Gasifier MCC B	163	196
480 V Fuel Handling MCC A	224	269
480 V Fuel Handling MCC B	156	188
480 V Fuel Dryer Switchboard A	500	602
480 V Fuel Dryer Switchboard B	500	602

Many of the existing power equipment will be retained, however new equipment will be added to accommodate additional load:

- One 13.8-kV switchgear
- Two 4.16-kV MCCs
- Eight 480 V MCCs
- Two 480 V Switchboards

- Two 13.8 kV to 4.16 kV transformers
- Two 13.8 kV to 0.48 kV transformers
- Two 4.16 kV to 0.48 kV transformers
- One grounding transformer

All new electrical and some of the new process control equipment will be stored in power distribution center (PDC) buildings.

3.3.5. Utilities Requirement

Utilities requirements of the RNG production plant are summarized in Table 11 below.

Table 11. Summary of Utilities Requirements[1]

Utility	Unit	Values
Oxygen	kg/hr (lb/hr)	10,917 (24,068)
Nitrogen	kg/hr (lb/hr)	717 (1,581)
1,200 kPag (200 psig)-Steam	kg/hr (lb/hr)	14,622 (32,236)
4,144 kPag (600 psig)-Steam	kg/hr (lb/hr)	14,169 (31,238)
8,301 kPag (1,200 psig)-Steam	kg/hr (lb/hr)	49,787 (109,762)
HP BFW	kg/hr (lb/hr)	56,507 (124,577)
Natural gas	Std m^3/hr (SCFH)	115 (4,042)
Power import	kW	9,974
City water	lpm (gpm)	1,560 (412)

[1] LP cooling water, and hot process water requirements will be provided in the next engineering phase

Chemicals and catalyst requirements of the RNG plant operations are shown in Table 12 below.

Table 12. Chemicals and Catalysts Requirements

Description	**Unit**	**Values**	**Remarks**
Gasifier			
Dolomite	kg/hr (lb/hr)	407 (897)	
Amine Unit			
MDEA (BASF, OASE white)			
First year charge	L (Gal)	250,000 (66,043)	
Make-up rate	L/hr (Gal/hr)	1.5 (0.4)	
Desulfurizer			
Sulfa Trap	kg/hr (lb/hr)	0.045 (0.1)	
Water Treatment Chemicals (existing plant)[1]			
Cooling Tower			
Corrosion/Scale Inhibitor (Phosphate)	kg/hr (lb/hr)	1.8 (4)	
Non-oxidizing Biocide	kg/hr (lb/hr)	0.18 (0.4)	
Sodium Hypochlorite	L/hr (Gal/hr)	8.3 (2.2)	
Sulfuric Acid	kg/hr (lb/hr)	6 (13)	
Boiler System			
Phosphate (Optisperse HP9410)	kg/hr (lb/hr)	0.45 (1)	
Neutralizing Amine	kg/hr (lb/hr)	0.09 (0.2)	
Oxygen Scavenger (Cortrol)	kg/hr (lb/hr)	0.09 (0.2)	
Emission System			
Sodium Hydroxide (Caustic)	kg/hr (lb/hr)	13.6 (30)	
Ammonia Absorber			
Sulfuric Acid Solution	L/hr (Gal/hr)	30 (8)	
Catalysts			
Tar adsorbers - activated carbon	kg/hr (lb/hr)	0.77 (1.7)	lifetime: 2 years
Sour shift - CoMo - Topsoe SSK10	kg/hr (lb/hr)	0.8 (1.8)	lifetime: 3 years
Sulfur Guard - ZnO - Topsoe HTZ-51	kg/hr (lb/hr)	1.3 (2.8)	lifetime: 3 years
Gas conditioning - Ni - Topsoe GCC-2	kg/hr (lb/hr)	0.09 (0.2)	lifetime: 3 years
Methanation - Ni - Topsoe MCR-8	kg/hr (lb/hr)	0.2 (0.5)	lifetime: 3 years
Methanation - Ni - Topsoe PK-7R	kg/hr (lb/hr)	0.09 (0.2)	lifetime: 3 years
Dryers - Silica Gel - SG W 127	kg/hr (lb/hr)	0.005 (0.01)	lifetime: 2 years
Dryers - Mol Sieve - MS 564C	kg/hr (lb/hr)	0.14 (0.3)	lifetime: 2 years
Tar Reformer - Topsoe Mega Monolith	kg/hr (lb/hr)	5.6	lifetime: 2 years

[1] Chemicals consumption for the new water treatment will be determined at a later stage

3.3.6. Site Plan

Figure 11 shows the equipment lay out of the plant. Other drawings can be found in the Appendix 3 (not included in this version of the report).

- Drawing #196880-CGAU-G20000: two-dimensional plan lay-out, including property lines, roads, equipment / structures to be demolished or abandoned, and boundaries for the subsequent partial plans.
- Drawing #196880-CGAU-G20001: equipment lay-out, including the Gasification Process Island, which will be built in place of the existing power block, and the HTAS Syngas and Methanation Process Island, which will be constructed on the vacant South Lot. New road will be required around the Methanation Island and new pipe rack will be required between process islands. Construction lay-down is expected to locate at the southeastern part end of the site.
- Drawing #196880-CGAU-G20002: partial plan for the HTAS Syngas Cleaning and Methanation Process Island.
- Drawing #196880-CGAU-G20003: partial plan for the Gasification Process Island
- Drawing #196880-CGAU-G20004 and #196880-CGAU-G20005: biomass feedstock drying / conveyance and receiving / storage, respectively. Both are located across Washington St. from the main plant area.
- Drawing #196880-CGAU-G20006: mid and upper levels for the HTAS Syngas Cleaning and Methanation Process Island.

3.3.7. Control System

The Black and Veatch Project Scope Book (Appendix 9, not included in this version of the report) outlines the control system principles for the Stockton plant conversion.

The existing PLC will be reused as much as possible, but expansion of the existing control system to accommodate new I/O and control systems will be required, such as:

- The PLC for balance of plant will be expanded to accommodate approximately 545 new I/O from HTAS Syngas Cleaning and Methanation Process Island and process condensate systems.
- The existing boiler PLC will be expanded to include 218 new I/O from the ASU, BFW and process condensate systems.
- The fuel handling PLC will be expanded to accommodate new 363 I/O for feedstock handling equipment
- New PLC system package for air compressors, the Gasification Process Island, auxiliary boiler burner management system, auxiliary boiler combustion controls, the steam turbine, the thermal oxidizer burner management system, and water treatment plant.

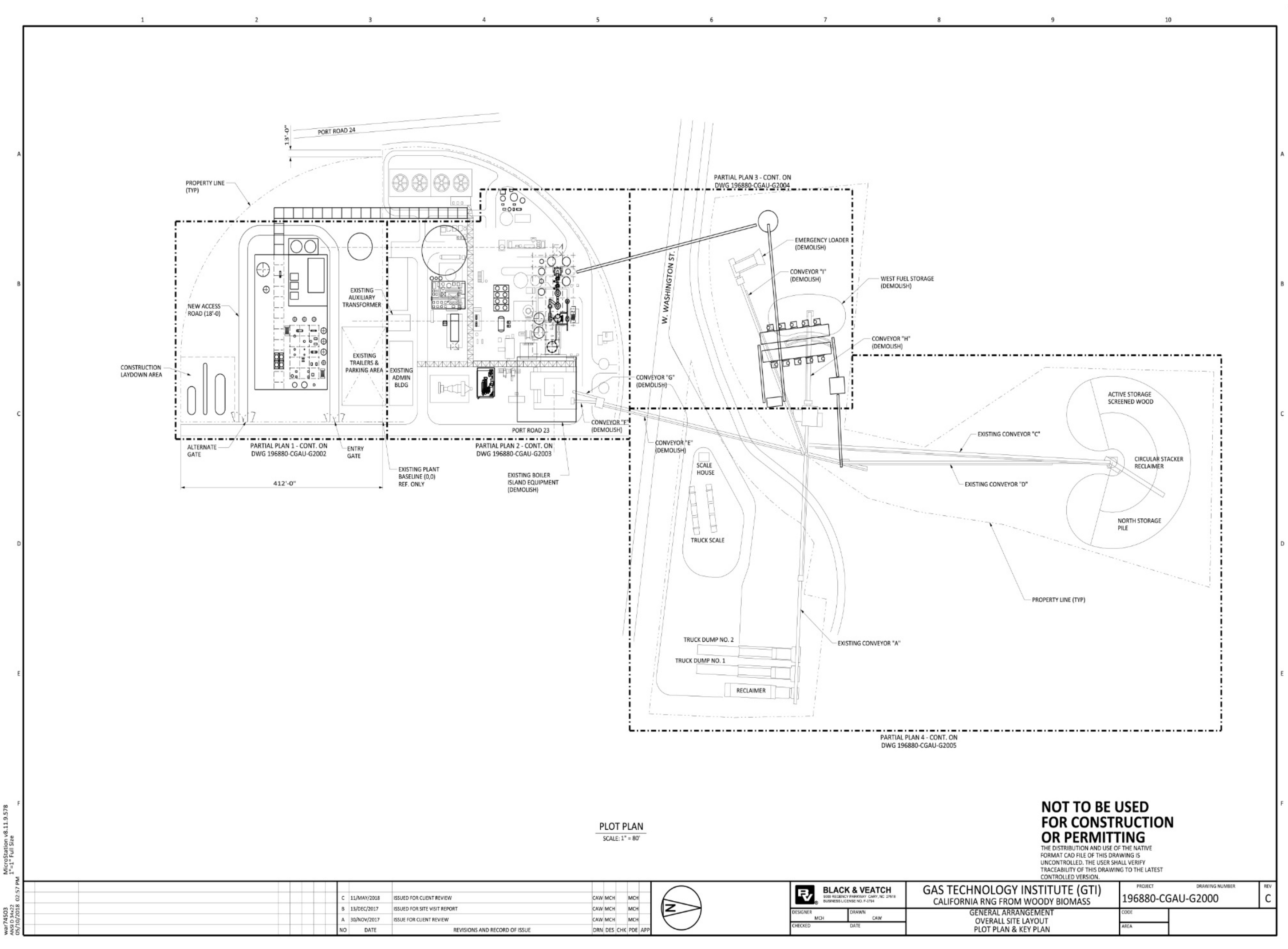

Figure 10. Overall Site Layout for the RNG Plant

1	Gasifier	7	Flare	13	HP N_2 Tank	19	Water Treatment	25	Bulk Absorber
2	Cyclones	8	Storage Silos	14	Gasifier Ash Storage	20	Biological Treatment	26	Methanation Reactor
3	Syngas Reformer	9	Aux Boiler	15	Filter Ash Storage	21	Thermal Oxidizer	27	Sulphur Guard
4	Syngas Scrubber	10	O_2 Tank	16	ASU	22	Syngas Compressor	28	Air Cooler
5	Tar Adsorbers	11	CO_2 Tank	17	Hot Water Air Cooler	23	Tar Adsorbers	29	Solution Storage Tank
6	Syngas Filter	12	LP N_2 Tank	18	Steam Turbine	24	Sour Shift	30	Acid Gas Desulfurizers

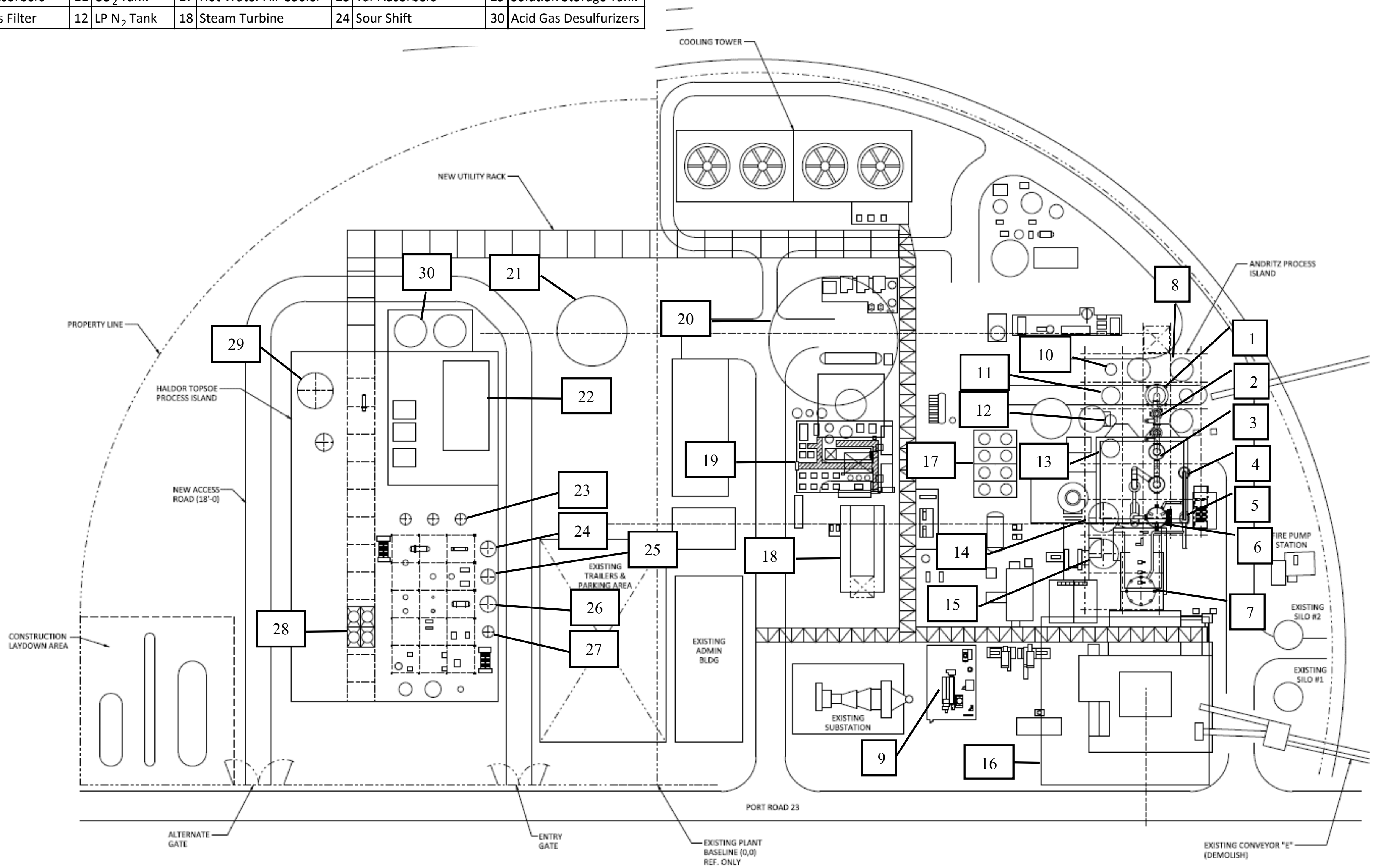

Figure 11. Equipment Layout of the RNG Plant

3.3.8. Stockton Site-specific Issues

Although the DTE Energy Stockton plant was determined to have many favorable characteristics for the conversion to RNG production, there were also some noteworthy limitations with the site. The following list of issues should be considered when a determination is made as to whether the project should continue at this location or new sites should be evaluated.

1. Space limitations at Stockton site. Demolition of existing equipment needs to be done to make room for the new equipment. Space limitations also had an impact on the preliminary engineering design including:
    a. Material handling equipment: need for a new feedstock conveyors, length of the conveyors and bins, and length of hot water piping for feedstock dryers.
    b. Additional pipe rack and the length of interconnecting piping requirement to connect HTAS process island with the other process islands and utilities.
    c. Requirement for new ash handling / storage for the gasification island rather than reusing the existing equipment.
    d. Demolition of the existing air instrument package to make room for the wastewater treatment facility. A slipstream from ASU will be used to supply instrument air to the plant. Other sites may be able to save some costs by using the existing instrument air system.
2. No demolition scope was included in the cost estimate, assuming that equipment salvage and demolition cost are roughly equivalent. For other sites with older equipment, this assumption may not hold.
3. The local gas transmission just outside the plant boundary does not have enough capacity to accommodate additional production. The closest mainline at 5,515 kPag (800 psig) where RNG could be injected into the system is several miles away. A new dedicated RNG supply line to the main high-pressure pipeline need to be added as well as additional compression to meet the pipeline pressure.
4. Biomass feedstock received at Stockton site from current suppliers is sized for < 4 inches, but gasification process requires feedstock sized for < 1.5 inches. It may be possible at another site to receive properly sized feedstock, thereby circumventing the need for an on-site hogger.
5. In discussions with plant operators, it was determined that a new emergency generator set would be required due to reliability issues. At other sites, this expense could be avoided.
6. The Stockton site currently has a long-term Power Purchase Agreement (PPA) that may result in a significant loss of income during demolition and construction of the RNG production facility.

3.4. Front-end Engineering Design (FEED) / FEL-3 Plan

Further engineering at FEL-3 fidelity would be required to develop the details sufficient to establish design information to form the design basis and technical package for budget authorization and permit applications. Note that the first commercial plant might be some other site and not Stockton. The FEL-3 study scope, schedule, and budget are offered as references for this phase, and a different site would require some pre-work before the FEL-3 phase.

3.4.1. Process Engineering

- Design basis assumptions: update the design basis based on information developed in the FEL-2 and throughout FEL-3.
- Heat and material balance diagrams: update the heat and material balance developed in the FEL-2 and provide heat and mass balance data sheets.
- Water and steam mass balance diagram: develop a plant water mass balance diagram showing the water usage and alternate operation conditions. The diagram will show the sources of water to the site, water treatment plant, and waste streams.
- Plant configuration and system descriptions: update descriptions of major plant systems, major equipment included within the system, equipment size parameters, equipment electrical load requirement, PFDs and prepare preliminary P&IDs.
- Termination point schedule: provide a diagram of the termination point for major packages and equipment as well as a list of termination points.

3.4.2. Process Hazard Analysis

- Provide a preliminary HAZOP and Safety Assessment based on information obtained from process engineering
- Identify and develop hazardous area classification
- Identify and review potential sources of overpressure in the process and verify these issues are appropriately mitigated
- Perform a preliminary Life Safety Review to ensure all access and egress provisions are provided as required by the U.S. Occupational Safety and Health Administration codes.

3.4.3. Site Plans

- Update site plan which will show the location and layout of major structures and facilities
- Initiate an infrastructure assessment using the utility requirements previously identified
- Develop elevation drawings showing the vertical elements of the plant

3.4.4. Instrumentation

- Develop an I / O count to support the development of the ± 10% cost estimate
- Prepare a preliminary PLC specification outlining hardware, software and high-level controls architecture to support the development of the ± 10% cost estimate

3.4.5. Electrical

Update the one-line diagram detailed load list.

3.4.6. Civil/Structural

Perform full geotechnical evaluation to inform foundation design requirements and determine structural steel requirements for process and balance of plant equipment.

3.4.7. Environmental Support

- Request emissions guarantees from equipment vendors in coordination with soliciting firm price proposal
- Update point source emissions. Emissions estimate will be updated based on the most current design basis, selected facility locations, and emissions guarantees
- Identify solid and/or liquid effluent streams, and perform characterization of the individual components
- Develop preliminary methods of handling these components based on local regulations and GTI's waste handling approach

3.4.8. Cost Estimating and Scheduling

Update the Level-1 schedule based on equipment lead times and other information developed during this phase.

It is estimated that the completion of the FEL-3 would require 8 months to complete, 20,000 – 25,000 staff-hours at a price of about $3.5M to $4.0M.

3.5. RNG Project Economics Estimate

3.5.1. Project Spend

The overall pre-revenue project development spend and schedule assumptions are shown in Table 13. The other required project costs in addition to the plant capital cost estimate are included. On a FEL-2 plant cost estimate of $315MM, a total pre-revenue project development spend of $339.9MM was estimated, which includes the to-date FEL-2 spending ($2MM), FEED engineering ($4MM), permitting and consulting ($3MM), and commissioning and start-up expenses ($12.6MM). Only the $315MM plant cost was assumed to be capitalized and depreciated. All other project costs were assumed to be expensed. Additionally, an independent project development team was assumed, with increasing expenses throughout project development, leveling off at $1.5MM/year in the year of startup and throughout the project life.

Table 13. Project Development Costs and Spend Profile (in MM$).

Item	2018	2019	2020	2021	2022	Total
G&A for Project DevCo	$0.25	$0.50	$0.75	$1.00	$1.00	**$3.50**
FEL-2	$2.00					**$2.00**
FEED		$4.00				**$4.00**
Permitting & Consulting		$2.40	$0.60			**$3.00**
Plant Engineering & Construction			$94.44	$157.40	$62.96	**$314.80**
Commissioning and Startup					$12.60	**$12.60**
Total	**$2.25**	**$6.90**	**$95.79**	**$158.40**	**$76.56**	**$339.90**

3.5.2. Operating Costs

Operating costs, including expensed items prior to startup, are shown in Table 14. Project development and G&A comprise all costs in years 2018 – 2021. Operations, maintenance, overhead, and facility insurance expenses were assumed to begin in 2021, associated with hiring and training of staff and preparation for plant starting in 2022. After plant startup in 2022, a 3-year plant ramp-up is assumed, with plant availability increasing from 50% in 2022 to 85% in 2023, and reaching a steady state of 95% in years 2024 and beyond.

Table 14. Table of Operating Cost Items by Year from Project Start Through Steady State (in MM$).

Item	2018	2019	2020	2021	2022	2023	2024+
Project Development	$2.00	$6.40	$0.60				
Feedstock					$3.68	$8.34	$9.32
Electricity					$3.28	$7.43	$8.31
Other Variable OPEX					$2.02	$4.58	$5.12
Operations and Maintenance				$1.92	$5.75	$7.67	$7.67
Other Fixed OPEX (incl. C&SU)	$0.38	$0.75	$1.13	$3.09	$19.42	$8.80	$8.91
Total OPEX	**$2.38**	**$7.15**	**$1.73**	**$5.01**	**$34.15**	**$36.82**	**$39.33**

3.5.3. Levelized Costs

A breakdown of the overall levelized costs is shown in Figure 12, with operating costs totaling $13.76/MMBtu, and total costs including depreciation but before any interest and taxes totaling $17.29/MMBtu. It can be seen that the majority, 67% of variable operating expenses are attributable to feedstock and electricity (for which retail rates were used) with the remaining 33% comprised of water sourcing, treatment and disposal, and solid waste disposal. Approximately 57% of fixed costs are attributable to operations and maintenance, with the balance comprised of catalyst replacement, plant overhead, G&A, insurance and property tax. Depreciation is a substantial item given the large capital cost of the facility.

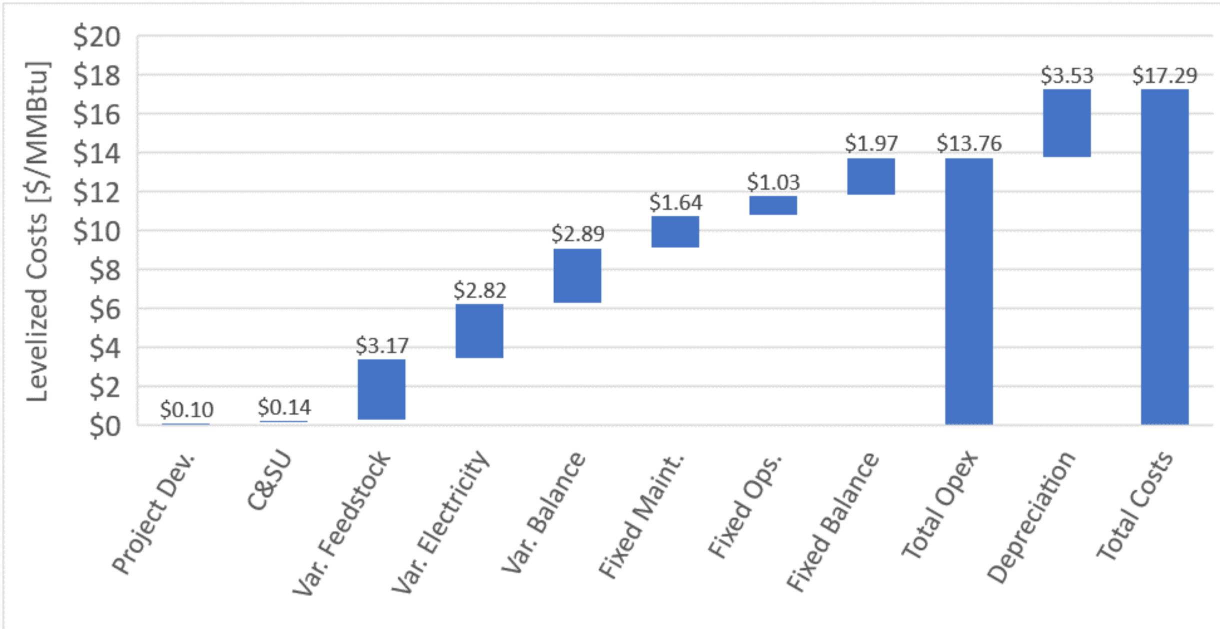

Figure 12. Levelized Cost Profile of the RNG Project.

3.5.4. Sensitivities

The total levelized cost sensitivities to individual cost items are shown on Figure 13. As is typical, capital depreciation and price sensitivity on feedstock dominate. The electrical price sensitivity is also large given the large plant electrical load.

An aggregate sensitivity to all operating cost uncertainties, excluding capital depreciation was calculated using Crystal Ball, and is shown in Figure 14. All uncertainties were modeled with triangular distributions. The P10 – P90 range of operating cost is approximately $13 - $15/MMBtu. The deterministic case assumptions correspond to the P58 value, implying the upside and downside cost uncertainties are fairly balanced. However, it should be noted that some uncertainties were not modeled, which would likely have an overall negative impact on the netback. These include the payment of interest in a debt-financed scenario as well as spending of project contingency.

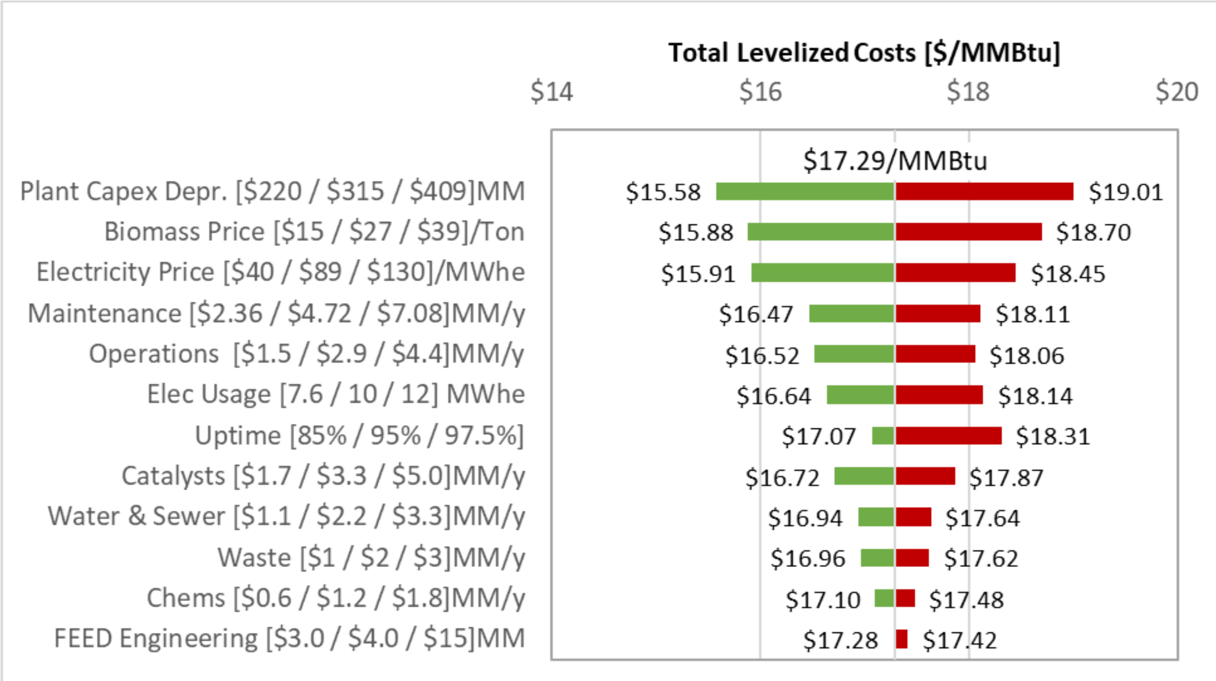

Figure 13. Total Levelized OPEX Sensitivities.

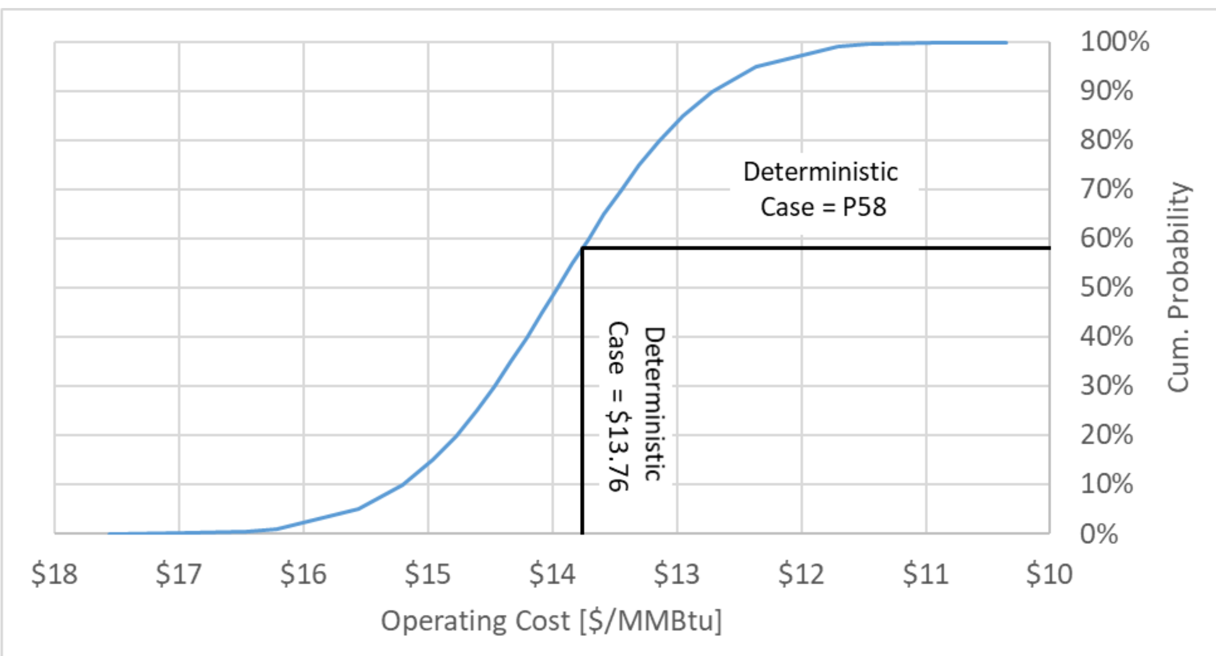

Figure 14. Aggregate Impact of Price and Operating Cost Uncertainties on Total Levelized Operating Cost.

3.5.5. Methodology, Assumptions and Inputs

Key economic assumptions are shown in Table 15 – Table 17. A real 2018 dollar basis was used.

Table 15. Key Economic Assumptions Used for Economic Model

Item	Value
Inflation	2.5%
Nominal Discount Rate	10%
Real Discount Rate	7.3%
Depreciation	10 year straight line
Debt	Zero debt-financing
Equity	100% equity financing
Tax Rate	25%
Plant Operating Life	30 Years

Table 16. Key Operational Assumptions

Item	Value
Operators/shift	6
Operator Shifts	4
Lab Technicians	2 total
Shift Supervisors	1 total
Plant Managers	1 total
Plant Overhead	50% of Labor
Maintenance†	1.5% of Total Installed Cost
Insurance	0.5% of Total Installed Cost
Property Tax	1% of Gross Revenue
G&A Rate	$1.5MM/y steady state

†includes parts, labor, and contracting

Table 17. Key Pricing Assumptions

Stream Pricing Assumptions	Units	Mid	Low	High
Biomass Feedstock				
Biomass FOB Source	[$/ton]	$27.00	$15	$39
Biomass Transportation to Plant	[$/ton]	$-		
Biomass at Plant	[$/ton]	$27.00		
Electrical Pricing				
Electrical Purchase Price[14]	[$/MWhe]	$88.86	$40	$130
Electricity Delivery Charge[14]	[$MM/y]	$0.975		
Waste Pricing				
All solid waste	[$/ton]	$100	$50	$150
Water Pricing				
Make-up and Waste Water	[$/kgal]	$8.7	$50	$150
OPEX Items				
Total Consumable Chemicals	[$MM/y]	$1.18		
Catalysts and Packings	[$MM/y]	$3.30	$1.65	$4.95
Operations				
Operator FTE	[$MM/y]	$0.10		
Lab Technician FTE	[$MM/y]	$0.10		
Shift Supervisor FTE	[$MM/y]	$0.15		
Plant Manager FTE	[$MM/y]	$0.20		

[14] Yearly average cost, based on the PG&E E-20 industrial rate table for Transmission Voltage service. https://www.pge.com/tariffs/electric.shtml

3.6. Life-Cycle Analysis

Environmental impacts resulting from the use of fossil-derived fuels have been widely discussed. On first inspection, it would be reasonable to assume that any resource that would displace some of the fossil fuel use would undoubtedly result in environmental benefit. However, the impacts must be inspected case by case given that quantifying them can be quite complex, as there can be many variables in play. Some aspects may help reduce the environmental impacts while others may contribute to them[15]. One example would be the proportion of emissions from transporting a biomass (green) resource to a processing facility and the delivery of the product. Other effects include the degradation or erosion of land, the loss of biodiversity, the disposal of industrial and agricultural waste and chemicals, smoke from open burning, etc.

Proper forest management and agricultural practices, along with green energy conversion technologies, have a critical role to play in attempting to reduce the accumulation of GHG. These practices have great potential to help decarbonize the energy portfolio and reduce GHG emissions. Wood and agricultural wastes can be converted to a clean burning transportation fuel such as biomethane (RNG). Further environmental benefits can be obtained if the RNG production is coupled with carbon sequestration. In very broad terms, the carbon cycle from energy production from biomass goes as follows: plants grow as they take in CO_2 from the atmosphere and convert it to carbohydrates. As the plant matter is harvested and converted to fuels and energy, CO_2 is returned to the atmosphere, yielding no net carbon emission.

In this context, biomass is defined as the material of recent biological origin. Some additional examples of biomass include wood chips, sawdust, tree trimmings, urban wood waste, and agricultural wastes such as cornstover. In the state of California, biomass is generally converted to electricity and sold to the local utilities[16]. There are many benefits to the conversion of biomass, including reducing the volume of material that is landfilled, reducing forest fire hazards, generating renewable energy, creating jobs, and reducing GHG emissions.

The table below provides an estimate of the amount each feedstock by the energy content of each feedstock. Often conversion facilities process more than one type of biomass feedstock.

Table 18. Biomass Use in California by Energy Content (2011)[16]

Biomass Type	Energy Content (MMBtu)	Percentage
Agricultural Waste	19,000,000	28%
Forest Wood Waste	24,000,000	36%
Urban Wood Waste	24,000,000	36%
Total	67,000,000	100%

[15] Brown, Robert C.; Biorenewable Resources: Engineering New Products from Agriculture, 1st Ed, 2003 Iowa State Press

[16] *Biomass Conversion*. https://www.arb.ca.gov/cc/waste/biomassconversion.pdf

Although RNG can be produced through biochemical processes such as anaerobic digestion, these processes cannot fully convert all carbon in the feedstock; therefore, decomposable materials are treated as waste and are disposed in landfills or applied to soil as fertilizer displacement. Instead, thermochemical processes can be employed to break down waste materials fully while generating RNG.

For this study, the engineering design focused on how an existing wood waste power plant can be transformed into a RNG producing facility of approximately 82 million cubic meters (2900 million cubic feet). It utilizes waste materials such as wood waste (a mixture of urban/demolition wood), agricultural waste, and forest waste to produce RNG via gasification and methanation. The design includes a tie-in to the natural gas pipeline system and the production of RNG that meets the existing utility requirements for pipeline quality. An LCA quantifying the environmental benefits of the RNG produced is one of the key design elements.

The environmental impact analysis of the proposed conversion pathway covers from the source (field or forest), through the pipeline (plant gate), and down to the end use point which in this case is combustion in internal combustion vehicles. The results include carbon intensities in grams of CO_2 GHG equivalent emissions (gCO_2e) per MJ of RNG, taking into account the avoided emissions one additional hypothetical scenario.

The information gained from a site-specific engineering design study creates the knowledge and framework needed to help policymakers, regulators, elected officials, utilities and potential RNG facility developers more clearly understand the risks, costs and potential benefits of repurposing California biomass power plants into RNG producing facilities. The project team believes this will lead to accelerated investment in the development of RNG production facilities throughout California.

Figure 15 shows the system boundary for the LCA analysis of RNG production using gasification and methanation with end-use in transportation. The feedstock used in this facility consists of wood waste, agricultural waste, and forest waste. Once the feedstock is transported and treated, it is fed to a gasification reactor where it is thermochemically converted into syngas that mainly consists of H_2, CO, CO_2, and CH_4. The syngas goes through a cleanup process that involves catalytic chemical reactions. Cleaned syngas is then fed to a methanation reactor where pipeline quality RNG is generated. The CH_4 concentration in the RNG product is around 97% by volume. RNG is distributed to nearby end users where it is combusted. All upstream energy use and emissions associated with inputs such as natural gas, electricity, chemicals, and catalysts are considered.

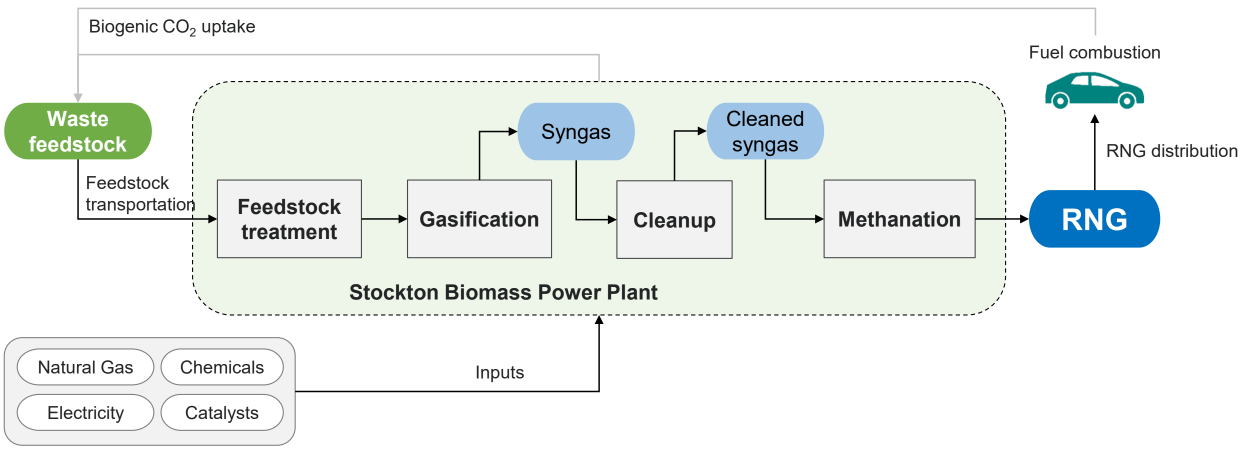

Figure 15. System Boundary of RNG Production Pathway via Gasification and Methanation that Covers from Feedstock Recovery to Fuel Combustion.

3.6.1. Summary of LCA Inputs and Assumptions

The feedstock materials available for conversion are waste streams, therefore this life-cycle assessment does not allocate upstream energy use and emissions for converting this waste to RNG. The feedstock are presumed to have no market demand or inherent value as mulch or other soil amendment. Absent this technology pathway, these feedstock would otherwise remain to decay in the orchard, forest, or in a landfill. However, for the purpose of this report, disposal fates for this feedstock were not considered.

Feedstock transportation and treatment are additional processes due to RNG production, so energy use and emissions associated with these processes are accounted for. The moisture content of the feedstock is estimated at 37%. Heavy-duty trucks with a payload of 20 tons are used to transport the feedstock 75 miles, and 146 wet grams of feedstock (before treatment) is used per one MJ of RNG produced (base case).

The feedstock is processed through crushing, screening, conveying, and drying, which requires electricity inputs. The processes reduce moisture content from 37% to 17%, and there is 5% of solid feedstock loss. For these processes, 44 kJ of electricity is used per one MJ of RNG produced. The treated feedstock has a lower heating value of 18.8 MJ/kg and a carbon content of 49.2 wt. %. Table 19 shows a summary of the inputs to the model.

Table 19. Summary of LCA Inputs for GREET (Base Case, per One MJ RNG)

Gasification			
Inputs	Feedstock	105	wet g
	Electricity	83.5	kJ
	Ni-based catalyst	7.6	mg
	Dolomite	1,199	mg
Outputs	Syngas	1.25	MJ
	Bottom ash	2.19	g
	Fly ash	3.81	g
Syngas cleanup			
Inputs	Syngas	1.25	MJ
	Electricity	58.8	kJ
	MDEA make-up rate	4.37	mg
	Activated Carbon	2.34	mg
	CoMo based catalyst	2.43	mg
	ZnO based catalyst	3.81	mg
Outputs	Cleaned syngas	1.19	MJ
RNG production			
Inputs	Cleaned syngas	1.19	MJ
	Electricity	0.34	kJ
	Ni based catalyst	1.15	mg
	Dryer (Silica Gel)	0.01	mg
	Dryer (SiloBead, Molecular Sieve)	0.414	mg
Outputs	RNG	1	MJ
	Electricity	85.9	kJ
Utilities and Chemicals			
Inputs	Electricity	24.7	kJ
	Natural gas	12.1	kJ
	Sodium hydroxide	44.1	mg
	Phosphate	6.36	mg
	Cortrol (O_2 scavenger)	0.24	mg
	Amine	0.24	mg
	Sulfuric acid	61.9	mg
	Non-oxidizing biocide	0.59	mg
	Sodium hypochlorite	26	mg
	Ammonium sulfate	57.5	mg

Figure 16 presents the life-cycle GHG emissions for RNG production pathways via GTI's gasification and methanation processes. The life-cycle GHG emissions of these pathways are compared with baseline fossil fuels. In the LCFS, the CIs of gasoline and diesel in 2018 are 93.55 and 96.91 gCO_2e/MJ (CARB, 2015[17]). The base case shows life cycle GHG emissions of 16.8 gCO_2e/MJ (0.16 $MtCO_2e/Mt$ of dry biomass) which is 82% lower compared to the CI of fossil-based gasoline. With carbon capture (Case 1), life-cycle GHG emissions become -60.6 gCO_2e/MJ, which shows a 165% reduction relative to the CI of fossil-based gasoline.

Life cycle GHG emissions of 16.8 gCO_2e/MJ (0.16 $MtCO_2e/Mt$ of dry biomass) which is 82% lower compared to the CI of fossil-based gasoline.

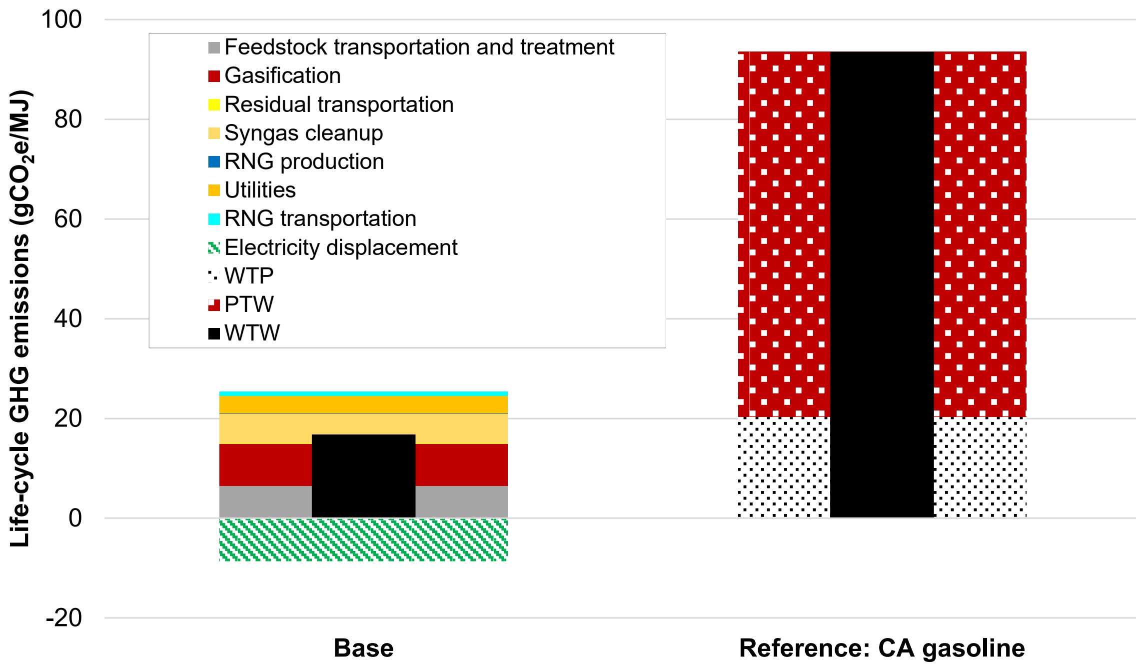

Figure 16. Life-cycle GHG Emissions for RNG Production Pathway via Gasification and Methanation Compared to Gasoline (gCO_2e/MJ of RNG Produced and Used)

Figure 17 shows the CI of the RNG base case from this study superimposed on CARB's volume-weighted average CIs of LCFS certified pathways by fuel type. The RNG result is shown only as an average and not proportional to volume of the fuel.

[17] *Low Carbon Fuel Standard.* https://www.arb.ca.gov/regact/2015/lcfs2015/lcfsfinalregorder.pdf

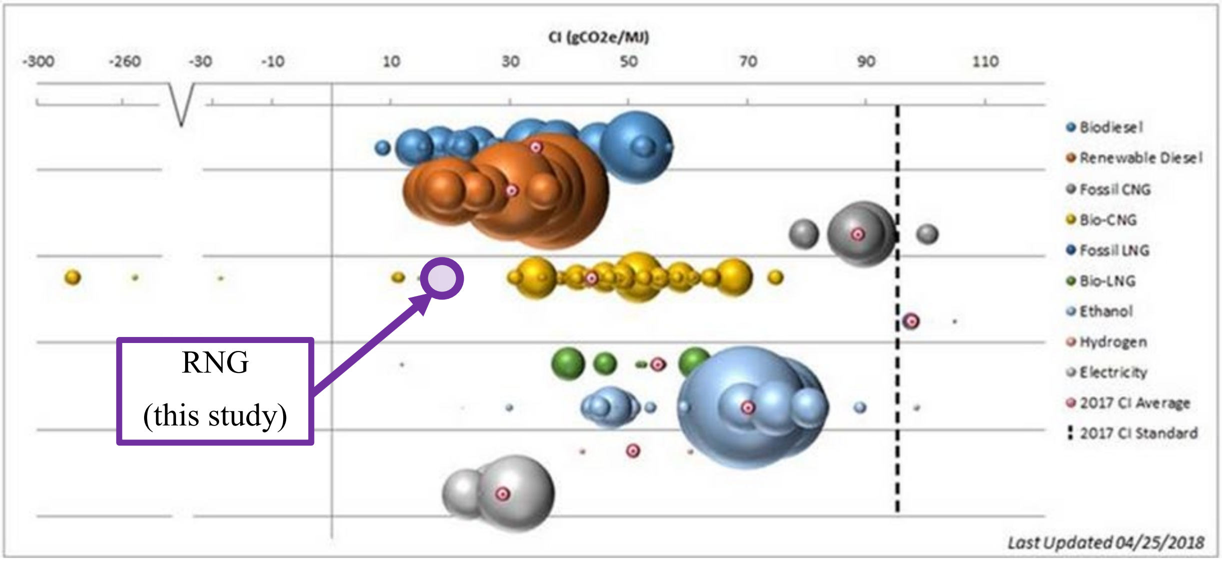

Figure 17. Carbon Intensity for RNG (this study) Compared to Certified Pathways by Fuel Type
(Source: CARB 2017. Current base case study result added as a purple circle to show the average, not volume-weighted)

Collecting and converting forest trimmings and slash would add the benefit of reducing the potential of these wastes and dead trees to become potentially polluting and dangerous wildfires that are common in the state of California. Up to 3% of annual U.S. GHG emissions come from wildfires[18]. The LCA does not take into account the utilization of forest waste that would otherwise contribute to wild forest fires.

In addition to the basic design for a gasification-based RNG plant, a case scenario was explored to compare the environmental impacts. Case scenario #1 looks into the opportunity to sequester the maximum CO_2 possible from the plant by transporting it via a hypothetical dedicated greenhouse gas pipeline to a carbon capture site. Other potential scenarios that could be explored relate to integration of power-to-gas into the RNG process. These cases are interesting because they explore the possibility to simultaneously eliminate the need for an air separation unit, maximize the RNG productivity, and further improve the emissions profile of the technology. A preliminary study showed the potential for significant reduction of the facility direct emissions from power-to-gas while increasing the RNG production rate and biomass carbon utilization.

3.6.2. Case Scenario 1

The goal in this case is to sequester the maximum amount of CO_2 possible. Not all of the CO_2 produced can be reasonably disposed of in this way. A portion of the CO_2 produced will continue to be required to be recycled for use for within the process (pressurizing lock-hoppers, to use in the reformer quenches, etc.). Approximately 16% of the total biogenic CO_2 produced, and will be part of the emission profile, as it would not be easily recovered. The remainder of the CO_2 would be cleanly separated from the product gas via acid-gas removal. A resulting concentrated stream

[18] https://www.forestfoundation.org/wildfires-and-climate-change

of CO_2 (approximately 84% of the CO_2 produced) would then be compressed and injected into a hypothetical GHG pipeline for processing in a carbon sequestration facility.

This case is interesting because it explores the possibility to improve the emission profile of the technology. In this case, in the form of sequestering carbon that originated from the atmosphere while producing RNG. The key assumption is that an additional compressor would be needed to pressurize the CO_2 in order to inject into a hypothetical GHG pipeline near the site.

Table 20. Life-cycle Carbon Intensities for Base Case plus an Alternative Case 1

Cases	Base†	Case 1†
Feedstock transportation and treatment	6.47	6.47
Gasification	8.43	8.43
Residual transportation	0.0850	0.0850
Syngas cleanup	5.99	5.99
RNG production	0.0418	0.0418
Miscellaneous¶	3.54	3.54
Electricity displacement¥	-8.60	-8.60
RNG transportation	0.856	0.856
Carbon capture	0	-77.4
Carbon Intensity (CI)	**16.8**	**-60.6**

* California GREET® 3.0 CI for base case = 17 gCO2e/MJ

¶ Miscellaneous include water treatment, sour water stripping, cooling water systems, thermal oxidizer, etc.

¥ There is co-produced electricity, which indirectly reduce GHG emissions by displacing CA electricity.

† CA electricity grid is used.

A more detailed assessment of agricultural waste from orchards (one of the wood waste feedstocks) might have led to further reductions of GHG emissions and lower CI numbers in the table above. In many cases these sources are currently being landfilled or burned and the avoided emissions from those activities were not considered in this assessment.

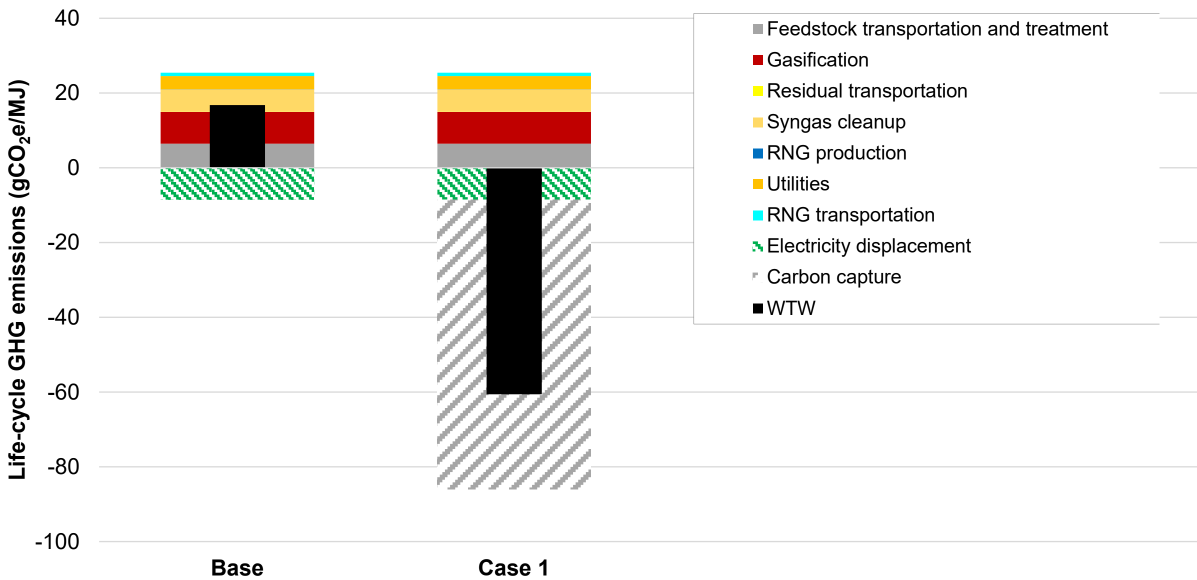

Figure 18. CIs Comparing both Cases

4. Discussion

The goal of this engineering design study was to provide critical information regarding the conversion of an existing wood waste-fed biomass power plant into an RNG producing facility utilizing thermal gasification and methanation. The project accomplished the goal by specifying equipment, developing a plant layout integrated with the host site, and estimating CAPEX and OPEX for a commercial facility producing nearly 3 BCF of RNG annually. The project relied on core technology components from Andritz and Haldor Topsoe, selected because of their commercial maturity at the scale of this project. The work also provided important analyses regarding the substantial reductions in environmental impacts, including carbon intensity of the RNG product.

The key insights were:

1. Conversion of existing biomass power plants to RNG production facilities will yield substantial environmental benefits to the state of California including:
    a. Production of a biomethane (RNG) with a very low or negative carbon intensity (depending on plant configuration) that can be injected into the natural gas pipeline
    b. Continued means for processing wood wastes in a responsible and very environmentally beneficial manner
    c. Means for a large quantity of forest wastes to be processed
    d. Opportunity to improve the environment of economically disadvantaged areas through the substantial reduction of criteria pollutants
2. Conversion of existing biomass power plants to RNG production facilities will yield substantial economic benefits:
    a. Continuation of economic value for urban, wood and agricultural wastes

   b. An increase in new jobs to staff RNG facilities, and protection of existing jobs in wood waste collection and delivery
   c. New economic opportunity to convert heavy-duty trucks that deliver wood wastes to RNG production facilities to RNG-fueled engines
3. CI of the gasification-based RNG product based on GREET 2017 analysis is very low
   a. CI of 16.8 gCO2e/MJ or 82% lower than fossil gasoline for the base plant
   b. CI of -60.6 (165% lower than fossil gasoline) is possible with carbon capture
4. Costs to convert a biomass facility to RNG production at the scale of this study are in the range of \$3400/kW ±30% (\$2400-4400/kW)
   a. The all-in capital cost estimate for this site (CAPEX ±30%) is \$340 MM
   b. Costs would likely be less at a site with all the best attributes
   c. The production cost for RNG from the designed plant would be \$13.80 per MMBtu, which is equivalent to 4.7 ¢/kWh. OPEX would be reduced with lower electricity and water costs (retail costs were used)

4.1. Efficient Use of Wood Waste Resources

One valuable attribute of the base case RNG plant described in this study is the relatively high conversion efficiency. Most of the energy within the wood waste is transferred to the RNG product. This is a much higher efficiency than existing biomass power plants where conversion efficiencies are usually between 25 to 35%.

Table 21. Conversion Efficiency of Base Case RNG Plant

Energy conversion	Unit	Values
Higher Heating Value of biomass (moisture and ash free basis)	Btu/lb	8,564
Heat content of biomass	MMBtu/hr	535
RNG Product	lbs/hr	15,621
HHV/LHV of product	Btu/lb	22,706/20,597
Heat content of net product (HHV/LHV)	MMBtu/hr	355/320
Net Power Import	MMBtu/hr	33

Conversion Efficiency (heat content of product-net energy import/heat content of biomass) = 60%

The study shows that the feedstock now producing 45 MW of electric power at the Stockton plant could produce 94 MW equivalent of RNG product.

4.2. Site-Specific Issues

GTI selected the Stockton Biomass Power Plant as the site for this engineering design study based on the centrality of the location with respect to the California-based utility members, the size of the plant, the mix of biomass resources it was using, and the cooperation of the site owner/operator, DTE Stockton, LLC. In addition, Stockton had established feedstock supply agreements, accessibility of transportation options for feedstock and supplies (roads, railway, and a maritime port), and adequately sized utilities and balance of plant to match the new construction. The engineering design study permitted a real-world scenario for the plant layout and associated economics. The site presented several constraints that added complications and costs to the current proposed plant. The main constraint is the very limited available site land area. Other limitations include non-contiguous site parcels, a long distance to a natural gas transmission pipeline for injection, and the need for demolition of the current ash handling equipment and instrument air package (among some other equipment).

The engineering design study at the Stockton site reinforced some attributes that the ideal site would have. These are:

- Additional space for flexibility to optimize the layout of new equipment
- Pipeline capacity that can easily absorb 3+ BCF of RNG annually
- On site water resources (i.e. water wells)
- A readily available supply of wood wastes

4.3. Economic Incentives

The engineering design study demonstrates that there is the potential to produce substantial amounts of a renewable substitute for natural gas with a very low or negative carbon intensity.

Currently, the transportation market is the most economically incentivized of all the uses of RNG in California. With incentives available through the LCFS and the Renewable Fuel Standard (RFS), the economics of producing and selling RNG into the California transportation market are favorable and help to drive new projects. With the penetration of RNG into the CNG vehicle market in California estimated to be as high as 91%, it is unclear if the LCFS incentives would be available to a large producer of RNG.

While increasing use of heavy-duty CNG vehicles is one way to ensure incentives would be available for a new and substantial influx of RNG, new policies and incentives for other end uses of RNG should be considered. The 2016 capacity-weighted average construction costs for solar photovoltaic power, according to the US EIA[19], was $2,436/kW. We estimate the first-of-a-kind gasification-based wood waste-to-RNG plant to cost in the range of $2400-4400/kW. If the economics for a large-scale RNG production facility are to attract developers or investors, incentives like those provided by the LCFS and RFS or some type of market signal that would encourage the use of RNG from wood wastes would be helpful.

California, currently has substantial incentives for other renewables like wind and solar. Policies and or incentives for RNG from gasification of wood wastes seem reasonable and in line with the climate goals of the state, considering

- reduction of criteria pollutants compared to existing biomass power plants,
- opportunity to process wood wastes that exacerbate forest fires and lead to open burning
- potential for significant RNG production volumes,

[19] U.S. Energy Information Administration, Form EIA-860, Electric Generator Construction Costs, August 2018.

- low carbon intensity of the RNG product, and
- production of an infrastructure-compatible, storable, renewable energy product.

Converting biomass power plants to RNG-producing facilities will provide substantial economic and environmental benefits to the residents of California.

5. Summary and Conclusions

Summary

California air quality continues to be exacerbated by black carbon and conventional air pollutants produced from the open burning of agricultural wastes and from forest fires. Expanding opportunities for the processing of agricultural, forest and urban wood wastes provides a means to reduce black carbon, which is one of the most potent climate change pollutants and to reduce conventional air pollutants that can lead to increased incidences of asthma and other breathing disorders. Additionally, with the continued closing of biomass power plants that processed wood wastes to produce electricity, there is now not enough facilities to process all the wood waste being produced. This situation has contributed to open burning of agricultural wastes in the San Joaquin valley and rampant forest fires throughout the state every year.

This project provides much needed design and engineering information to transform existing biomass power plants into RNG producing facilities. RNG production facilities for wood waste conversion will create a means to process these waste streams and virtually eliminate all criteria pollutants associated with existing biomass electricity production facilities. Additionally, an almost zero carbon replacement for natural gas will be produced, providing opportunities for carbon emission reductions in the transportation, business, and residential energy sectors. Increasing interest in decarbonizing the energy portfolio for the state of California and the incentives from the LCFS have sparked interest in exploring options to produce cleaner fuels for transportation and stationary power applications.

Recently, technologies have become commercially available that can turn wood waste into RNG. Repurposing biomass power plants with these technologies will eliminate almost all criteria air emissions and provide a concentrated CO_2 stream that can be utilized to create more RNG or other by-products. Such a facility would provide a closed loop production system with very low net emissions while creating a storable renewable energy product that can be used like natural gas, delivered through the pipeline, with a very small carbon footprint.

GTI led a team of engineers and scientists to produce an engineering design that provides a blueprint to transform an existing biomass power plant into an RNG producing facility utilizing some of the existing infrastructure and all the wood waste feedstock. The DTE biomass power plant in Stockton was the host site for the engineering design. The design study quantified the ability to produce large amounts of high quality, low carbon RNG for use in all energy sectors. Products of the study are:

- A resource analysis, site layout, and operations status for the Stockton, CA biomass-to-power facility
- An RNG process and preliminary layout specific to the Stockton Biomass Power Plant site
- A complete set of RNG PFDs including the required auxiliary systems
- Specifications for the major equipment
- Estimated electrical loads and an electrical load list for all new equipment
- A preliminary layout of major vessels and equipment and a set of preliminary general arrangement drawings

- Mass and energy balances based on the GTI gasification simulation model , addressing input parameters such as temperature, pressure, fluidized bed material, velocities, residence time, char recycle, and feedstock properties
- Mass and energy balances for the gas cleanup and methanation stages of the process
- A cost estimate for the engineering, procurement, installation, and integration of the new equipment needed for RNG production
- An estimate for the cost of producing RNG, including a sensitivity analysis.
- A standalone compilation of the project scope, engineering documents, costs estimates, execution approach, and schedule
- An LCA to evaluate the environmental impacts of the gasification pathway to produce RNG based on the engineering study at the Stockton site

The engineering design study documented costs and issues surrounding the conversion of an existing biomass power plant into an RNG producing facility utilizing the technologies highlighted. The deployment of the RNG process provides substantial environmental benefits, reducing criteria pollutants by approximately 99% and producing a very low carbon fuel in the base case and below zero in a case utilizing carbon capture. The study confirms the value of RNG produced from wood wastes in a low-carbon future from both a product standpoint and the opportunity to reduce the potential for forest fires and open burning of agricultural wastes in the San Joaquin Valley and other areas in California.

Figure 19 shows an aerial view of the current DTE site in Stockton, CA; and the proposed locations of the new process islands.

Figure 19. Layout of the New Process Islands and Biomass Drying/Storage

A site assessment determined that the Stockton site had many favorable characteristics for an RNG production facility conversion. The site is strategically located with direct access to major highways, train, and waterways. Many of the existing balance of plant utility systems are adequately sized for the new RNG plant requirements. The facility is well-maintained and all equipment is in good condition. There are some noteworthy limitations of the site, which need to be considered in the future when the determination of the actual location of a commercial plant is made. While connection to the existing natural gas pipeline adjacent to the site would be easy, currently, it cannot adequately handle the additional production from the site, which necessitates a dedicated RNG pipeline from the plant to the main high-pressure line miles away. Space constraint at Stockton site requires demolition of some existing equipment to accommodate new equipment. Revenue losses during construction associated with the long-term power purchase agreement at Stockton may be unfavorable compared with an idled plant. The value of integration of the RNG process technologies into an existing facility was constrained by specific attributes of the site itself. The learnings from this study will help identify the most advantageous sites in California and throughout the United States and world for conversion from biomass power to RNG production.

A conceptual design basis was developed for site-specific and discipline specific engineering design criteria. Scopes for each project contributor were defined and included Andritz providing the Gasification Process Island, HTAS providing the Syngas Cleaning and the Methanation Process Island and B&V providing specifications for the new balance of plant for integration of the process islands with the existing equipment. As part of engineering deliverables, process flow diagrams, material balance table, and equipment lists were defined across nineteen unit operations. The site plan determined the ASU, Gasification Process Island, and Wastewater Treatment will be located in place of the existing power block. The Syngas Cleaning and Methanation Process Island will be sited on the vacant South Lot. The West Fuel Pile will be demolished and replaced with new biomass feedstock drying and sizing equipment.

Electrical capacity at the site was determined to be sufficient for the new plant requirement. The existing PLC will be reused but an expansion of the existing control system to accommodate new I/O and new control systems will be required. The overall gross electrical load is expected to be a maximum of 27 MW. The gross normal load of the facility is 18.1 MW. The net power import for the normal operating condition is approximately 9,974 kW or 10 MW.

A preliminary execution schedule was developed and indicated about 44 months would be required from project start to commercial operating date. The capital cost for installed equipment at the Stockton site was estimated as \$315MM ± 30% including contingencies.

Table 22. Summary of CAPEX, Stockton Site-specific RNG Study

Subtotal Direct and Indirect	$ 138,140,000
Contractor Contingency (10%)	$ 13,810,000
Contractor EPC Fee	$ 11,510,000
Balance of Plant Total Cost	$ 163,460,000
Gasification Process Island	$ 87,500,000
Gas Cleanup and Methanation Process Island	$ 63,840,000
TOTAL COST*	$ 314,800,000

*Detailed information of the cost can be found on page M-1 Appendix 9 (not included in this version of the report)

The cost of operation, OPEX, was determined as the other input to the overall financial performance of the project. The project was 100% cash-financed. A straightforward, real dollar, levelized cost approach was used. Key sensitivities impacting the operation costs were modeled.

The cost analysis was not done to develop an investment prospectus, given the many variables that would require. Nor explored were various possible project financing approaches, sensitivities to financial terms, and the effect of potential financial incentives.

The OPEX included the levelized cost of the project (including commissioning and startup), cost of feedstock, consumables, power requirements, workforce, management, and maintenance. The economic and pricing assumptions are detailed in the body of the report and are shown again below and on the next page.

The raw operating costs were estimated to be in the range $13-15 per MMBtu of RNG as shown as the total OPEX bar below (third bar from the right).

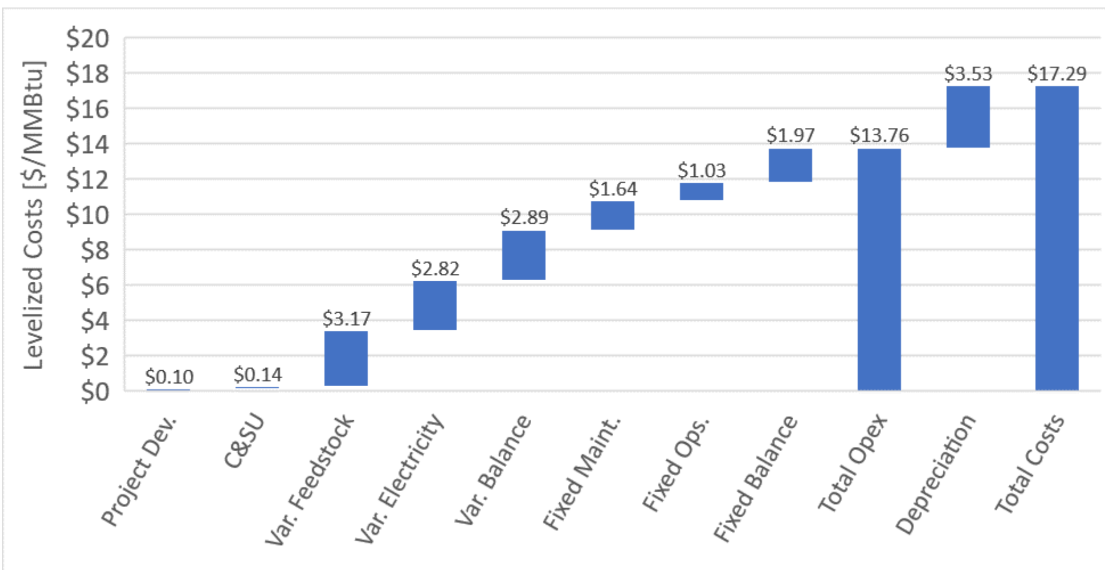

Figure 20. Levelized Cost Profile of the RNG Project.

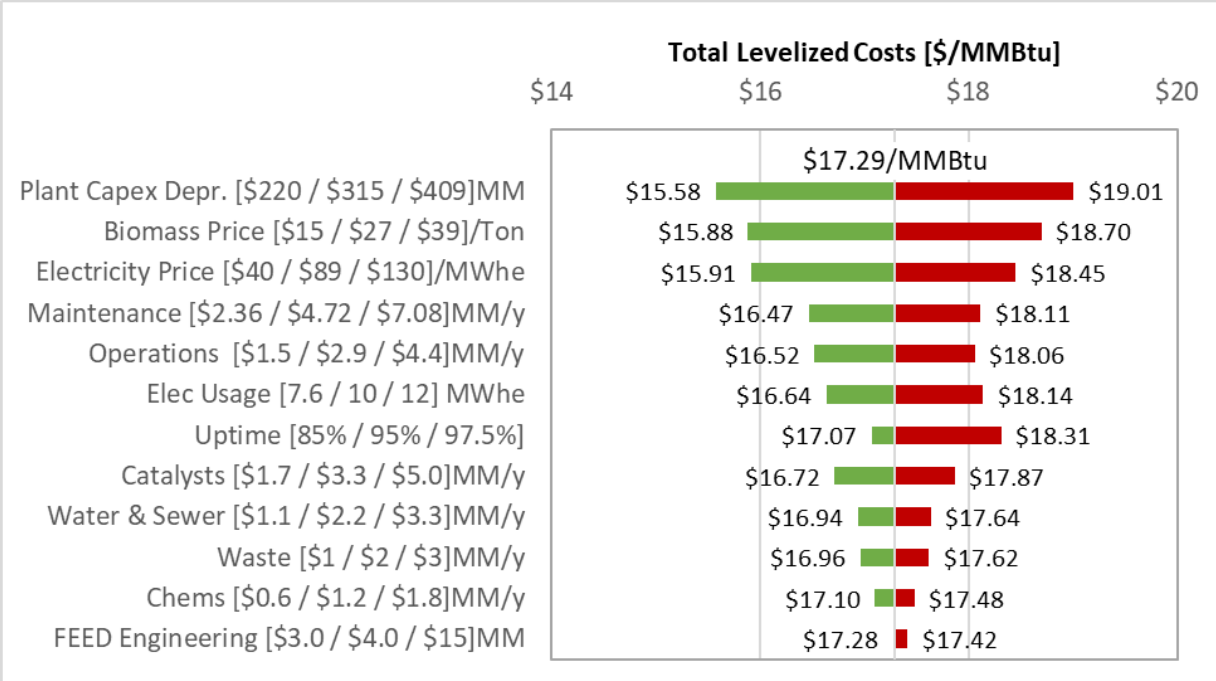

Figure 21. Total Levelized OPEX Sensitivities

The alternative case scenario developed:

- Case 1 - the possibility of modifying the base design to inject a concentrated stream of CO_2 into a carbon capture pipeline or geologic formation.

The purpose of this Case 1 was to determine what would be the maximum environmental benefit of the process. The effect of Case 1 is strictly on the carbon intensity, since the modifications would be minimal, only affecting a single stream which is already relatively clean, and it will not require a large enough relative increase in equipment or operating cost to be measurable.

Table 23. Plant's RNG Production Capacity, Both Cases

Case*	Plant Capacity MMm^3/yr (BCF/yr)
Base Case	82 (2.9)
Case 1 – Carbon Sequestration	82 (2.9)

* Biomass plant input (tons/yr) 310,000 (17% moisture)

A WTW LCA analysis based on Argonne National Laboratory's GREET® model, which is the tool used for LCFS calculations in California, showed that the base case engineering design has a CI of approximately 16.8 gCO_2e/MJ. To put in perspective, the gasoline CI for 2018 was estimated to be over 93 gCO_2e/MJ.

Table 24. RNG Plant CI (Base Case) and Emission Profile

GREET® Life cycle carbon intensity, gCO_2e/MJ	16.8*
PM, g/MJ (lb/MMBtu)	0 (0)
VOC, g/MJ (lb/MMBtu)	0.002 (0.005)
SO_2, g/MJ (lb/MMBtu)	0.0001 (0.0003)
NOx, g/MJ (lb/MMBtu)	0.0009 (0.002)

*California GREET® 3.0 CI for base case = 17 gCO_2e/MJ

The LCA case for carbon capture (Case 1) resulted in a carbon intensity of -60.6 gCO_2e/MJ. In the sequestration scenario, not all of the CO_2 can be captured, as it was discovered that some of it is still required to be recycled back to support the operation of the feedstock train.

Conclusions

The state of California needs facilities that can dramatically reduce GHG emissions and black carbon production by cleanly using forest, agricultural and urban wood wastes to produce large quantities of a very low-carbon fuel. The closing of biomass power plants is leading to open burning of agricultural wastes and uncollected forest wastes, not to mention the fire hazards of dead and dying trees, which is leading to devastating results. Proper forest management will create additional wastes that need to be effectively processed to mitigate emissions and risks from uncontrolled and rampant wildfires.

Material quantities in the tens of billions of cubic feet per year of RNG can be produced using commercially available technologies.

RNG is a low-carbon fuel that can be used in transportation, industrial, commercial, and residential sectors of the economy. Material quantities in the tens of billions of cubic feet per year of RNG can be produced using commercially available technologies from the wastes that are now producing biomass-based electricity in California. This site-specific engineering design project has rigorously documented how conversion of one such biomass power plant would supply nearly 3 BCF/yr of RNG. In fact, an RNG facility gasifying wood wastes with the technologies in this study would produce more than twice the energy output of an electric power plant with the same feedstock consumption, while emitting 99% less criteria pollutants. Furthermore, the RNG pathway based on this analysis (16.8 gCO2e/MJ, or 17.0 in CA-GREET 3.0) would have a lower carbon intensity than most other transportation fuel pathways now certified in the California Low Carbon Fuel Standard.

Our preliminary assessment indicates a negative carbon intensity with the deployment of carbon sequestration.

This project has reinforced the environmental value of RNG production from wood wastes. We have determined the economics of production for a plant gasifying 945 tons/day of wood wastes with commercial process technologies at a specific site in Stockton, CA. The capital required to build a plant of the capacity to produce about 3 BCF/yr of RNG at that site is $340 million ±30%. Excluding capital costs, the production cost for RNG is in the range of $13-15/MMBtu.

6. Recommendations

The substantial value and environmental benefits of RNG produced from wood wastes is clear. These benefits can positively impact the timeline and cost of reaching critical GHG and criteria air emission goals for California and other parts of the country. Because of these substantial environmental benefits, incentives and policies should be developed to improve the potential for construction of these facilities.

The engineering design study performed by the project team provided information critical to transforming an existing biomass power plant into an RNG production facility. This engineering design study has confirmed the substantial environmental benefits regarding the application of gasification-based RNG production. The engineering design pointed to the opportunity to produce a renewable natural gas substitute with a very low carbon intensity.

The cost of electricity, and the CO_2 footprint of the current grid in California, has a large effect on both the economics and the carbon intensity of the RNG being produced. A low-carbon fuel production facility could benefit from surplus or low-cost, renewable electricity (sometimes shed from the grid). This surplus has often been written about, but a process to purchase surplus renewable electricity has still not been developed. Creating a means to capture that potential value for a wood waste to RNG production facility could improve fuel production economics and take a very low carbon RNG into the carbon neutral realm.

Next steps in the RNG project development would be the use of site-specific learnings from this FEL-2 study to assess alternative sites for their potential to host an RNG project. Then an FEL-3 level of design effort will be needed to produce a more refined and detailed process layout and plant integration plan. This level of engineering would yield a ±10% accuracy on CAPEX. In addition, the present assumptions for OPEX factors would be replaced through analyses that are more detailed. For example, all of the currently proposed energy inputs, excluding flare or oxidizer fuel, consist of grid power at retail rates. It should be possible to diversify the input energy blend to the plant and secure lower utility rates to improve costs, efficiency, and carbon intensity. Self-generation of electricity could also be explored as a further aspect of an optimized power strategy. Power-to-gas scenarios are also worth further exploring, as preliminary assessments have shown the potential for synergies that allow the elimination of some of the hardware, nearly doubling the gas production, and reducing the carbon intensity significantly when the power is renewably sourced. We solicit guidance from our project sponsors on these matters.

The substantial value and environmental benefits of RNG produced from wood wastes is clear. These benefits can positively impact the timeline and cost of reaching critical GHG and criteria air emission goals for California and other parts of the country. Incentives and policies should be developed to improve the potential for construction of these facilities.

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8. List of Inventions Reported and Copyrighted Materials Produced

None

9. Glossary of Terms, Abbreviations, and Symbols

ºC	Degrees Celsius
ºF	Degrees Fahrenheit
AF	As Fed Basis
AGR	Acid Gas Removal
ANL	Argonne National Laboratory
AQCS	Air Quality Control System
AR	As Received Basis
ASU	Air Separation Unit
BFW	Boiler Feed Water
BoP	Balance of Plant
BCF or BSCF	Billion Standard Cubic Feet
B&V	Black and Veatch
BWR	Boiling Water Reactor
$CaCO_3$	Calcium Carbonate
CA Blend	Power source blend in the state of California
CAPEX	Capital Expenditure
CARB	California Air Resources Board
CH_4	Methane
CI	Carbon Intensity
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CO_{2e}	Carbon Dioxide Equivalent
CoMo	Cobalt Molybdenum (catalyst)
COS	Carbonyl Sulfide
C&SU	Commissioning and Start-up
daf	Dry As Fed Basis
DB	Dry Basis
DC	Direct Current

Demin	Demineralized Water
DevCo	Development Company. A company managing the necessary aspects of project development, including project financing, commercial arrangements, marketing, permitting, contracting, staffing.
DTE	DTE Energy Stockton
EBITDA	Earnings Before Interest, Taxes, Depreciation and Amortization
EER	Energy Economy Ratio
FEED	Front-end Engineering Design
FEL	Front-end Loading
ft	Feet
ft^3	Cubic Feet
gCO_2e	Grams of CO_2 Greenhouse Gas Emission Equivalent
gge	Gallon of Gasoline Equivalent
GHG	Greenhouse Gas
gpm	Gallons per Minute
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Transportation
GTI	Gas Technology Institute
H_2	Hydrogen
H_2S	Hydrogen Sulfide
HAZOP	Hazard and Operability Study
HHV	High Heating Value
HMI	Human Machine Interfaces
hp	Horse Power
HP	High Pressure
hr	Hour
HTAS	Haldor Topsoe A / S
I/O	Input / Output
kg	Kilogram
Kgal	Hilogallon
km	Kilometer
kPa	Kilopascal Absolute

kPag	Kilopascal Gauge
kV	Kilovolt
kW	Kilowatt
lb	Pound
LCA	Life-Cycle Analysis
LCFS	Low Carbon Fuel Standard
LHV	Lower Heating Value
LP	Low Pressure
lpm	Liter per Minute
LV	Low Voltage
m	Meter
MCC	Motor Control Center
MDEA	Mono Diethanol Amine
mg	Milligram
MgCO3	Magnesium Carbonate
MJ	Mega Joule
mm	Millimeter
MMBtu	Million British Thermal Unit
MMSCFD	Million Standard Cubic Feet per Day
MMSCMD	Million Standard Cubic Meter per Day
MV	Medium Voltage
MVA	Megavolt Ampere
MW	Megawatt
MWhe	Megawatt Hour Electrical
NEC	National Electric Code
NFPA	National Fire Protection Agency
NG	Natural Gas
Ni	Nickel (catalyst)
NOx	Nitrogen Oxides
O_2	Oxygen
O&M	Operations and Maintenance

OPEX	Operating Expenditure
P&ID	Process and Instrumentation Diagram
PDG	Power Distribution Building
PEM	Proton Exchange Membrane
PFD	Process Flow Diagram
PG&E	Pacific Gas and Electric
PLC	Programmable Logic Control
PM	Particulate Matter
PPA	Power Purchase Agreement
ppm	Parts per million
psia	Pound per Square Inch Absolute
psig	Pound per Square Inch Gauge
RFS	Renewable Fuel Standards
RIN	Renewable Identification Number
RNG	Renewable Natural Gas
RO	Reverse Osmosis
SCFD	Standard Cubic Feet per Day
SCFM	Standard Cubic Feet per Minute
SCMD	Standard Cubic Meters per Day
Sm^3	Standard Cubic Meter
SMUD	Sacramento Municipal Utility District
SoCalGas	Southern California Gas Company
SO_2	Sulfur Dioxide
tph	Tons per Hour
UPS	Uninterruptable Power System
US	United States of America
VAC	Alternating Current Voltage
VOCs	Volatile Organic Compounds
WTW	Wells to Wheels, usually referring to life cycle carbon intensity
ZnO	Zinc Oxide (catalyst)

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