CALIFORNIA ENERGY COMMISSION

CALIFORNIA NATURAL RESOURCES AGENCY

Clean Transportation Program

FINAL PROJECT REPORT

Thermochemical Conversion of Forest Biomass into Biomethane Transportation Fuel

Prepared for: California Energy Commission

Prepared by: G4 Insights, Inc.

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California Energy Commission

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PREFACE

Assembly Bill 118 (Núñez, Chapter 750, Statutes of 2007) created the Clean Transportation Program. The statute authorizes the California Energy Commission (CEC) to develop and deploy alternative and renewable fuels and advanced transportation technologies to help attain the state's climate change policies. Assembly Bill 8 (Perea, Chapter 401, Statutes of 2013) reauthorizes the Clean Transportation Program through January 1, 2024, and specifies that the CEC allocate up to $20 million per year (or up to 20 percent of each fiscal year's funds) in funding for hydrogen station development until at least 100 stations are operational.

The Clean Transportation Program has an annual budget of about $100 million and provides financial support for projects that:

- Reduce California's use and dependence on petroleum transportation fuels and increase the use of alternative and renewable fuels and advanced vehicle technologies.
- Produce sustainable alternative and renewable low-carbon fuels in California.
- Expand alternative fueling infrastructure and fueling stations.
- Improve the efficiency, performance and market viability of alternative light-, medium-, and heavy-duty vehicle technologies.
- Retrofit medium- and heavy-duty on-road and nonroad vehicle fleets to alternative technologies or fuel use.
- Expand the alternative fueling infrastructure available to existing fleets, public transit, and transportation corridors.
- Establish workforce-training programs and conduct public outreach on the benefits of alternative transportation fuels and vehicle technologies.

To be eligible for funding under the Clean Transportation Program, a project must be consistent with the CEC's annual Clean Transportation Program Investment Plan Update. The CEC issued PON-09-604 to provide funding opportunities for the development of new, California-based biofuel production plants and to enhance the operation of existing ethanol production plants to increase statewide biofuel production and reduce greenhouse gas emissions. In response to PON-09-604, the recipient submitted an application that was proposed for funding in the CEC's notice of proposed awards on August 12, 2010. The agreement was executed as ARV-10-023 on April 14, 2011 in the amount of $1,229,966.

ABSTRACT

The purpose of this project was to advance technology for producing an ultra-low-carbon fuel from California-based renewable biomass. Currently, no large-scale commercial technology is available to generate low carbon fuels from forest woody biomass. G4 Insights, Inc. advanced its pyrocatalytic hydrogenation process, a proprietary technology for low temperature thermochemical conversion of forestry residue into high quality biomethane, or renewable natural gas. The G4 Insights, Inc. process uses fast pyrolysis rather than gasification of the biomass to generate a vapor from the solid phase. This enables a low temperature pyrocatalytic hydrogenation process.

The goal of this agreement was to design and demonstrate a pilot scale pyrocatalytic hydrogenation production unit that converts California wood waste into transportation grade renewable natural gas.

G4 Insights, Inc. designed and constructed a demonstration test unit. The project used woody biomass collected from California forest trimmings during fuels management operations to successfully produce low carbon, renewable natural gas using forest biomass waste. Placer County used the fuel in a natural gas fleet vehicle.

Keywords: woody biomass, waste wood, forest biomass, pyrolysis, thermochemical, pyrocatalytic hydrogenation, biomethane, renewable natural gas, compressed natural gas, wildfire.

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Project Purpose

G4 Insights, Inc's goal for this project is to advance the thermochemical conversion technology for producing an ultra-low-carbon fuel from renewable forest biomass. California forests have been damaged by a series of droughts and bark beetle infestations, which have killed millions of conifer trees and substantially increased fire risk during the summer and fall months. Forest management policies to reduce the fire risk could include large-scale removal of woody biomass from California forests. Currently, no large-scale commercial technology is available to convert woody biomass wastes into useful energy products, such as renewable natural gas. The technology being advanced is the pyrocatalytic hydrogenation process, a proprietary technology for low temperature thermochemical conversion of forestry residues into high quality biomethane, or natural gas. The proprietary process uses fast pyrolysis rather than gasification of the biomass to generate a vapor from the solid phase. This fundamental difference enables a low temperature pyrocatalytic hydrogenation process.

The thermochemical conversion process offers a promising, cost-effective technology for converting large volumes of forest biomass into low carbon biofuel. If successful at commercial scale, the technology could provide significant economic benefits in rural forest communities, commonly areas of high unemployment.

Widespread implementation could divert a large fraction of the wood waste generated from forest restoration and forest fuel reduction projects, helping to offset project costs while lowering fire risk, and producing enough biomethane to displace significant volumes of fossil fuel in the state.

Project Approach

G4 Insights, Inc's approach to advancing the conversion technology is to develop and demonstrate the pyrocatalytic hydrogenation process demonstration test unit in a real world field setting. Additional phases of the project include:

- Develop a biomass testing facility to test various tree species and types of biomass for their feedstock suitability;
- Conduct performance tests on a benchtop unit to evaluate enhanced conversion characteristics;
- Demonstrate fuel quality and viability by using the renewable natural gas to fuel a Placer County compressed natural gas vehicle;
- Conduct a pilot plant techno-economic feasibility study;
- Prepare a California-focused siting and feasibility study to assess technology viability and commercial-scale economics; and
- Identify the regulatory, technology and economic challenges to injecting the transportation-grade biomethane into the natural gas pipeline grid in California.

Results

G4 Insights, Inc. successfully completed all project phases as defined in the grant scope of work. G4 Insights, Inc. designed and fabricated the demonstration test unit to test and evaluate the pyrocatalytic hydrogenation process. The initial design and fabrication of the trailer-mounted demonstration test unit proceeded as planned and was completed in November 2013. However, the commissioning phase required nearly a full year and was not completed until October 2014. G4 Insights, Inc. needed this extra time for process tuning and design adjustments. The demonstration test unit was shipped to Placer County in April 2015 and began test operations.

G4 Insights, Inc. began processing batches of waste wood in the demonstration test unit. The proprietary technology using low temperature fast pyrolysis successfully converted waste wood to gas, but the purification unit could not achieve the desired purity levels for transportation grade biomass.

Figure ES-1: Demonstration Test Unit Onsite in Placer County

Source: G4 Insights, Inc.

G4 Insights, Inc. continued to operate the demonstration test unit in the Placer County facility with the support of the Placer County Maintenance group. This work was completed between May to September 2015. Further alterations to the purging sequences decreased the nitrogen content of the manufactured gas. This allowed the existing purification equipment to increase the purity of the fuel gas. Further batches were performed with the system producing fuel gas at a purity level of 75 to 85 percent methane. This gas was then routed to the on board fuel reservoir. In June 2015, G4 Insights, Inc. fueled a county vehicle with gas produced from Californian forest thinning for the first time.

Ongoing operations in August and September resulted in additional fuel being produced. The fuel was generated by the demonstration test unit in the 80 to 97 percent purity level. The gas mixture was hydrogen and methane, which can be run unmodified in a compressed natural gas vehicle.

Environmental Benefits

The pyrocatalytic hydrogenation process carbon intensity for a compressed natural gas fuel application is 14.4 grams of carbon dioxide per mega joule. This is far below the diesel baseline of 95 grams of carbon dioxide per megajoule of energy. and is one of the lowest carbon intensity values of all pathways shown in the Low Carbon Fuel Standard Look-Up Table.[1] It is also 8 points lower than the other pathway for forest residues, cellulosic ethanol. For example:

- California Diesel = 95 grams of carbon dioxide per mega joule
- Compressed Natural Gas = 75 grams of carbon dioxide per mega joule
- Compressed Natural Gas From Dairy Digester Biogas = 15 grams of carbon dioxide per mega joule
- Cellulosic Ethanol From Forest Residues = 22 grams of carbon dioxide per mega joule

The conversion of waste wood to renewable compressed natural gas can benefit California with a substantial reduction in carbon dioxide. A state total estimate of 10 small and one large pyrocatalytic hydrogenation process plants translates into roughly 1,000 bone dry tons/day of wood demand for 330 days per year. Using this fuel as renewable natural gas to displace gasoline usage could lead to a reduction of over 350,000 tons carbon dioxide per year.

G4 Insights, Inc. identified three potential end uses for its renewable natural gas product; as transportation-grade fuel, as replacement gas for petroleum refinery operations, or as replacement gas for combined cycle natural gas plants.

California Commercial Plant Siting and Business Feasibility

Locating a commercial-scale biomethane facility in an area of high wildfire danger is desirable because of the need for fuel reduction forest management and the continual availability of sustainably harvested feedstock. Spatial analysis of CalFire high priority landscapes for wildfire hazard management overlain with natural gas transmission lines of the 3 major utilities, PG&E, Southern California Gas, and San Diego Gas & Electric, shows three areas with potential siting

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[1] ARB's carbon intensity "Look Up Tables" were used from 2009 to 2016: https://ww3.arb.ca.gov/fuels/lcfs/fuelpathways/method1lookuptable.htm

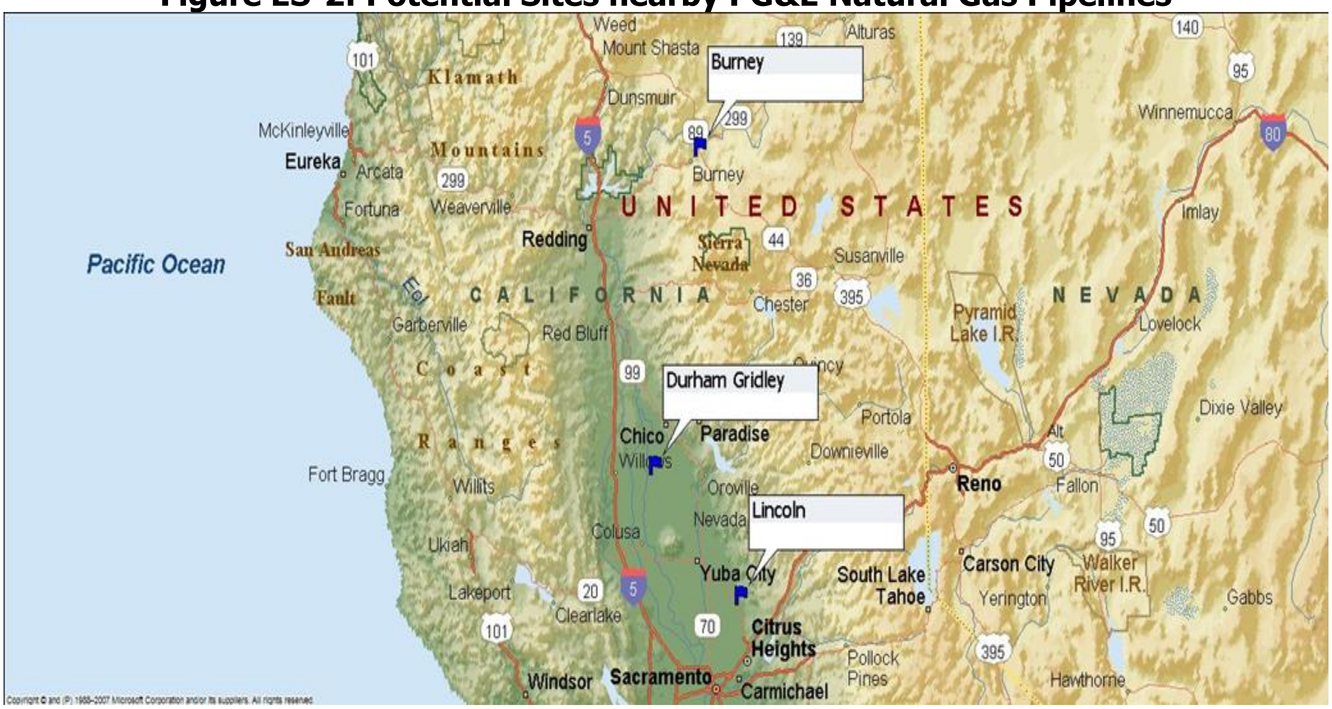
Please note that many carbon intensity values have changed substantially since the original Look Up Tables were developed.

opportunities; surrounding the Los Angeles and San Diego basins, the Sierra Range, and the Northern Sierras and Klamath Range.

G4 Insights, Inc's interest in siting a large-scale facility utilizing 750 bone dry tons per day is constrained to a location with a significant sustainable woody biomass supply. The five-year average for timber harvest volumes in California for the period 2006 through 2010 is 1.3 million board-feet. Applying the biomass recovery factors of 0.9 bone dry tons/million board-feet to 2.8 bone dry tons/million board-feet would yield a range of 1.2 to 3.7 million bone dry tons per year for the entire state of California. A facility sized for 273,000 bone dry ton/year would consume between 7 and 23 percent of the entire state's potential production. Only the Northern Sierra and Klamath Range were deemed suitable for delivery of such large volumes of feedstock.

Analysis indicated that the location at Burney, situated between the Northern Sierra and Klamath Range and on a major PG&E natural gas transmission line, offered the best potential combination of volume from forest operations and delivered pricing. Currently, the location at Burney would encounter competition for this feedstock source from a number of existing biomass utilization enterprises, including cogeneration facilities.

Figure ES-2: Potential Sites nearby PG&E Natural Gas Pipelines



Source: G4 Insights, Inc.

Additional research into the pyrocatalytic hydrogenation technology, project economics and project siting are needed for G4's conversion technology of woody biomass to transportation grade renewable natural gas to become commercially viable.

CHAPTER 1: Project Introduction

Project Purpose

The goal for the G4 Insights, Inc. (G4) project is to advance the thermochemical conversion technology for producing an Ultra-Low-Carbon fuel from renewable biomass. California forests have been damaged by a series of droughts and bark beetle infestations, which have killed millions of conifer trees and substantially increased fire risk during the summer and fall months. Forest management policies to reduce the fire risk could include large-scale removal of woody biomass from California forests. Currently, no large-scale commercial technology is available to convert woody biomass wastes into useful energy products, such as renewable natural gas. The technology being advanced is the G4 pyrocatalytic hydrogenation (PCH) process, a proprietary technology for low temperature thermochemical conversion of forestry residues into high quality biomethane.

The goal of this agreement is to design and demonstrate a G4 PCH production unit that converts woody biomass waste into transportation grade compressed natural gas (CNG).

Project Approach

G4's approach to advancing the conversion technology is to develop and demonstrate the PCH demonstration test unit (DTU) in a real world field setting. Additional phases of the project include:

- Develop a biomass testing facility to test various tree species and types of biomass for their feedstock suitability;
- Conduct performance tests on a benchtop unit to evaluate enhanced conversion characteristics;
- Demonstrate fuel quality and viability by using the renewable natural gas to fuel a Placer County CNG vehicle;
- Conduct a pilot plant techno-economic feasibility study;
- Prepare a California-focused siting and feasibility study to assess technology viability and commercial-scale economics; and
- Identify the regulatory, technology and economic challenges to injecting the transportation-grade biomethane into the natural gas pipeline grid in California.

The project will include a technical and environmental feasibility study for a renewable natural gas pilot plant. This will be done to ensure that the planning, design, and operation of any G4 PCH conversion facility will conform to all environmental and technical regulations in California.

G4 will also investigate the feasibility of future pilot and commercial scale renewable natural gas fuel production in California. This will focus on finding the best site locations for combining collection of wood waste, building a conversion facility, and delivering Ultra-Low-Carbon CNG to end users.

CHAPTER 2: Project Activities

Design and Construction of the Demonstration Test Unit

Prior to design and fabrication, G4 collected and approved the following baseline information, which generated the landscape for the design of the equipment.

The Conditions at a site to be determined in Placer County are expected to fall within the range of selected average site design conditions shown in Table 1.

Table 1: Average Site Design Conditions

Parameter	Units	Low	Average	High
Elevation*	Meters	300	374	420
High Temperature	Centigrade	12.4	22.2	33.2
Low Temperature	Centigrade	3.1	9.7	17.6
Air Pressure	Kilopascals	82.8	101.1	101.3
Relative Humidity	Percentage	61.5	82.2	90.0
Wind speed	Kilometers per hour	13.3	28.3	46.4
Rainfall	inch/year		43.7	
Snow load	Pounds Per Square Foot			20
Voltage	Volts		240	
Frequency	Hertz			
Phase			Single	
Power	Kilowatts		54	
Current	Amperes		225	

***Elevation relative to sea level = 0 m**

Source: G4 Insights, Inc.

The target process requirements were confirmed, as shown in Table 2.

Table 2: Process Target Requirements

Description	Quantity	Units	Comment
Wood Mass	50-70	Pounds	Per batch
Methane Produced	10-20	Pounds	Unpurified
Methane Purified	10	Pounds	Per batch
Hydrogen Consumed	5-8	Pounds	Per Batch
CNG Pressure	2500-3000	Pounds Per Square Inch	Into vehicle
Wood Quality	5-50	Mesh	Screen sizing
Wood Quality	10-40	Percentage by weight	Moisture content

Source: G4 Insights, Inc.

The following Codes and Standards were adopted in their entirety and were followed for the design, fabrication, inspection, testing, and operation of the DTU. Where two or more codes, standards, or regulations conflict the most conservative requirement, as judged by the subject matter expert or appropriate inspection agency, shall be implemented.

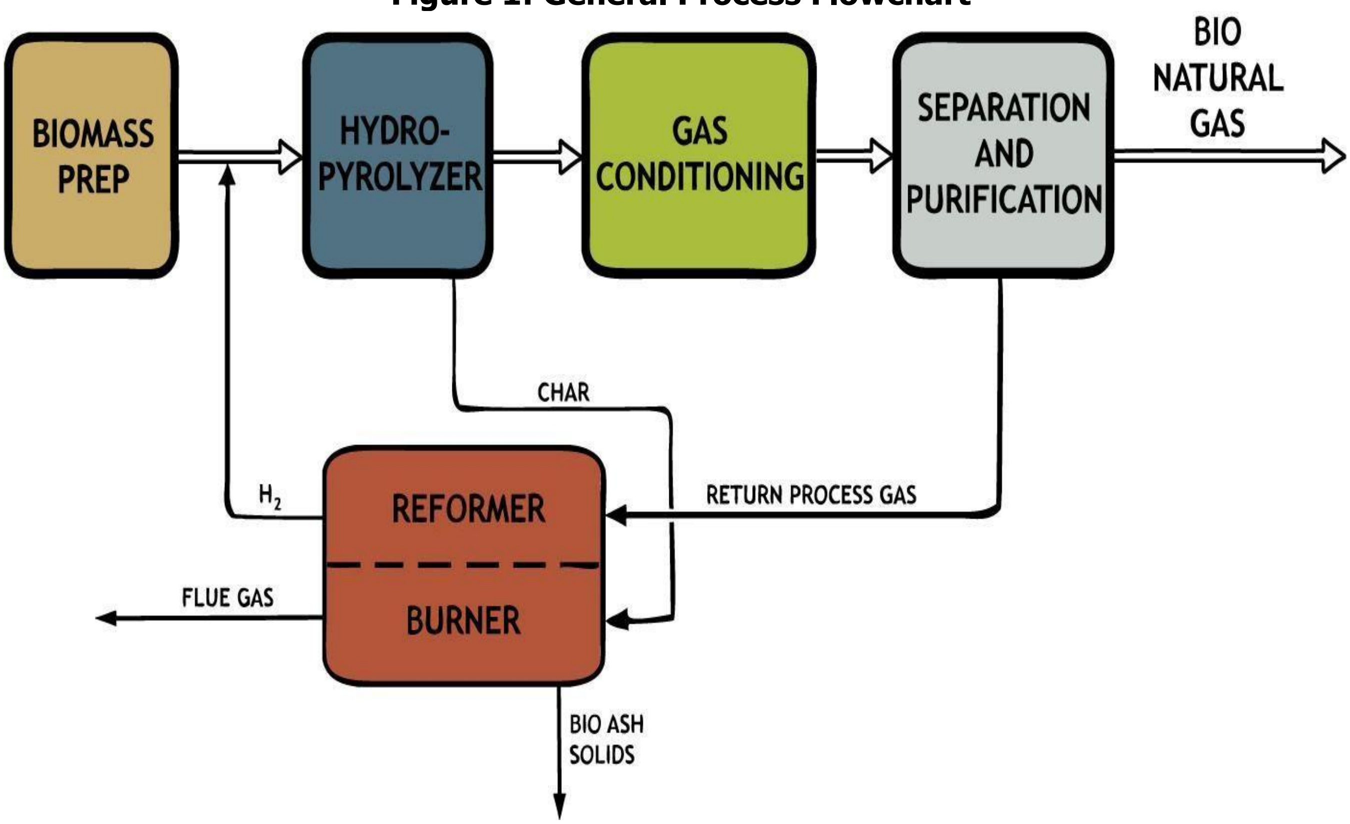
- National Fire Protection Agency 55 Compressed Gases and Cryogenic Fluids Code 2013 Edition
- Statutory Provisions
  - State of California's Division of Occupational Safety and Health Title 8, Chapter 4 Regulations
  - Placer County Air Pollution Control District Regulations
  - Placer County Code, Chapter 15, Articles 15.04.700 and 15.04.710 (Fire Code)
  - Province of British Columbia's Safety Standards General Regulation
  - Province of British Columbia's Power Engineers, Boiler, Pressure Vessel and Refrigeration Safety Regulation
  - Province of British Columbia's Electrical Safety Regulation
  - Province of British Columbia's Gas Safety Regulation

General Process Description

The proprietary G4 process uses fast pyrolysis rather than gasification of the biomass to generate a vapor from the solid phase. This fundamental difference enables a low temperature pyrocatalytic hydrogenation process (Figure 1) consisting of the following components:

1. **Biomass Preparation** – Forest biomass is prepared by cleaning, comminution, and partial drying.
2. **Hydropyrolysis** – Biomass is vaporized in a pressurized hydrogen atmosphere by using a recirculating heating media to create a fast pyrolysis process. The generated vapors and aerosols are separated from the resulting solid phase of char and media. The char is further separated from the heating media for use in the reformer.
3. **Gas Conditioning** – The pyrolysis vapors are catalytically converted into methane and steam in the presence of hydrogen gas. This is performed at catalyst temperatures below 650C and minimizes the formation of poly-aromatic hydrocarbons.
4. **Separation and Purification** – the hot gases are cooled in a controlled process and the methane gas is separated and purified from the liquids and remaining hydrogen.
5. **Hydrogen Generation** – A portion of the methane, water, and excess hydrogen is recirculated into a steam methane reformer to generate the hydrogen required for the hydropyrolyzer. The heat source for the endothermic reforming process is the combustion of the char generated in the pyrolysis process.

Figure 1: General Process Flowchart



Source: G4 Insights, Inc.

Process Equipment

Table 3 lists the major equipment used in the demonstration test unit.

Table 3: Process Equipment List

Tag #	Equipment Name	Heater	Motor
C-180	BNG Compressor to CNG		
C-200	Compressor		
CT-301	Cooling Water Cooling Package		M-301
CT-350	BNG Chiller Package		
D-100	Wood Reservoir		M-100
D-110	Media Reservoir		
D-125	Spent Media Reservoir		
D-140	Product Gas Knockout Tank		
D-150	Desiccant Drier		
D-170	BNG Product Holding Tank		
D-200	C-200 Inlet Dampening Tank		
D-201	C-200 Outlet Dampening Tank		
E-125	Media Cooler		M-125
E-130	Hydrogen Heater	HE-130	
E-140	Gas Cooler Exchanger		
E-142	Gas Chiller Exchanger		
E-232	Oil Cooler		
FDR-100	Wood Feeder		M-105
FDR-110	Media Heater	HE-110	M-110
MX-120	Pyrolyzer	HE-120	M-120
P-300	Cooling Water pump		M-300
R-130	Methanation Reactor	HE-230	
R-190	Off Gas Thermal Oxidizer	HE-190	
TK-300	Cooling Water supply Tank	HE-300	
X-160	Methane Purifier, PSA Package		
X-165	Odorizer Package		

Source: G4 Insights, Inc.

Technical Process Description

The DTU meters wood particles from a reservoir which is filled for each batch. In operation, wood particles stored in the Wood Reservoir (D-100) are transferred by the Wood Feeder (FDR-100) into a Pyrolyzer (MX-120). Simultaneously, heat transfer media flows from the Media Reservoir (D-110) and is heated by the Media Feeder (FDR-110) before entering the Pyrolyzer to mix with the wood particles. Pyrolysis gas (pygas) generated in the Pyrolyzer is separated from solids and flows on in the catalytic process, while spent heat transfer media and char are cooled by the Media Cooler (E-125) and deposited into the Spent Media Reservoir (D-125).

A hydrogen supply stream heated by the Hydrogen Heater (E-130) combines with the pygas before passing through the Methanation Reactor (R-130). A closed loop oil bath system maintains temperature in the Methanation Reactor by the Oil Cooler (E-232).

The converted gas exits the reactor and is cooled by the Gas Cooler Exchanger (E-140). Liquids are collected in the Knockout Tank (D-140), and the remaining gases pass through a second heat exchanger, the Gas Chiller (E-142).

The cooled converted gas is directed to the Pressure Swing Adsorption (PSA) Unit (X-160) for separation into product gas. A Compressor (C-200) combined with an Inlet Damping Tank (D-200) and an Outlet Damping Tank (D-201) direct flow in the PSA unit. The waste gas stream from the PSA is sent to the Thermal Oxidizer (R-190). Product gas enters a Desiccant Drier (D-150), is treated by the Odorizer (X-165) before being directed to the Product Holding Tank (D-170). A CNG Compressor (C-180) compresses the treated product gas and delivers it directly into a CNG vehicle.

A closed loop water system utilizing the Water Tank (TK-300), a pump (P-300), and the Water Cooling System (CT-301) is used for cooling process gas and as a pressurized barrier fluid for the mechanical seals. A separate chilling system CT-350 is used for E-142. A Programmable logic controller system is selected to control and monitor the system.

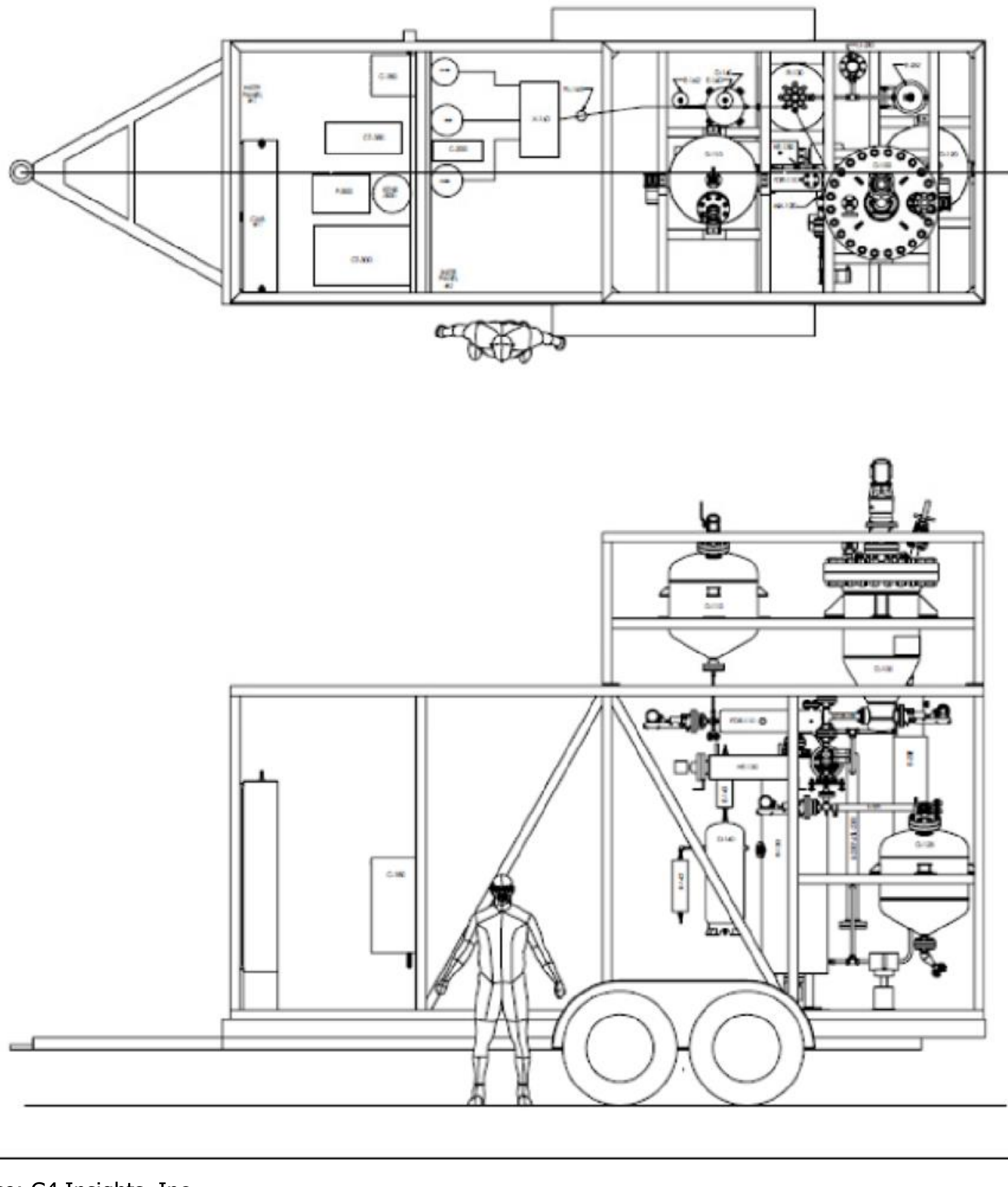
The DTU is designed to be operated as a batch system, where the process is stopped and (1) additional biomass loaded into a reservoir, (2) heating media is cleaned and reloaded into a reservoir. The product gas must be withdrawn from the system within each batch cycle due to limited storage capacity. Special purging procedures to start and end each batch are developed to ensure safe operation.

The small scale of the DTU necessitates the use of cylinder hydrogen rather than using an integrated hydrogen generator as for a commercial unit.

Plant Layout

The plant design basis requires a transportable mode going from Vancouver BC to Auburn CA, as well as a stable operations mode. A highway-capable 20 ft. long flatbed trailer with a 14,000 lb. payload capacity was chosen as a basis for the unit. A general layout of the plant was designed, taking into account required coupling, alignment, operability and maintainability. The general layout is shown in Figure 2.

Figure 2: Design Layout of Demonstration Test Unit



Source: G4 Insights, Inc.

The design of the layout placed the heated components near the back end of the trailer while placing the ambient equipment such as cooling system and control panel near the front. A metal frame to support the process units was designed and fabricated. Due to the height of the wood and media reservoirs, a separate removable sub-frame was designed and fabricated to support the vessels. This sub-frame is removed for transport of the DTU in order to keep the total height of the trailer below 11 ft.-6 in. The sub-frame with vessels is shipped on a separate flat deck and reassembled at the operations site.

The wooden deck was stripped, and a metal floor placed in to eliminate combustible materials.

Construction

G4 submitted a construction plan timetable at the construction kick-off meeting.

G4 hired a local skidded plant construction firm to perform the fabrication and assembly of the unit. Work started in March 2013. The frame was completed by July 2013 and stored in a construction bay (Figure 3).

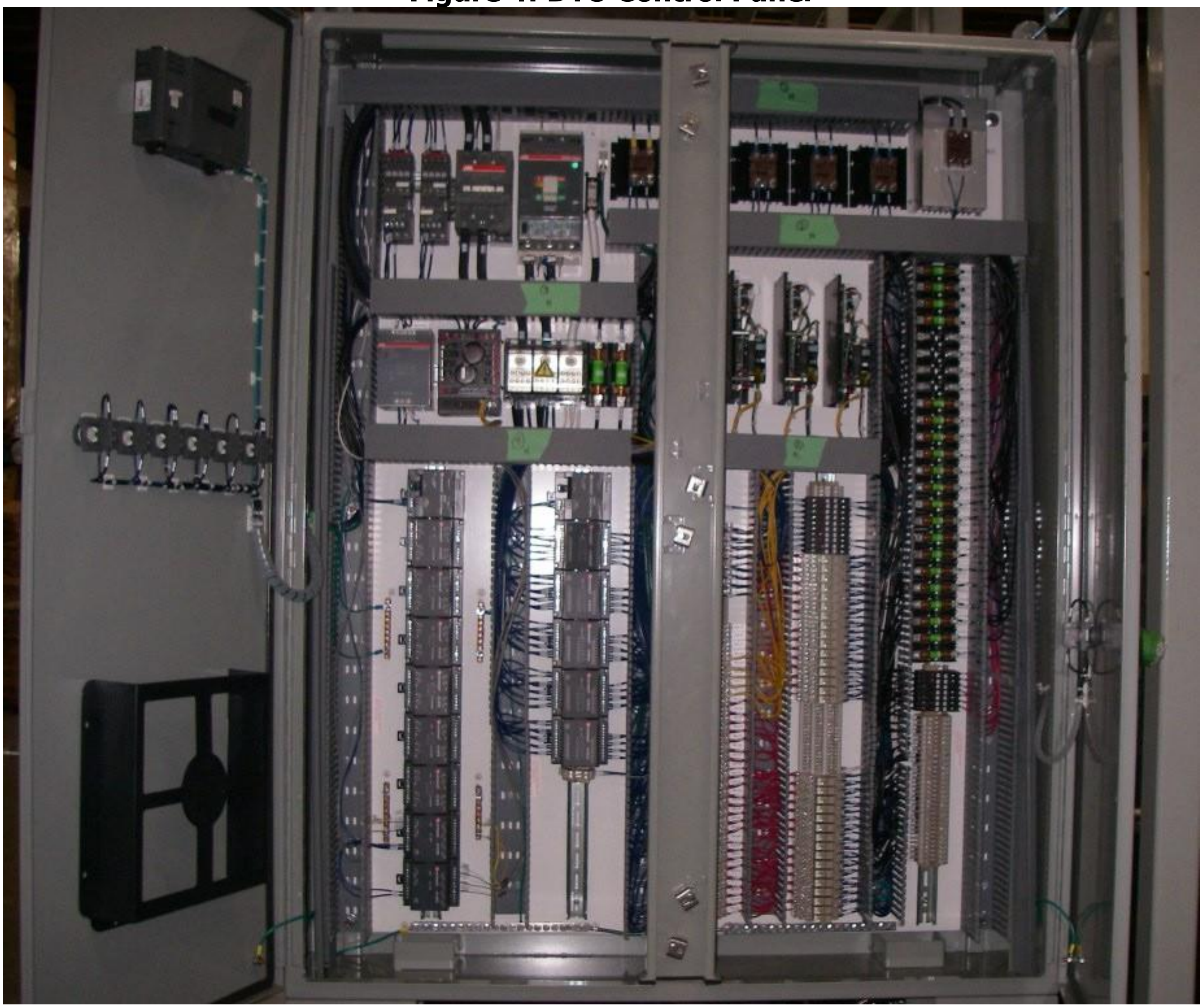
Figure 3: Frame Construction

Source: G4 Insights, Inc.

Lengthy delays occurred due to the local firm's multiple commitments and priorities. G4 decided to cancel the contract with the local firm and perform the construction itself. The partially completed equipment was shipped to G4 facilities in September 2013 for completion.

Construction continued as G4 performed all the project management, trades hiring and control, and engineering support. The electrical panel was sub-contracted to a local panel builder licensed to perform work for North America. The electrical panel was received and installed in October 2013 (Figure 4 and Figure 5).

Figure 4: DTU Control Panel



Source: G4 Insights, Inc.

Figure 5: DTU Assembly

Source: G4 Insights, Inc.

Transportation and Commissioning

The DTU was disassembled for transport to the commissioning site in November 2013. A secure outdoor location was required. Transportation configuration is shown in Figure 6. The top portion housing the two main reservoirs is detached and shipped separately in order for the unit to meet road height restrictions.

The commissioning of the mechanical and electrical components took place over 11 months between December 2013 and November 2014. Commissioning was delayed by a series of issues, including construction and vendor errors, process tuning, and design adjustments.

System testing of the full conversion process started 12 months after start of commissioning. A series of tests were run to generate performance data and test controls. The tests were all prematurely stopped before target batch lengths due to various issues.

Figure 6: Transportation of DTU to Commissioning Site

Source: G4 Insights, Inc.

Gas Chromatograph Analysis

A gas chromatograph analysis of the converted gas showed full conversion of the pyrolysis gases. Methane concentration increases as the dilution effect is reduced over time (Figure 7). Initial gas composition is 4 percent nitrogen in hydrogen.

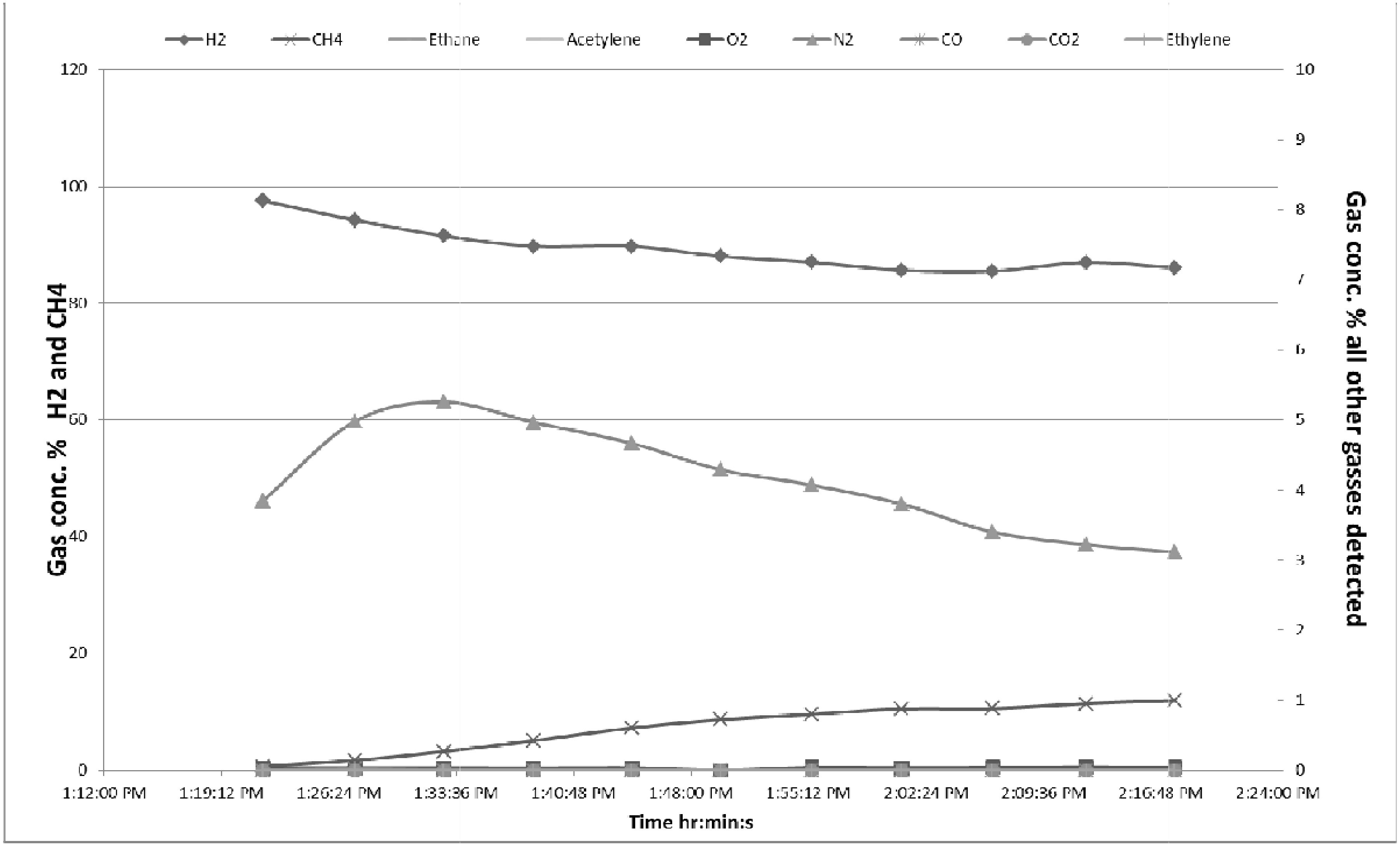
The concentration of carbon oxides and all other hydrocarbons was at the non-detect level. This result was expected, as known from previous operations with smaller process units. The system nitrogen content is the leftover nitrogen from the purging operation. The methane content in the raw gas will be upgraded to 98 percent by use of the PSA separator in the next stage. The PSA separator was not in operation for this test result.

Factory Acceptance Test

A Factory Acceptance test was run on April 15 and 16, 2015. The full process from loading wood to pressurization and operation was demonstrated. A recently failed heater cable and leaking mechanical seals necessitated a reduced mass flow process regime. The PSA separator was in operation for this test. However, it did not purify the methane to 98 percent as designed. Analysis and inspection suggested that a faulty valve may have contributed to this result.

The Construct Demonstration and Test Unit was completed in April 2015 and shipped to the Placer County demonstration site in the same month.

Figure 7: Gas Chromatograph Results



Source: G4 Insights, Inc.

Operation of the Demonstration Test Unit

Plant Reassembly

The DTU was disassembled for transport and shipped to the test site in Placer County. Figure 8 shows the DTU as transported. The reservoir frame is taken off the top of the trailer and mounted separately on the flat bed (blue tarp).

Figure 8: Transport from Commissioning Site to Operating Site

Source: G4 Insights, Inc.

The unit was set up adjacent to a building with existing power supply. Gases were procured for operation. A hammer mill and sieving machine was set up to reduce the wood to the appropriate size. The operating site is shown in Figure 9. A complete inspection of the equipment and leak check was performed prior to operation. No structural, electrical, instrumentation or piping component was damaged. Of note, two mechanical seals failed after the transport phase, although they were suspected of being damaged before shipping. These seals were repaired on site.

Figure 9: Operating Site of DTU

Source: G4 Insights, Inc.

Operation of DTU

The DTU was fueled with waste wood collected in Placer County (Figure 10). A load was brought in and stored inside the building adjacent to the DTU. The size of particles was too large for the DTU. Wood was hammer milled, sieved and loaded into the wood reservoir.

Figure 10: Waste Wood Particles

Source: G4 Insights, Inc.

A standard purge and pressurizing sequence were performed. Wood flow was started after temperature and pressure stability was reached. The DTU ran for approximately six hours producing methane. The purification unit was run after the methane content reached five percent. However, the purification unit did not perform as expected. The quality of the methane product was diluted by the residual nitrogen (coming from the necessary purge sequence) and did not meet the specifications for a vehicle fuel.

Vehicle Fueling

The refueling apparatus was tested and is expected to operate as designed. However, it was not used due to out-of-standard fuel produced by the DTU.

The vehicle was not fueled due to nitrogen dilution of the methane. This will be performed and reported on in a subsequent demonstration test.

Site Feasibility Study

G4 contracted the services of TSS Consultants (TSS) of Rancho Cordova, California to investigate feasibility of pilot and commercial scale PCH plants in California. TSS is an interdisciplinary consulting firm that provides renewable energy, natural resources management, environmental permitting and compliance management, greenhouse gas management, and financial assessment services.

The G4 thermochemical conversion process offers a promising, cost-effective technology for converting large volumes of forest biomass into low carbon biofuel. If successful at commercial scale, the technology could provide significant economic benefits in rural forest communities, commonly areas of high unemployment.

Widespread implementation could divert a large fraction of the wood waste generated from forest restoration and forest fuel reduction projects, helping to offset project costs while lowering fire risk, and producing enough biomethane to displace significant volumes of fossil fuel in the state.

Scope of Work

G4 contracted TSS to conduct activities in support of a siting and feasibility study for pilot and commercial-scale biomethane facilities in California. The report titled "*Siting and Feasibility Study for Pilot and Commercial Scale Biomethane Facilities in California*" was submitted to G4 and the scope of work is summarized in the following sections.

Placer County Pilot Plant Siting Study

TSS conducted a siting feasibility study for the proposed development of a pilot plant in Placer County. The siting study takes into consideration the availability of woody biomass resources available to be purchased and delivered to the nominal 2.2 tons per day proposed facility. The siting study specifically took into consideration:

- Feasibility to secure a sustainable woody biomass feedstock supply during the planned operational period of the facility;
- The ability of the proposed siting locations to secure woody biomass resources that are produced through low-impact methods to ensure the environmental sustainability of feedstocks and to improve forest ecosystem health surrounding the proposed facility locations;

- An assessment of available water resources and water discharge requirements at proposed sites; and
- Local regulations regarding zoning, noise, odor, traffic, and other factors.

Placer County Pilot Plant Logistics and Business Feasibility Study

TSS conducted a logistics and business feasibility study for the proposed development of a pilot plant in Placer County. The logistics and business feasibility study assesses the following for the preferred candidate site selected in the siting feasibility study:

- Ability for the planned pilot-scale facility to maintain a sustainable supply of clean woody biomass feedstock;
- Determine feedstock processing infrastructure and requirements necessary to accept available woody biomass feedstocks from the local procurement zone;
- Assess the feedstock transportation requirements to deliver woody biomass feedstock to the proposed facility storage yard;
- Assess woody biomass feedstock pricing including pricing of feedstock transport, if transport is required; and
- Assess and identify potential end-users for the biomethane product produced in the Placer County pilot scale facility. Determine feasibility and logistics for transport of biomethane from the pilot scale facility to potential end users. Investigate whether the biomethane product will require market subsidy to be competitive with existing end-user fuels.

Placer County Pilot Plant Permitting Activity

TSS identified the California Environmental Quality Act lead agencies in Placer County that will be responsible for environmental permitting related to the proposed facility. This included:

- Identifying lead agencies related to land use, air, and water permitting and will identify tasks and schedules to be followed to successfully permit the planned pilot-scale facility in Placer County; and
- Developing a schedule and punch list of required activities necessary to comply with all California Environmental Quality Act lead agency requirements for necessary permitting of the proposed pilot plant.

California Siting and Logistics for Commercial Scale PCH Plants

TSS conducted a business feasibility study for the potential future development of a commercial plant in Placer County or sited in other California counties. The study included the investigation taking into consideration:

- Sustainable woody biomass availability for a potential 30 tons per day facility and a larger, potential 750 tons per day scale facility;
- Optimal sites where woody biomass can be acquired using processes to enhance opportunities for wildfire risk mitigation projects;
- Optimal sites where the facility can access the established California natural gas pipeline infrastructure. Investigate logistics and requirements for biomethane product to be delivered and injected to existing natural gas pipeline infrastructure; and

- Optimal sites where the facility can utilize existing and potential future abandoned forest harvest residuals piles.

Pilot Plant Requirements

The goal of this task is to evaluate technical, economic and environmental impact elements of a potential biomethane production plant in California, especially focusing on the County of Placer. The approach of this work was to subcontract a portion of the work to TSS, an expert Californian consulting engineering group. G4 then synthesized the information with pilot plant specific information to generate this report.

Economic Elements for Pilot Plant

G4 and TSS performed a capital cost study of a pilot plant based on the preliminary equipment list.

An outline of functions was made in order to estimate personnel requirements, as well as an examination of operating costs, maintenance, utilities, consumables and yard activities.

Environmental Elements for Pilot Plant

A study on the proposed pilot plant air and water emissions included investigation of any requirements for water and other natural resources. The main heating source for the plant is the produced pyrolysis char; an analysis of this produced char was performed in order to estimate the air emissions.

Benchtop Enhanced Operations

The goals of this task are to design, upgrade, commission, and test a Benchtop unit at the G4 company site. The main objective was to upgrade the Benchtop unit in order to operate it to study and enhance catalyst behavior in the PCH process.

Operational Study

The Benchtop study was performed in two sections: preliminary work with small samples and scaled up operation on the Benchtop unit. The preliminary work was conducted by a catalyst scientist using a controlled laboratory setting to investigate catalytic behavior in a series of conditions. Based on the results, a plan was generated to test the catalysts in the Benchtop unit. An operational plan was undertaken including an analysis of results. Work was also conducted on a study to transport heating media.

CHAPTER 3: Project Results

Operational Performance of the Demonstration Test Unit

The DTU was run for a series of batches trials from November 2014 to May 2015. Process stability improved steadily over this time. Almost all the issues encountered were due to mechanical and electrical failures. Sequencing of air purge, pressurization, operation, shut down, depressurization and fuel purge was generated and tested. This led to batch runs with minimal operator input and repeatable results.

Estimated performance of the pyrolysis function is 88 percent of target commercial function. This is expected to increase with larger equipment dimensions of bigger units. The estimated performance of the conversion function compared with commercial target is 90 percent. This function is expected to reach 100 percent at commercial scale. The purification function has not yet performed properly on the DTU, although 100 percent of commercial target was achieved in a lab unit.

Based on the data collected from DTU operations, no tars, oxygenated hydrocarbons, or hydrocarbons other than methane was present in the product gas. A normal functioning PSA system would produce 98 percent+ purity methane product gas.

Performance of the Benchtop Unit

The preliminary catalyst operations study resulted in finding a high efficiency operating point in the conversion process. The maximum yield to methane at this operating point was at or near to 100 percent for all of the species tested. This information was used in upgrading the Benchtop unit.

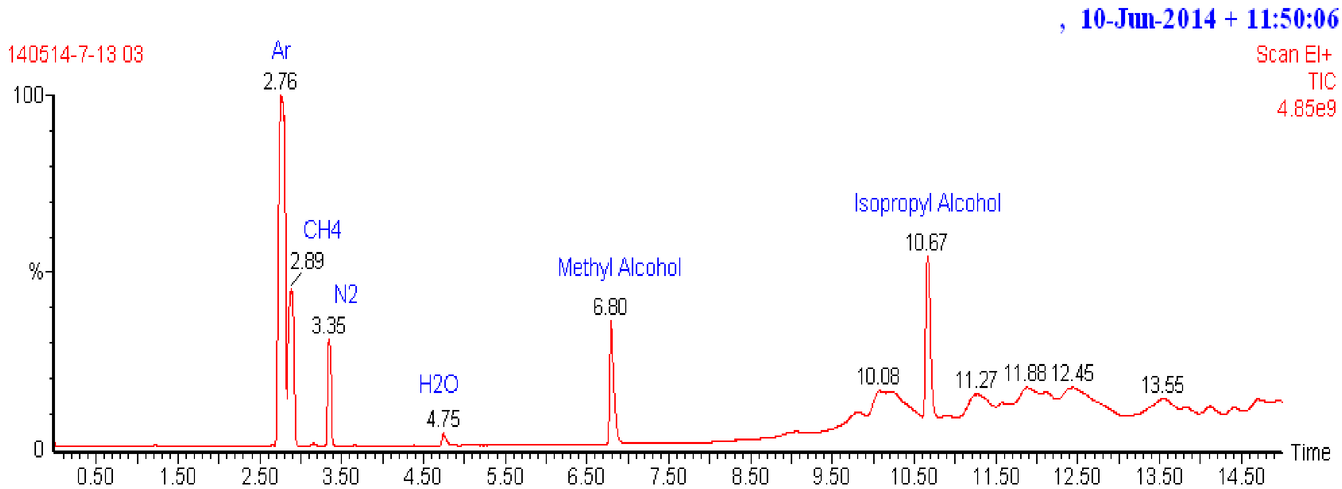
The Benchtop Unit is a test apparatus that performs the pyrolysis and conversion operations. It is not equipped with a product (methane) purifier. The rated biomass flow is one order of magnitude less than that of the DTU. Although the flows are small, the unit is still comparatively large due to the pressure and temperature requirements of the process (Figure 11).

Figure 11: Benchtop Unit Test Apparatus

Source: G4 Insights, Inc.

Tests performed prior to using the information generated by the catalyst scientist exhibited relatively impure product gas after the conversion process. Figure 12 is a GC- MS spectra of the produced gas (hydrogen is present but not measurable by this equipment) where the compounds detected after 8.5 minutes are hydrocarbons or oxygenated hydrocarbons. These compounds are the typical tars produced by pyrolysis of wood. Note that the isopropyl alcohol content is due to the use of an inline impinger with Benchtop tests. Also, argon is used in the Benchtop unit tests as a gas flow tracer and is not part of the conversion process. Neither argon nor isopropyl alcohol is used in the operation of the DTU.

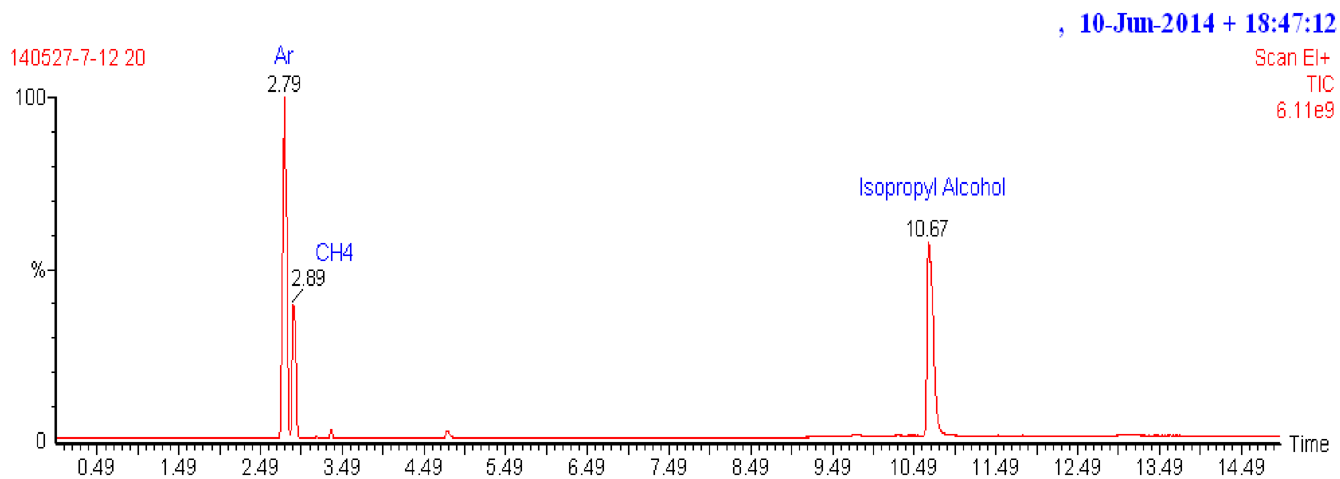
Figure 12: Benchtop Product Gas Spectra Without Calibrated Catalyst



Source: G4 Insights, Inc.

Process conditions were altered to the specification of the lab work performed. The same wood was used in the process. Resulting analysis (Figure 13) shows a substantially purer output from the conversion process.

Figure 13: Benchtop Product Gas Spectra With Calibrated Catalyst



Source: G4 Insights, Inc.

The results of these tests were used in the operation of the DTU. This provides a clear picture of the operation of the conversion process prior to the purification step.

Pilot Plant Feasibility Results

The pilot plant is estimated to produce approximately 20 MMbtu/day of methane. The plant is a step towards a commercial size and is too small to be considered commercially viable. It is expected to only operate 5 days per week.

Placer County Pilot Plant Siting

The pilot plant is estimated to use 2.2 tons per day biomass feedstock, for a maximum of 803 BDT annually. A forest-based woody biomass feedstock supply analysis across a five county feedstock supply area indicates sustainable feedstock availability estimates of 63,428 (low range) to 199,444 (high range) BDT per year. This estimate includes forest residual yields from commercial timber harvest and fuel reduction and stand improvement projects on both private and public lands.

However, TSS believes the opportunities for feedstock from stand improvement and fuel reduction management are not consistent and can have limited acquisition potential.

Commercial even-aged forest operations provide the largest and most reliable source of forest residual biomass. The final feedstock supply estimate relies mostly on commercial timber harvest residuals. The available feedstock coverage ratio is over 80 to 1 (BDT feedstock for every BDT that the plant requires). Since TSS finds that a 2:1 to 3:1 coverage ratio is acceptable for most projects, a more than adequate feedstock supply is available.

TSS reviewed sites throughout Placer County in conjunction with the Placer County Planning Service Division and discussions with Pacific Gas and Electric (PG&E) representatives to identify two preferred potential sites that balance feedstock availability, market access, and land use zoning. The primary markets in Placer County for biomethane are compressed natural gas for transportation fuel and pipeline quality natural gas for purchase by PG&E or a local power plant. There are some CNG fueling facilities in Placer County. TSS coordinated with PG&E regarding the pipeline injection siting process. The selected sites were determined to be sufficiently close to a PG&E transmission pipeline that fits required criteria outlined in the PG&E review.

Potential sites were filtered first through market accessibility to provide flexibility for the project and to minimize costs associated with reaching the marketplace. The second filter was feedstock availability and transportation infrastructure. Having discerned an adequate woody biomass supply, the feedstock availability filter focused on transportation infrastructure from forested lands to the potential site. The third filter applied was land use zoning.

The pilot plant siting analysis found the preferred site to be located at the junction of West Wise Road and Lincoln Sheridan Road (formerly Route 65), north of Lincoln, CA. This site best balances the availability of feedstock with accessibility to the market.

Placer County Pilot Plant Economic Impacts and Feasibility

As mentioned above, the pilot plant requires a maximum of 803 BDT biomass feedstock annually. Low range and high range feedstock supply estimates are expected to be recoverable from within a 60-mile haul radius. Delivered feedstock prices range from $50.22/BDT for the low range to $56.22/BDT for the high range. Upon feedstock delivery at the pilot facility, woody biomass will be either utilized or stored. The small volumes required by the pilot project are impractical for commercial-scale biomass recovery operators working with forest timber harvest operations. Options for the 2.2 tons per day facility will be to have a feedstock storage area for long-term storage of large loads from a commercial-scale contractor, or to locate a small-scale biomass processing contractor for just-in-time delivery. When possible, just-in-time delivery schedules with delivery directly to the receiving bay will avoid the costs and time associated with biomass storage. However, some biomass storage will likely be required if using exclusively forest-sourced biomass due to the cessation of forest operations for approximately 4 winter months.

The pilot plant capital cost of equipment for the major components are shown in Table 4.

Table 4: Pilot Plant Capital Costs

ITEM DESCRIPTION	CAPITAL COST ESTIMATE ($)
Wood Handling And Feeding	350,000
Pyrolysis Unit	265,000
Hydrogenation System	280,000
Purification	150,000
Hydrogen Generator	375,000
Ancillaries	325,000
Equipment Total	1,745,000

Source: G4 Insights, Inc.

Major operating costs are shown in Table 5

Table 5: Pilot Plant Operating Costs

ITEM DESCRIPTION	AMOUNT
Operating Personnel	2
Burdened Labor Cost	$200,000/year
Power Consumed	160 MWh/year
Estimated Power Cost	$13,000/year
Maintenance., Consumables, Etc.	$52,000/year
Operating Costs Total	$265,000/year

Source: G4 Insights, Inc.

TSS identified two local market options for biomethane. They included CNG for transportation fuel or sale to the local natural gas utility provider to blend with their natural gas before selling to consumers. There are 12 CNG fueling stations within 30 miles of the selected pilot site, and another 9 within a 30 to 75 mile zone. All of the CNG fueling stations identified source natural gas from PG&E, the local natural gas provider. PG&E sells natural gas for transportation use under Gas Schedules G-NGV1, G-NGV2, and G- NGV4, all three of which could apply to the pilot facility.

G4 would qualify for renewable fuel incentives available from the California Air Resources Board carbon market program, Low Carbon Fuel Standard credits. The average California Low Carbon Fuel Standard credit price January through March 2015 was approximately $25.00 and provides a subsidy of $2.23 per MMBTU. Given a natural gas price of $2.80 per MMBTU, and a Low Carbon Fuel Standard credit price of $2.23 per MMBTU, G4 would receive a total of $5.03 per MMBTU. This amount is below G4's stated production cost of $8.44 to $12.67 per MMBTU. G4 would also qualify for United States Environmental Protection Agency Renewable Fuel Standard D-5 Advanced Biofuel RINS. The G4 registered pathway with United States Environmental Protection Agency would likely qualify for the slightly higher-priced cellulosic biofuel D-3 RINS. However, price instability arising from political uncertainty regarding the Renewable Fuel Standard makes it difficult to predict the availability or level of support from this subsidy.

Environmental and Permitting Considerations

Based on a preliminary analysis of land use and environmental permits needed for the proposed project, it appears the project is permittable at the preferred sites near Lincoln in Placer County. TSS lays out the various permits that are needed for the facility, their estimated costs, and potential timelines. It is expected that the Conditional Use Permit process, along with the concomitant California Environmental Quality Act process will be the most costly and time-consuming processes for the construction and operation of the proposed project.

The estimated permitting costs and timelines are summarized as follows:

Table 6: Pilot Plant Permitting Costs

Permit	Minimum Cost	Timeline
Land Use Permit	$13,152	5 months - 1 year +
Air Permits	$547	8 months
Water Permits	$3,095+$1,791/year	2 months
Hazardous Materials Storage	$1,037/year	1 month

Source: G4 Insights, Inc.

Design of the pilot plant would include a closed loop cooling system, eliminating the need for cooling water supply or discharge.

An estimate of the air emissions was based on empirical dynamic modeling analysis of char produced by pyrolysis of wood in the Benchtop Unit. The main inorganics found in the char were sodium, magnesium, chlorine, potassium, and calcium. Based on these tests, G4 does not believe that any emission from the pilot plant will trigger the Best Available Control Technology in the Placer County Air Pollution Control District by at least one order of magnitude.

Commercial Plant Study Results

California Commercial Plant Siting and Business Feasibility

Locating a commercial-scale biomethane facility in an area of high wildfire danger is desirable because of the need for fuel reduction forest management and the continual availability of sustainably harvested feedstock. Spatial analysis of CalFire high priority landscapes for wildfire hazard management overlain with natural gas transmission lines of the 3 major utilities, PG&E, Southern California Gas and San Diego Gas & Electric shows three areas with potential siting opportunities; surrounding the Los Angeles and San Diego basins, the Sierra Range, and the Northern Sierras and Klamath Range.

Analysis indicated that the location at Burney, situated between the Northern Sierra and Klamath Range and on a major PG&E natural gas transmission line, offers the best potential combination of volume from forest operations and delivered pricing. Currently, the location at Burney would encounter competition for this feedstock source from a number of existing biomass utilization enterprises, including cogeneration facilities.

G4 validated market demand for renewable natural gas at the time of its initial CEC proposal (2010) as adequately priced to support their production costs. G4's target production price is estimated between $8/ gigajoule and $12/ gigajoule with a biomass price of $50/BDT. The US Energy Information Agency natural gas market average price for Northern California from January through April 2015 was approximately $2.80/MMBTU. At G4's stated production cost of $8.44 to $12.67 per MMBTU, their biomethane is not competitive with the current market.

Sustainable Feedstock Availability

G4 is interested in siting a large-scale facility, potentially utilizing 750 tons per day, or an estimated 273,000 BDT per year. The five-year average for timber harvest volumes in California for the period 2006 through 2010 is 1.3 million board feet. Applying the biomass recovery factors of 0.9 BDT/MBF and 2.8 BDT/MBF would yield a range of 1,187,080 to 3,732,708 BDT per year for the entire state of California. A facility this size would consume between 7 percent and 23 percent of the entire state's potential production, and this production occurs from Tulare County to the Oregon border and from the western slopes of the coastal mountains to the eastern slopes of the Sierra Nevada range.

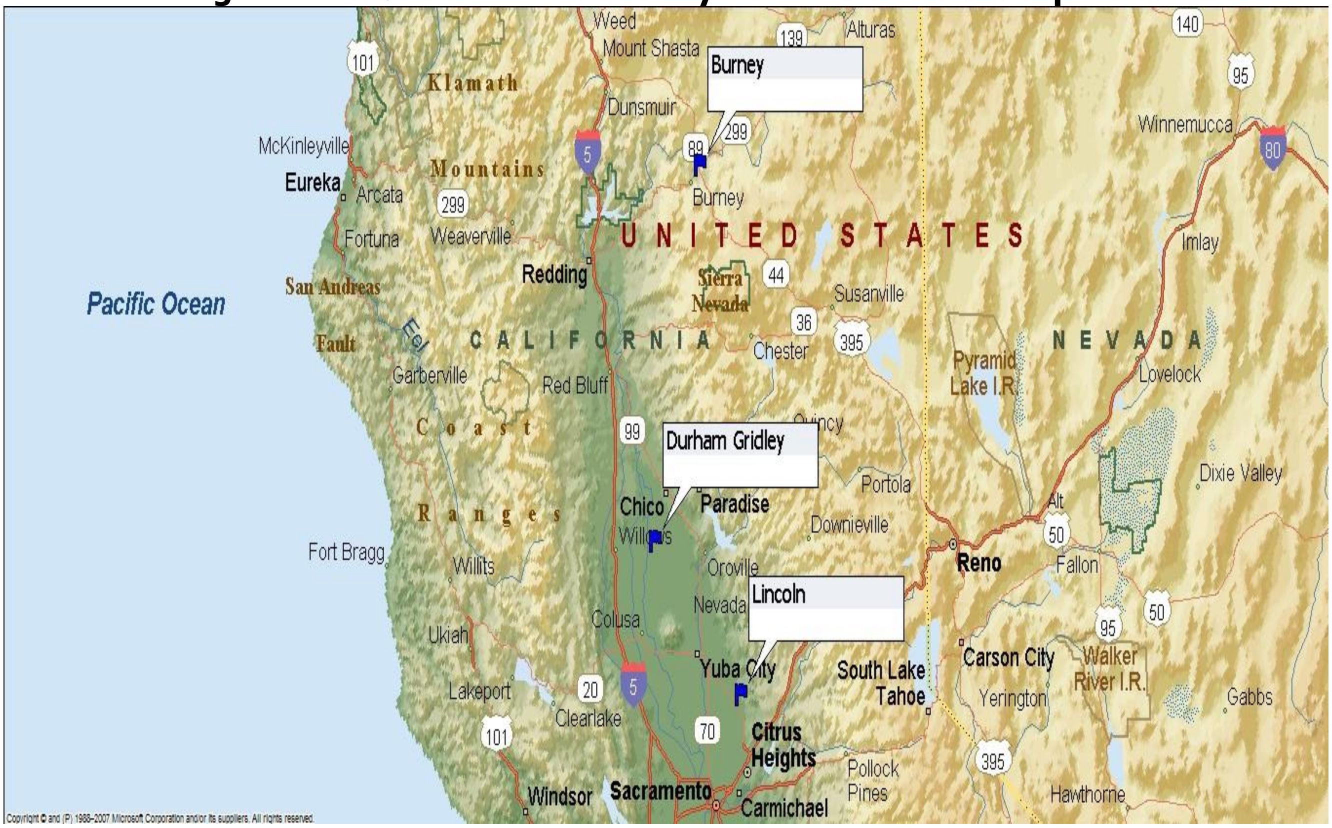
Acquiring such a significant volume of woody biomass feedstock from forest operations would be expensive primarily due to the extensive transport cost required to procure this volume from forest management operations. Figure 14 below shows the counties within the state of California and the range of woody biomass feedstock production annually predicated upon the five-year timber harvest average as discussed above.

There are only 3 counties producing over 100,000 BDT/year on an annual basis, and these three are located in northern and northwestern portions of the state. The review of potential feedstock for the large-scale facility was conducted using a high level analysis of both availability and pricing.

TSS conducted a haul-zone analysis using geographic information system technology to evaluate prospective woody biomass feedstock volumes from private operations and from US Forest Service managed lands for three potential sites: the site northwest of Lincoln to be used for the small scale facility; another between Durham and Gridley (Butte County); and one near Burney (Shasta County).

These sites are located next to major PG&E natural gas transmission pipelines.

Figure 14: Potential Sites Nearby PG&E Natural Gas Pipelines



Source: TSS Consultants

Optimal Sites in California

Locating a commercial-scale biomethane facility in an area of high wildfire danger is desirable because of the need for fuel reduction forest management and the continual availability of sustainably harvested feedstock. Spatial analysis of CalFire wildfire hazard zones overlain with natural gas transmission lines of the 3 major utilities, PG&E, Southern California, and San Diego Gas & Electric, shows three areas with potential siting opportunities; surrounding the Los Angeles and San Diego basins, the Sierra Range, and the Northern Sierras and Klamath Range.

G4's interest in siting a large-scale facility utilizing 750 BDT per day is constrained to a location with a significant sustainable woody biomass supply. The five-year average for timber harvest volumes in California for the period 2006 through 2010 is 1.32 million board feet. Applying the biomass recovery factors of 0.9 BDT/MBF to 2.83 BDT/MBF would yield a range of 1,187,080 to 3,732,708 BDT per year for the entire state of California. A facility sized for 273,000 BDT/year would consume between 7 and 23 percent of the entire state's potential production. Only the Northern Sierra and Klamath Range were deemed suitable for delivery of large volumes of feedstock.

A haul-zone analysis to evaluate woody biomass feedstock amounts and pricing led to the selection of three potential sites: Burney, CA, Durham-Gridley, CA and Lincoln, CA. Delivered feedstock prices increase with haul time, from a low of $50.22/BDT within a one-hour zone to a high of $104.67 within a 4-hour zone. Analysis indicated that the location at Burney, situated between the Northern Sierra and Klamath Range and on the PG&E natural gas transmission line, offers the best potential combination of volume from forest operations and delivered pricing. Currently, the location at Burney would encounter competition for this feedstock source from a number of existing biomass utilization enterprises, including cogeneration facilities.

Use of Technology for Renewable Energy

The methane produced is generated completely from wood waste. This fuel can be used as a renewable fuel source for production of renewable electricity. The production plant also generates excess heat which could be used for various applications. G4 has generated a PCH pathway by using portions of Air Resources Board Greenhouse gases, Regulated Emissions, and Energy use in Transportation studies as shown in Table 7.

For the G4 PCH pseudo-Greenhouse gases, Regulated Emissions, and Energy use in Transportation model, the G4 biomethane pathway to transportation fuel consists of:

1) Collect and transport forest waste to a production plant,
2) Produce renewable natural gas using the PCH process, and
3) Transport/distribute and compress the biomethane for CNG vehicle use. Note that this construction is not an approved Air Resources Board Greenhouse gases, Regulated Emissions, and Energy use in Transportation pathway.

The Air Resources Board Greenhouse gases, Regulated Emissions, and Energy use in Transportation scenarios utilized for this study are:

a) Detailed California-Modified Greenhouse gases, Regulated Emissions, and Energy use in Transportation Pathway Cellulosic Ethanol from Forest Waste Version 2.1 (Feb 27, 2009)

b) Detailed California-Modified Greenhouse gases, Regulated Emissions, and Energy use in Transportation Pathway Compressed Natural Gas (CNG) from Dairy Digester Biogas Version 1.0 (July 20, 2009)

G4's PCH carbon intensity pathway has 7 parameters, while the closest Air Resources Board pathways have just 3.

The G4 PCH carbon intensity for a CNG fuel application is 14.4 grams of carbon dioxide per mega joule. This is far below the diesel baseline of 95 grams of carbon dioxide equivalent per megajoule (gCO2e/MJ) and is one of the lowest carbon intensity values of all pathways shown in the Low Carbon Fuel Standard Look-Up Table. It is also 8 points lower than the other pathway for forest residues, cellulosic ethanol. For example:

- California Diesel = 95 gCO2e/MJ
- Compressed Natural Gas = 75 gCO2e/MJ
- CNG from Dairy Digester Biogas = 15 gCO2e/MJ
- Cellulosic Ethanol from Forest Residues = 22 gCO2e/MJ

Table 7: G4 PCH Pseudo- Greenhouse gases, Regulated Emissions, and Energy use in Transportation Model Pathway

	TOTAL ENERGY (Btu/mmBtu_ARB)	TOTAL ENERGY (Btu/mmBtu_G4)	TOTAL GHG (gCO2e/MJ_ARB)	TOTAL GHG (gCO2e/MJ_G4)
FOREST WASTE COLLECTION (Table 1.02 and 1.07, Cellulosic Ethanol from Forest Waste)	110,817	97,780	8.6	7.6
FOREST WASTE TRANSPORT (Table 2.02 and 2.06, Cellulosic Ethanol from Forest Waste)	47,773	42,153	3.67	3.24
G4 BIOMETHANE PRODUCTION FOREST WASTE (Table 3.02 and Section 3.2 from Ethanol from Forest Waste)		693,541		0
G4 BIOMETHANE PRODUCTION-ELECTRICITY (Table 1.02 and 1.07, CNG from Dairy Digester Biogas)	22,209	18,939	1.17	0.998
NATURAL GAS TRANSPORT & DISTRIBUTION (Table 3.01 and 3.04, CNG from Dairy Digester Biogas)		1,350		0.45
NATURAL GAS COMPRESSION TO CNG (Section 4.01 and Table 4.02, CNG from Dairy Digester Biogas)		40,746		2.15
FUEL COMBUSTION IN VEHICLES (Section 5.1, Cellulosic Ethanol from Forest Waste)		1,000,000		0
TOTALS WTW		1,894,509		14.4

Source: G4 Insights, Inc. and TSS Consulting

Use of Produced Gas for Power Generation

The use of the PCH process to produce pipeline grade methane allows potential injection into the gas grid. Various power producers in California are utilizing Natural Gas Combined Cycle plants. Using the G4 constructed Greenhouse gases, Regulated Emissions, and Energy use in Transportation scenario, the total energy to deliver the renewable product to the natural gas grid is 853,763 btu/MMbtu, and the total GHG is 12.29 gCO2e/MJ. The typical heat rate of modern Natural Gas Combined Cycle equipment is 6,719 btu/KWh. The overall conversion of waste wood energy to electric power is calculated at 42 percent by using the Natural Gas Combined Cycle technology. By comparison, a waste wood boiler to power plant runs at a conversion rate range of 25 to 30 percent.

A 30 tons per day plant will generate approximately 50-75 MMbtu/day of low grade heat suitable for hot water generation or home heating.

Fossil Fuel Displacement Estimates

Gasoline and/or Diesel Fuel Displacement

Direct displacement of liquid fuels by this product is only possible by conversion of vehicles to CNG or LNG. Medium and heavy-duty trucks use these fuels. There is just one light duty CNG vehicle – the Honda Civic.

A different scenario that adds renewable content to gasoline and/or diesel fuel has been investigated. All refineries in North America utilize natural gas for producing hydrogen, primarily to reduce sulfur and as a fuel. Although this hydrogen from natural gas does not generally remain in the liquid fuel, its generation adds considerable GHG emissions to the refinery. These emissions are part of Greenhouse gases, Regulated Emissions, and Energy use in Transportation studies. We calculate that refineries in the USA use (onsite or offsite) over 3,000 million cubic feet of natural gas per year to make hydrogen and over 700 million cubic feet for fuel. This is 22 percent of the GHG emissions in the refinery sector. By displacing the natural gas with renewable natural gas, a substantial reduction of 53.60 kg CO2e/Mcf in fossil GHG emissions is possible.

Gasoline uses an estimated 4.32 cubic feet of natural gas per gallon. Displacing the natural gas used could reduce wheel to well GHGs by 232 g CO2e/gallon gasoline produced. Total US potential is 75,900 tons CO2e/day reduction.

Diesel uses an estimated 7.62 cubic feet of natural gas per gallon. Displacing the natural gas used could reduce wheel to well GHG by 409 g CO2e/gallon diesel produced. Total US potential is 50,300 tons CO2e/day reduction.

The US potential for liquid fuels is dependent on available waste biomass. Current estimates of availability would not limit the total potential of 126,200 tons CO2e/day reduction.

Natural Gas Displacement

Renewable content in CNG is possible by wheeling the pipeline-injected content to the end distributor or user. In certain situations, the content of a natural gas refueling station can be directly supplemented or fully fueled by a plant, where pipeline gas can be used as a backup. The displacement of gasoline (95.86 gCO2e/MJ intensity) usage with G4 renewable CNG usage (14.4 gCO2e/MJ) could lead to a reduction of over 350 thousand tons CO2 per year.

Job Creation, Economic Development, and Tax Benefit to California

Biomass Collection and Transportation Jobs

Based on the studies G4 performed for this project, an estimated Californian total potential for operations of PCH plants is one 750 tons per day (10,000 gigajoule/day output) and 10 of 30 tons per day (400 gigajoule/day output) plants. This would create a potential collection of approximately 1,000 BDT/day from an estimated current and stable availability of 6,000 BDT/day in California. The main reasons for low percentage uptake of the available biomass in California are the a) large distance between most of the biomass and the pipeline grid or existing vehicle refueling stations, creating too expensive biomass costs and high use of offsetting transportation fuel, b) the low incentives for renewable fuel or power, and c) the high costs and long timelines of the permitting processes.

Table 8 shows potential collection and transportation jobs.

Table 8: Collection and Transportation Jobs Potential

FTE	Description	Salary (Cost / Time)	10-Year $ (2015-25)	Location
	6 of 400 gigajoule/day Commercial Plants in the 10 yr time frame	Average 4 Years		
	- Expenditures excluding labor	$8M each	48,000,000	California
100	- Engineering and construction per plant	$40k/year	24,000,000	California
2	- Plant management per plant	$120k/year	5,760,000	California
11	- Plant operations and admin per plant	$80k/year	21,120,000	California
8	- Biomass collection and hauling per plant	$35k/year	6,720,000	California
	One 10,000 gigajoule/day Commercial Plant	5 Years operations		
	- Expenditures excluding labor	$80M	80,000,000	California
1,000	- Engineering and construction	$40k/year	40,000,000	California
4	- Plant management	$120k/year	2,400,000	California
22	- Plant operations and admin	$75k/year	8,250,000	California
151	- Biomass collection and hauling	$35k/year	26,425,000	California
	Total direct economic benefit to California		262,680,000	
	Total indirect economic benefit to California		125,680,000	
	Total economic benefit to California 2015-2025		$388,350,000	
	California State Income Tax		$7,540,000	
	California Local Government Property Tax		$5,640,000	

Source: G4 Insights, Inc. and TSS Consulting

The 30 tons per day facility would be built and operating with a projected sequence of one plant per year, starting in 2019. The 750 tons per day plant would be built and operating in 2020.The major direct job benefits to California would be in engineering and construction ($64M), plant operations ($30M) and biomass collection ($33M). There would be approximately 300 permanent direct jobs created.

Criteria Emissions and Water Usage for Commercial Plants

Within New Source Review, there are two main requirements: a) Best Available Control Technology analysis and b) a determination if Emissions Offsets are needed for issuing the Authority to Construct.

Best Available Control Technology is required for new emission units that result in certain calculated emissions increases generally for the following pollutants: carbon monoxide, nitrogen oxides, course particulate matter, fine particulate matter, sulfur oxides, volatile organic compounds, lead, vinyl chloride, sulfuric acid mist, and hydrogen sulfide.

The emission levels at which Best Available Control Technology is triggered in the Placer County Air Pollution Control District are shown in Table 9.

Table 9: Best Available Control Technology Trigger Emission Levels in Placer County

CRITERIA POLLUTANT	EMISSIONS THRESHOLD
Carbon Monoxide	550 pound/day
Nitrogen Oxides	10 pound/day
Course Particulate Matter	80 pound/day
Fine Particulate Matter	80 pound/day
Sulfur Oxides	80 pound/day
Volatile Organic Compounds	10 pound/day
Lead	3.3 pound/day
Vinyl Chloride	5.5 pound/day
Sulfuric Acid Mist	38 pound/day
Hydrogen Sulfide	55 pound/day

Source: G4 Insights, Inc. and TSS Consulting

Emissions Profile

No work was planned or performed relating to the expected emission profile of the commercial scale plants. The main source of emissions is the flue gas of the burners used for combusting pyrolysis char. This substance is very combustible compared to wood and will pose fewer issues.

Water Usage and Wastewater Discharge

The DTU successfully operates with a closed loop cooling system. Water usage is negligible. There are no liquid discharges expected. A boiler blowdown process is envisioned to be incorporated into larger systems. The details have not been calculated.

CHAPTER 4: Advancements in Science and Technology

Technological Advancements

A major goal for this project was to convert Californian forest residue into an ultra-low carbon gaseous fuel for transportation. Within the framework of this program, G4 successfully converted Californian forest residue into transportation grade renewable natural gas. The conversion is unique in the fact that the gas is clean, and no other compounds derived from the wood are remaining in the gas stream. The only gases remaining are the fuel gas methane, nitrogen (a remnant of a safety purge operation) and hydrogen.

The final cleanup of this gas mixture is known to be achievable by a number of technologies. In the DTU, Pressure Swing Adsorption (PSA) technology was utilized. This PSA unit operation will be operating correctly shortly as it has already performed successfully on a lab scale.

For this scale up demonstration, many components and subsystem processes were developed, tested and placed into operation. These are all essential components to a successful and repeatable conversion process at a larger and more significant scale.

Public Assessment of Success and Benefits

G4 Insights proposed and conducted the grant program by conceiving and developing a combination of technologies for generating Ultra-low Carbon transportation fuel using Californian forest residue. The program focused on the scale up and enhancement of a novel technology to convert waste wood into methane gas (the G4 pyrocatalytic hydrogenation process). The key aspects of the process were demonstrated in a scale-up setting.

The conversion of waste wood to renewable CNG can benefit California with a substantial reduction in CO_2. A state total estimate of 10 small and one large process plants translates into roughly 1,000 BDT/day of wood demand for 330 days per year. Using this fuel as CNG to displace gasoline (95.86 gCO_2e/MJ intensity) usage could lead to a reduction of over 350 thousand tons CO_2 per year.

The economic factors of these process plants could lead to over $380M in direct and indirect benefits and create over 300 permanent jobs.

G4 Insights believes the "Thermochemical Conversion of Forestry Biomass into Biomethane Transportation Fuel" program provided a clear vision of a technology that can make a significant contribution to sustainable and renewable energy and transportation fuel in California.

CHAPTER 5: Conclusions and Recommendations

Conclusions

G4 has successfully demonstrated the conversion of wood and forest residue to methane. Estimated performance of the pyrolysis function is 88 percent of target commercial function. This is expected to increase with larger equipment dimensions of bigger units. The estimated performance of the conversion function compared with commercial target is 90 percent. This function is expected to reach 100 percent at commercial scale. The purification function has not yet performed properly on the DTU, although 100 percent of commercial target was achieved in a lab unit. Based on the data collected from DTU operations, no tars, oxygenated hydrocarbons, or hydrocarbons except methane were present in the product gas. A normal functioning PSA system would produce 98 percent + purity methane product gas. The results to date support the idea that commercial scale PCH process may be viable and achievable.

The conversion of waste wood to renewable CNG can benefit California with a substantial reduction in CO2. A state total estimate of 10 small and one large process plants translates into roughly 1000 BDT/day of wood demand for 330 days per year. Using this fuel as CNG to displace gasoline (95.86 gCO2e/MJ intensity) usage could lead to a reduction of over 350 thousand tons CO2 per year. As well, the technology has potential to generate financial and employment benefits to California by sustainably producing renewable natural gas. The major direct job benefits to California would be in engineering and construction ($64M), plant operations ($30M) and biomass collection ($33M). There would be approximately 300 permanent direct jobs created.

The scheduling challenges for developing technologies such as PCH have been highlighted. Many of the issues encountered by G4 in the DTU project were due to the lack of readily available and proven components suitable for the relatively small scale but industrial operating conditions (high pressure, high temperature, hydrogen service). Future projects such as the G4 pilot plant will be significantly larger scale and suitable industrial components will be more readily available and proven. The results to date support the readiness to move forward with a pilot plant in Placer County, California.

Recommendations for Future Projects

This program was able to produce equipment that operated in California to convert forest residue into methane. Further work in producing renewable CNG and using it in a CNG vehicle for a period of time will be a first step in solidifying the results.

In order to place commercial operating plants into California, the technology requires an intermediate step of building and operating a pilot plant. The pilot plant outlined in the report fits this requirement. The resulting fuel could be coupled directly to a refueling station or be injected into a gas pipeline. The activities with respect to a pilot plant would develop continuous process functionality necessary for commercial plants and generate additional demand for renewable natural gas by demonstrating the potential for economic and large scale production of renewable natural gas from forestry biomass.

CHAPTER 6: Addendum to Final Report

G4's grant contract with the CEC ended in late March 2015. This *Addendum* describes post-grant activities by G4 and Placer County.

G4 continued to operate the DTU in the Placer County facility with the support of the Placer County Maintenance group. This work continued from May to September 2015. Further alterations to the purging sequences decreased the nitrogen content of the manufactured gas. This allowed the existing purification equipment to increase the purity of the fuel gas. Further batches were performed with the system producing fuel gas at a purity level of 75 to 85 percent methane. This gas was then routed to the on board fuel reservoir. In June 2015, G4 fueled a county vehicle with gas produced from Californian forest thinning for the first time. The refueling compressor appliance was started after delivery hose connection to the Placer County CNG vehicle.

After fueling, the vehicle (shown in Figure 15) was driven by Placer County personnel. The driver could not notice any difference in the performance of the vehicle during the test run.

Figure 15: Placer County CNG Vehicle Filled with G4 Biogas

Source: G4 Insights, Inc.

G4 continued operations in August and September, which resulted in the production of additional fuel. The fuel was generated by the DTU in the 80 to 97 percent purity level. The gas mixture was hydrogen and methane, which can be used in a CNG vehicle.

The DTU is shown below in Figure 16:

Figure 16: G4's Demonstration Test Unit On-Site in Placer County

Source: G4 Insights, Inc.

To the right of the picture can be seen the hydrogen gas cylinders and the biomass hammer mill. The gas cylinder in the middle of the picture is the purge gas reservoir.

G4 and Placer County hosted a public demonstration in mid-September 2015 under the direction of the Placer County Media Services.

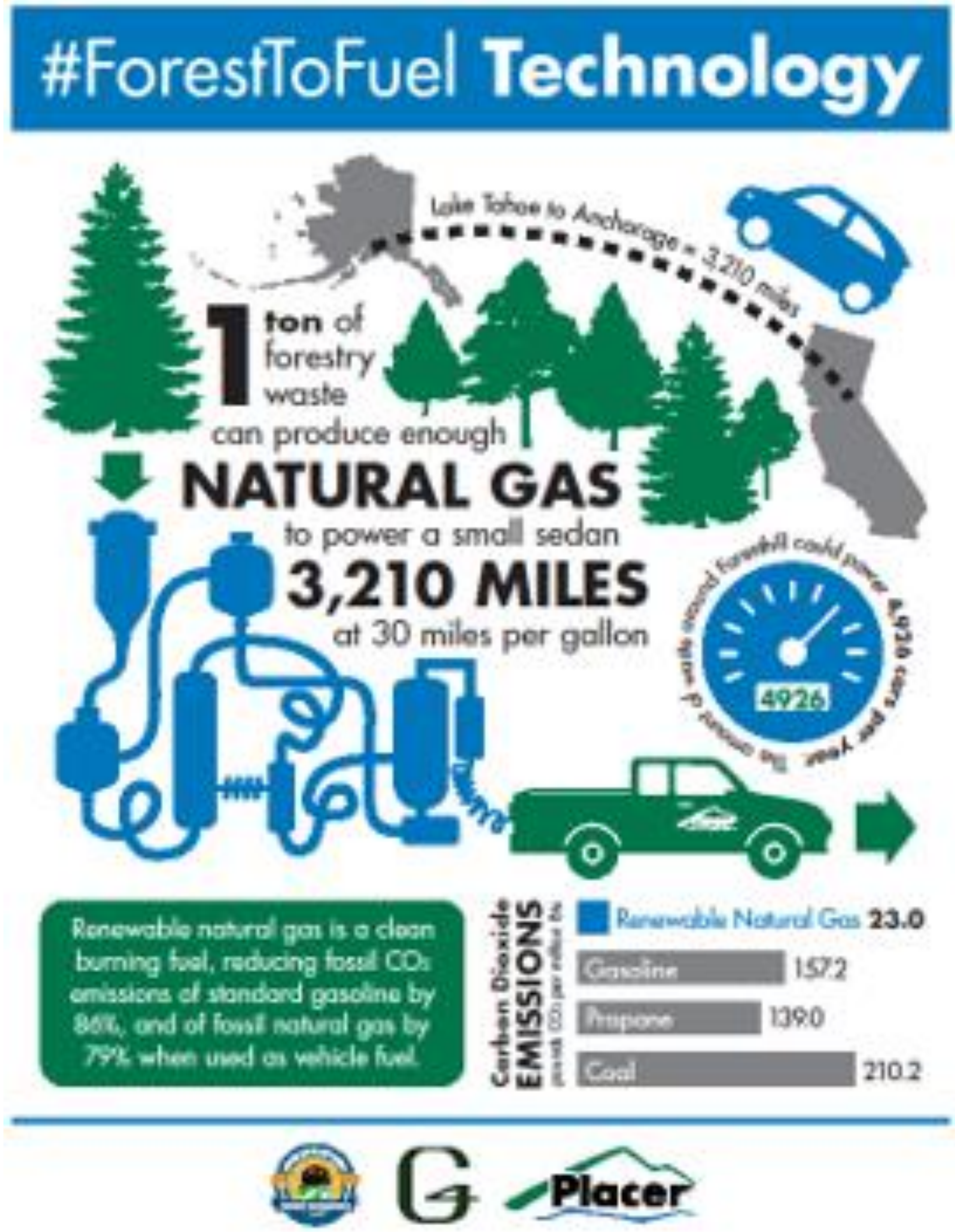
The vehicle fueling demonstration during media event is shown below. Biomass and biochar are shown in foreground of Figure 17:

Figure 17: Fueling the CNG Test Vehicle at Placer County Media Event

Source: G4 Insights, Inc.

An info-graphic (Figure 18) was produced for the media event:

Figure 18: Media Informational Graphic for G4's "Forest to Fuel Technology"



Source: G4 Insights, Inc. and TSS Consulting

Project dissemination also included a visit with students from the Colfax High School (Figure 19).

Figure 19: Media Demonstration Event With Colfax High School Students

Source: G4 Insights, Inc.

The G4 Thermochemical Conversion of Forestry Biomass into Biomethane Transportation Fuel project concluded in September 2015.

GLOSSARY

BONE DRY TON (BDT)—A bone dry ton = 2,000 lbs of woody material at 0% moisture content.[2]

CALIFORNIA ENERGY COMMISSION (CEC)—The state agency established by the Warren-Alquist State Energy Resources Conservation and Development Act in 1974 (Public Resources Code, Sections 25000 et seq.) responsible for energy policy. The Energy Commission's five major areas of responsibilities are:

1. Forecasting future statewide energy needs
2. Licensing power plants sufficient to meet those needs
3. Promoting energy conservation and efficiency measures
4. Developing renewable and alternative energy resources, including providing assistance to develop clean transportation fuels
5. Planning for and directing state response to energy emergencies.

CARBON DIOXIDE (CO2)—A colorless, odorless, nonpoisonous gas that is a normal part of the air. Carbon dioxide is exhaled by humans and animals and is absorbed by green growing things and by the sea. CO2 is the greenhouse gas whose concentration is being most affected directly by human activities. CO2 also serves as the reference to compare all other greenhouse gases (see carbon dioxide equivalent).

COMPRESSED NATURAL GAS (CNG)—Natural gas that has been compressed under high pressure, typically between 2,000 and 3,600 pounds per square inch, held in a container. The gas expands when released for use as a fuel.

DEMONSTRATION TEST UNIT (DTU)—G4's name for the small scale, portable conversion system built for this grant project.

G4 INSIGHTS, INC. (G4)— G4 Insights Inc. produces clean, low cost renewable natural gas (RNG) from lignocellulosic biomass utilizing its PyroCatalytic Hydrogenation (PCH) technology. G4 technology delivers significantly higher energy conversion and lower capital intensity compared to other RNG producers.[3]

GRAMS OF CARBON DIOXIDE EQUIVALENT PER MEGAJOULE (gCO2e/MJ)—The average carbon intensity of renewable diesel is measured in grams of carbon dioxide equivalent per megajoule.[4]

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[2] J.R. Shelly. "Woody Biomass Definitions and Conversion Factors." 2007. UC Berkeley, Department of Agricultural and Resource Economics. https://ucanr.edu/sites/WoodyBiomass/newsletters/IG003_-_Woody_Biomass_Definitions_and_Conversions_Factors31510.pdf

[3] G4 Insights Inc. - About us http://g4insights.com/about.html

[4] U.S. Energy Information Administration - EIA - Independent Statistics and Analysis https://www.eia.gov/todayinenergy/detail.php?id=37472

GREENHOUSE GAS (GHG)—Any gas that absorbs infra-red radiation in the atmosphere. Greenhouse gases include water vapor, carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), halogenated fluorocarbons (HCFCs), ozone (O3), perfluorinated carbons (PFCs), and hydrofluorocarbons (HFCs). (EPA)

MMBtu: One million (10^6) British thermal units.[5]

PACIFIC GAS AND ELECTRIC COMPANY (PG&E)—An electric and natural gas utility serving the central and northern California region.

PRESSURE SWING ADSORPTION (PSA)— a well-established gas separation technique in air separation, gas drying, and hydrogen purification separation. Recently, PSA technology has been applied in other areas like methane purification from natural and biogas and has a tremendous potential to expand its utilization.[6]

PYROCATALYTIC HYDROGENATION (PCH)—G4's name for its proprietary, thermochemical fast pyrolysis process for converting wood waste to a clean, low carbon biomethane, or renewable natural gas.

TSS CONSULTANTS (TSS)— Established in 1986 with headquarters near Sacramento, California, TSS is a renewable energy, natural resource management, and financial consulting firm that provides evaluations of existing and proposed renewable energy projects, new energy technologies, biomass waste disposal alternatives, and life cycle analyses.[7]

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[5] U.S. Energy Information Administration https://www.eia.gov/tools/glossary/

[6] Carlos Grande. "Advances in Pressure Swing Adsorption for Gas Separation." *International Scholarly Research Notices*. 2012. https://www.hindawi.com/journals/isrn/2012/982934/

[7] About Us - TSS Consultants https://tssconsultants.com/about-us/