CALIFORNIA
ENERGY COMMISSION

ENERGY RESEARCH AND DEVELOPMENT DIVISION

FINAL PROJECT REPORT

Production of Pipeline-Grade Renewable Gas and Value-Added Chemicals from Forest Biomass Residues

January 2026 | CEC-500-2026-004

PREPARED BY:

Li Wang
Matthew D. Summers, Ph.D.
Jonathan Wells, Ph.D.
Wesley Kraintz
Michael Long
West Biofuels LLC
Primary Authors

Zack Bradford
Project Manager
California Energy Commission

Agreement Number: PIR-18-001

Kevin Uy
Branch Manager
ENERGY SUPPLY BRANCH

Jonah Steinbuck, Ph.D.
Director
ENERGY RESEARCH AND DEVELOPMENT DIVISION

Drew Bohan
Executive Director

ACKNOWLEDGEMENTS

This project was made possible through the generous funding support of the California Energy Commission. The entire West Biofuels team is deeply grateful for their contribution.

This report reflects the collective efforts of a diverse group of dedicated professionals. Above all, a heartfelt appreciation is extended to the staff at West Biofuels. Their expertise, dedication, and support were vital in advancing this work and pushing the boundaries of scientific and technological progress.

West Biofuels – Woodland: Mackenzie Castruita, Chang-hsien Liao, An Nguyen, Ashley Keating, Andrew Ramirez, Brandon Bruning

West Biofuels/Headlands – Petaluma: Peter Paul, Kristen Decker, Lisa Jones

The entire West Biofuels team acknowledges the contributions of the following individuals and their organizations that contributed to the success of this project and the content of this report. This work could not have been completed without the hard work of these dedicated professionals:

- National Renewable Energy Laboratory: Abhijit Dutta, Gary Grim
- University of California, Davis: Yen Chun Chou
- Colorado School of Mines: Carolyn Koh
- University of California, San Diego: Robert Cattolica, Reinhard Seiser
- Placer County Air Pollution Control District: Bruce Springsteen.

PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division manages the Gas Research and Development Program, which supports energy-related research, development, and demonstration not adequately provided by competitive and regulated markets. These natural gas research investments spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

The Energy Research and Development Division conducts this public interest natural gas-related energy research by partnering with RD&D entities, including individuals, businesses, utilities and public and private research institutions. This program promotes greater gas reliability, lower costs and increases safety for Californians and is focused in these areas:

- Buildings End-Use Energy Efficiency
- Industrial, Agriculture and Water Efficiency
- Renewable Energy and Advanced Generation
- Natural Gas Infrastructure Safety and Integrity
- Energy-Related Environmental Research
- Natural Gas-Related Transportation

Production of Pipeline-Grade Renewable Gas and Value-Added Chemicals from Forest Biomass Residues is the final report for the project (PIR-18-001) conducted by West Biofuels. The information from this project contributes to the Energy Research and Development Division's Gas Research and Development Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the Energy Research and Development Division at ERDD@energy.ca.gov.

ABSTRACT

This project demonstrates a novel conversion pathway for transforming forest biomass into mixed alcohol and renewable gas. The system integrates key process units, including a circulating fluidized bed gasifier, a mixed alcohol synthesis reactor, and a gas separation system to purify the produced renewable gas.

Data analysis showed an overall process efficiency of up to 36 percent, with 75 percent of the total energy input being retained in the renewable gas product, while the remaining energy was distributed into the mixed alcohol product. A methane recovery rate of about 70 percent was also achieved. Based on techno-economic modeling, the selling price of renewable gas of $12 per million British thermal units is feasible with sufficient revenue for the mixed alcohols to provide the balance needed to operate the plant. On a commercial scale, the production of biomass-derived renewable gas can reduce greenhouse gas emissions by up to 90 percent, contributing significantly to California’s clean energy and decarbonization goals.

This project demonstrates a scalable and sustainable approach for producing low-carbon renewable gas from forest biomass providing a viable alternative to fossil-based natural gas that supports wildfire risk mitigation and greenhouse gas reduction goals.

Keywords: Biomass Gasification, Renewable Gas, Mixed Alcohol Synthesis, Gas Separation, Membrane Separation, Pressure Swing Adsorption, Water Gas Shift

Please use the following citation for this report:

Li Wang, Matthew D. Summers, Jonathan Wells, Wesley Kraintz, Michael Long. 2025. *Production of Pipeline-Grade Renewable Gas and Value-Added Chemicals from Forest Biomass Residues.* California Energy Commission. Publication Number: CEC-500-2026-004

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Executive Summary

Background

California consumes more than two trillion cubic feet of natural gas annually, supplying over half of the state's electricity, heating, and cooling, and a growing share of transportation fuels. Despite being cleaner than other fossil fuels, natural gas significantly contributes to greenhouse gas emissions. With 90 percent of its natural gas imported, California faces supply risks and price fluctuations and loses more than $9 billion dollars annually in potential in-state revenue and jobs. To address this, renewable gas offers a promising solution. Renewable gas is biomethane derived from biomass, also known as organic matter, such as wood waste, used as fuel. While the state has 47 million bone dry tons (a measurement for biomass or pulp that accounts for moisture content) of biomass potential, only 10 million tons are currently used. Converting 30 million tons of biomass annually could produce 170 billion cubic feet of renewable gas, replacing eight percent of non-renewable gas and supporting greenhouse gas reduction goals. Additionally, using biomass helps reduce wildfire risks, lowers pollution, and promotes sustainable forest management.

Project Purpose and Approach

This project demonstrated the technical and economic feasibility of converting forest biomass into renewable gas and mixed alcohols (a mixture of methanol, ethanol, propanol, butanol, and pentanol) through a multistage process.

The research team designed and tested a complete system to turn biomass into valuable products and renewable gas. The system includes:

- Gasification to break down biomass into a gas mixture (mainly hydrogen, carbon monoxide, methane, carbon dioxide, and some nitrogen).
- Catalytic conversion to turn the gas into mixed alcohols, which are valuable byproducts as they can be used as additives for gasoline or further refined into valuable chemicals.
- Water-gas shift reaction to convert carbon monoxide into more carbon dioxide and hydrogen.
- Membrane separation to filter out hydrogen and carbon dioxide from the gas stream.
- Pressure swing adsorption to separate methane from nitrogen, producing high-quality renewable gas suitable for transport in existing gas pipelines.

This approach addressed key technical barriers in biomass-to-renewable gas conversion, including efficient methane separation from mixed alcohol synthesis tail gas and economic viability at commercial scale.

Key Results and Conclusions

This project represents a groundbreaking advancement in renewable gas production from biomass gasification. Renewable gas was successfully produced from gasification-derived syngas without methanation—a chemical process that converts carbon monoxide and hydrogen into methane using a catalyst—relying solely on advanced gas separation technologies. At a commercial scale, the techno-economic analysis reveals that renewable gas can be produced at a highly competitive price of $12 per million British thermal units (MMBtu) without relying on credits, which is significantly lower than traditional renewable gas production methods, which typically results in prices ranging from $13 per MMBtu to $30 per MMBtu.

What's more, this breakthrough technology achieves an impressive reduction in greenhouse gas emissions, with greenhouse gas emissions reduced by more than 90 percent compared to fossil natural gas, highlighting the environmental benefits of this innovative process. The carbon intensity of renewable gas produced through these gas separation methods ranged from five grams to eight grams carbon dioxide equivalent (CO_2e) per megajoule (MJ), which is lower than other renewable gas production methods, including the biomass gasification/ methanation method.

In summary, this project delivers affordable, clean energy to ratepayers while making a profound impact on reducing carbon footprints and enhancing wildfire management efforts. This groundbreaking approach sets a new standard for cost-effective, scalable renewable gas production, positioning it as a transformative solution to California's energy and environmental challenges.

Knowledge Transfer and Next Steps

The project team actively engaged with stakeholders, policymakers, and industry partners to share key findings and promote market adoption. Activities included:

- Presented technical findings and commercialization pathways at TCBiomass 2022 (Denver, CO) and TCBiomass 2024 (Itasca, IL), international conferences attended by industry leaders, utility representatives, and policymakers, to raise awareness of renewable gas technologies and their commercial potential. Presentations and proceedings were also made available via the TCBiomass website, providing broader access to technical outcomes.
- Delivered invited presentations and technical briefings to the California Energy Commission (CEC), Pacific Gas & Electric (PG&E), Southern California Gas Company, and the California Public Utilities Commission (CPUC) during site visits, project review meetings, and grant proposal discussions.
- Presented as invited speakers at the UC Davis AIChE General Meeting, engaging students and researchers in renewable gas applications and biomass conversion technologies.

To build on the project's success and move toward full-scale deployment, several key areas require further development:

Scaling Renewable Gas Production

- Further pilot and commercial-scale demonstrations are needed to validate system performance, optimize integration, and establish a cost-effective, forest biomass-to-gas pathway.

Addressing Long-Term Reactor Stability

- Research should focus on material durability, design optimization, and operational strategies to extend reactor lifespan and reduce maintenance costs.

Expanding Policy Incentives

- Continued support and enhancement of programs like the Low Carbon Fuel Standard and Senate Bill 1440 (Senator Ricardo "Ricky" Padilla, Statutes of 2010, Chapter 428) will be critical to drive investment and adoption.

Enhancing Grid Integration of Renewable Gas

- Strategic partnerships with gas utilities and suppliers will be essential to enable seamless pipeline injections and market access for renewable gas products.

Benefits to California Ratepayers

The project proved a technology that had the potential to provide numerous benefits to California natural gas IOU ratepayers, including:

Cost Reduction

Techno-economic analysis showed that renewable gas produced via this technology can be delivered at an estimated cost of $12 per MMBtu without credits, which is 30–50% lower than most existing renewable gas production pathways (e.g., anaerobic digestion or power-to-gas). As the technology matures and scales, it offers a realistic pathway to lower long-term utility procurement costs, reducing cost pressures passed on to ratepayers.

Air Emissions Reduction

The project produced renewable gas with a carbon intensity estimated at around 90 percent below that of fossil natural gas. Additionally, the project supports the reduction of greenhouse gases and air pollutants through the reduction of open pile burning in forests. Furthermore, using forest biomass in this process decreases the accumulation of flammable materials in forests, thereby reducing the risk of catastrophic wildfires and the release of particulate matter with diameters that are 2.5 micrometers and smaller ($PM_{2.5}$), volatile organics, and other air emissions.

Increased In-State Natural Gas Supply and Grid Reliability

The project demonstrated a promising innovative technology that will allow for in-state production of renewable gas from high hazard zone woody forest biomass, which is underutilized. This advancement creates opportunities to improve local fuel supply resilience by reducing California's reliance on out-of-state natural gas sources, which are subject to price volatility and supply chain disruptions. By enabling the production of low-carbon gas within California, the technology enhances energy security for both IOUs and ratepayers. It also diversifies the state's natural gas portfolio, contributing to a more stable and resilient energy system that supports long-term climate and reliability goals.

Economic Development and Job Creation

Commercial deployment of this technology is projected to create dozens of long-term jobs in forested and rural communities where facilities would be sited. This promotes equitable economic development while reducing ratepayer reliance on fossil fuel imports.

Forest Management and Watershed Protection

The project directly supports forest and watershed health, which benefits utilities and ratepayers by protecting critical infrastructure. Removing hazardous biomass from forests reduces the likelihood of catastrophic wildfires that threaten power lines, hydropower systems, and water supplies. It also helps maintain soil stability and watershed function, improving water retention and quality—important for ratepayers who rely on these services.

CHAPTER 1: Introduction

California consumes more than two trillion cubic feet of natural gas annually,[1] supplying 44 percent of the state's electricity generation.[2] 90 percent of the natural gas consumed in the state is imported. This dependence not only contributes to climate change but also results in economic losses exceeding nine billion dollars per year due to lost in-state production opportunities. Despite being cheaper and cleaner than other fossil fuels, natural gas still contributes significantly to greenhouse gas emissions and air pollution.

To address this, California has enacted progressive policies aimed at expanding renewable gas (RG) (biomethane derived from biomass) production and decreasing fossil natural gas dependence:

- Senate Bill 1383 (Lara, Statutes of 2016, Chapter 395): Requires a 40 percent reduction in methane emissions by 2030, increasing demand for low-carbon RG production.
- Senate Bill 1440 (Padilla, Statutes of 2010, Chapter 428): Mandates that gas utilities procure a certain amount of RG, creating a stable market for renewable methane.
- Low Carbon Fuel Standard: Provides financial incentives for RG production, particularly from dairy digesters and forest biomass.
- BioMAT Program: Supports small-scale biomass projects, including those that convert forest residues into energy.

Currently, most of California's RG supply comes from landfill gas recovery and anaerobic digestion at dairy farms and wastewater treatment plants. However, these sources alone cannot meet the state's increasing demand for renewable gas.

Forest biomass represents a critical untapped resource for renewable gas production. California generates approximately 47 million bone-dry tons of biomass annually, but only 10 million tons are utilized, mainly through direct combustion biomass facilities.[3] This leaves 37 million tons of underutilized biomass, which could be converted into clean energy. If just 30 million bone dry tons of biomass were converted annually, California could produce 6,000 megawatts (MW) of electricity or 170 billion cubic feet of renewable gas, equivalent to replacing eight percent of California's non-renewable gas supply.

---

[1] U.S. Energy Information Administration. "California Natural Gas Consumption by End Use." U.S. EIA. https://www.eia.gov/dnav/ng/ng_cons_sum_dcu_SCA_a.htm.

[2] California Energy Commission. 2023 Total System Electric Generation. California Electricity Data. https://www.energy.ca.gov/data-reports/energy-almanac/california-electricity-data/2023-total-system-electric-generation.

[3] California Energy Commission. Biomass energy in California. California Power Generation and Power Sources. https://www.energy.ca.gov/data-reports/california-power-generation-and-power-sources/biomass/biomass-energy-california.

Despite this potential, technological and economic challenges have hindered large-scale adoption of biomass-to-RG processes. Key barriers include:

- The cost to produce RG from biomass is still high compared to other RG production techniques.[4]
- Separation of nitrogen (N_2) and carbon monoxide (CO) from methane (CH_4). N_2, CO, and CH_4 share very similar physiochemical properties which make it challenging to separate them.
- Lack of commercially viable gas separation technologies tailored for biomass-derived syngas.
- Economic risks associated with new biomass-to-energy technologies, which limit investor confidence.

This project aimed to solve technical and cost challenges by creating a scalable process that turns biomass into RG and mixed alcohol. The alcohol produced can help lower the price of RG, making the process more affordable and ready for wider use.

Beyond environmental benefits, advancing RG production offers economic advantages, particularly for ratepayers in publicly funded projects. By diversifying the energy supply, RG can stabilize energy costs, reduce dependence on volatile fossil fuel markets, and create new job opportunities in rural and forested regions. Additionally, this project promotes a circular economy, transforming waste biomass into clean energy while reducing air pollution and improving public health outcomes.

Widescale implementation of this process could provide multiple benefits, including:

- Increased in-state RG production, reducing dependence on imported natural gas.
- Lower energy costs through multi-product revenue streams.
- Job creation in forested communities.
- Improved wildfire risk management through sustainable biomass utilization.
- Reduction of air emissions by providing an alternative to open pile burning.

Project Goals

The primary goal of this project was to develop and validate a viable process to convert higher hazard zone (HHZ) forest biomass into mixed alcohols and grid-quality RG to reduce the cost of RG and lower wildfire hazard risks. This was achieved through a series of specific targets and performance metrics.

---

[4] Barsun, Stephan, Ben Cheah, and Jean Shelton. August 2023. Renewable Natural Gas in California. Characteristics, Potential, and Incentives: 2023 Update. California Energy Commission. Publication Number: CEC-200-2023-010.

Goal 1: Convert woody biomass residue to multiple products including mixed alcohols and pipeline quality RG

- Use Sierra Nevada Region High Hazard Zone (HHZ) forest fuel hauled to the Woodland, California facility.
- Validate a process for tolerance of syngas contaminants.
- Produce syngas from forest waste biomass at a rate of at least 25 standard cubic feet per minute (SCFM).
- Complete more than 500 hours of testing producing RG from syngas. Complete at least two eight-hour steady state operational periods with the full process. These tests included complete data collection of process parameters and performance.
- Achieve less than five percent degradation of system output and efficiency during the 500-hour test period.

Goal 2: Develop and validate the integrated process steps demonstrating the production of gas grid-quality RG

- Demonstrate a pilot scale biomass-to-RG process including gasifier, catalyst reactor, and gas separation process.
- Separate RG from other products.
- Utilize syngas to produce upgraded RG at a rate of at least 2.5 SCFM.
- Achieve an overall process efficiency of 55 percent with at least 60 percent of energy in the RG product.

Goal 3: Assess Commercial Viability and Economic Feasibility

- Leverage by-products to achieve a wholesale cost of RG of $12 per MMBtu or lower.
- Demonstrate key financial metrics for a commercial plant, including a simple payback period of less than 15 years with a plant designed for 30 years of service.
- Complete a feasibility assessment for commercially deploying the technology across the Sierra Nevada Region.
- Evaluate the ability for commercial-scale facilities to meet the air emission requirements of air districts across the Sierra Nevada Region based on the pilot-scale performance.
- Demonstrate a Low Carbon Fuel Pathway carbon intensity of less than 15 grams CO_2e per MJ of transportation fuel.

CHAPTER 2: Project Approach

Project Management, Partnership, and Work Distribution

The project involves collaboration among multiple organizations, each contributing expertise in different areas. The lead and primary support for each task are listed in Table 1.

Table 1: Project Partners and Tasks

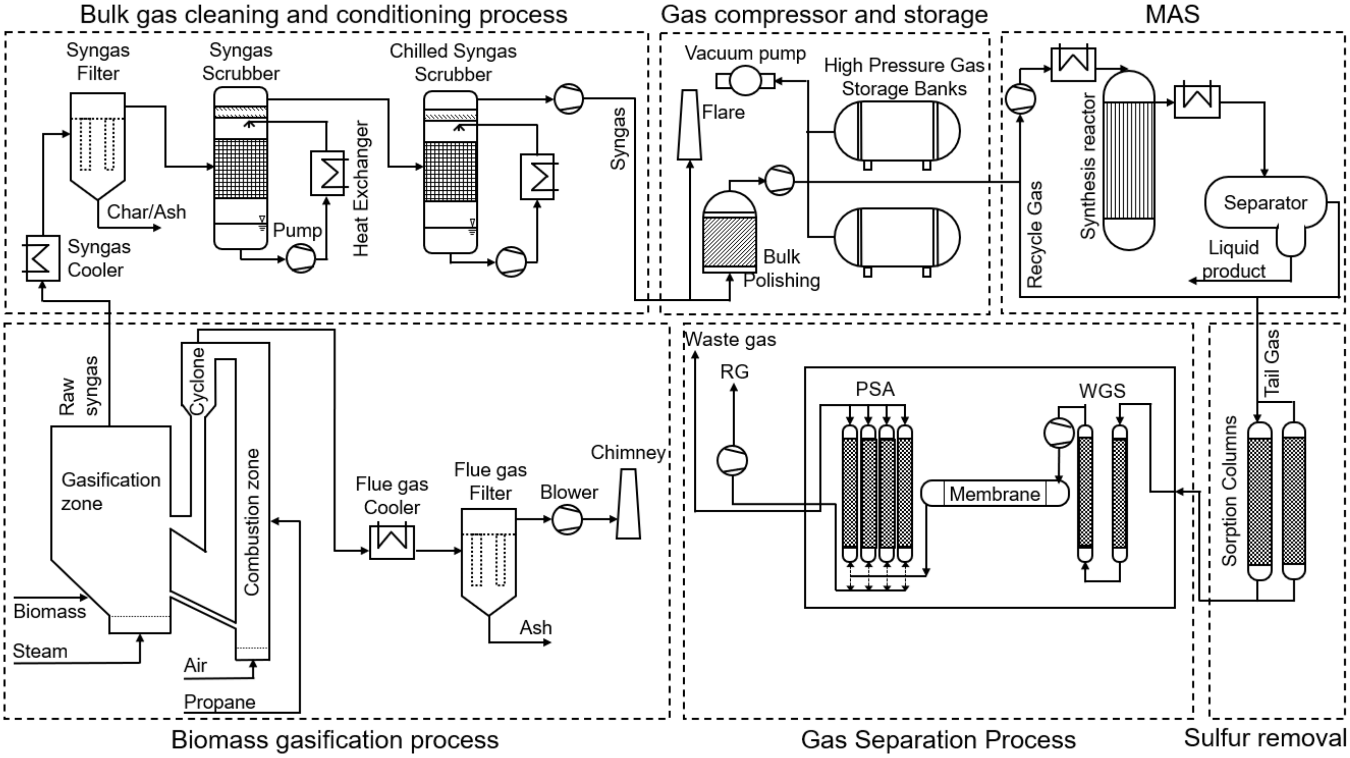
Task	Lead	Primary Support
1: General Project Tasks	West Biofuels	
2: Parameter Testing and Optimization	University of California San Diego (UCSD), Colorado School of Mines (CSMs)	West Biofuels, University of California, Davis (UC Davis), National Renewable Energy Laboratory (NREL)
3: Design and Construct Integrated Pilot System	West Biofuels	UCSD, NREL, CSMs
4: Test Pilot System	West Biofuels	UCSD, UC Davis
5: Long-term Pilot Testing	West Biofuels	UCSD, UC Davis, NREL, CSMs
6: Renewable Gas Testing	West Biofuels	UCSD, Southern California Gas Company (SoCalGas)
7: Evaluation of Project Benefits	West Biofuels	Placer County Air Pollution Control District
8: Technology/Knowledge Transfer Activities	West Biofuels	
9: Production Readiness Plan	West Biofuels	

Source: West Biofuels

Testing and Optimization

The process flow diagram (PFD) for the mixed alcohol and renewable gas (MARG) process is depicted in Figure 1. A fast internally circulating fluidized bed (FICFB) gasification system converted biomass into low-tar, high energy density product gas (syngas). Post-gasification filtration, scrubbing, and adsorption units removed bulk impurities, which resulted in high-quality syngas. A flaring unit exhausted any excess syngas production and in conjunction with the compression and storage module, effectively decoupled gas production from the remaining syngas processing systems. Decoupling allowed focused research and development on all downstream equipment independent of the gasification system. The Compression and Storage module allowed capture and storage of produced syngas.

Figure 1: PFD of the MARG Process



Source: West Biofuels

Alcohol production was achieved by converting compressed syngas into mixed alcohols using a commercially available sulfur-tolerant catalyst. The tail gas from the mixed alcohol synthesis passed through the sulfur removal unit and then was captured using the boosting sub-module.

Pipeline-quality RG was produced from the tail gases of the mixed alcohol synthesis (MAS) system using a series of separation unit operations. To convert the multi-species tail gas into pipeline-quality RG, various separation technologies were tested and integrated, including water-gas shift (WGS), membrane separation, and pressure swing adsorption (PSA).

Based on the study results, the selected RG separation pathway involved passing the tail gas through a water-gas shift reactor to convert CO into carbon dioxide (CO_2), followed by a membrane to selectively permeate H2 and CO_2 while retaining CH_4 and N_2, and finally through a PSA unit to remove N_2. This resulted in a high-purity CH_4 stream meeting pipeline-quality RG standards.

Each module within the system was designed to be tested independently before full integration to ensure optimal performance at each stage. The gasification, syngas cleaning, compression and storage, MAS, sulfur removal, and RG separation modules were evaluated separately under controlled conditions. This modular approach allowed for detailed performance assessments, troubleshooting, and optimization of individual unit operations. Once validated, the modules were systematically integrated to establish a complete process flow, ensuring seamless interaction between components and efficient conversion of biomass into pipeline-quality RG.

Commissioning

Gasifier Runs

The gasifier was a one-Megawatt Thermal (MWth) FICFB system designed to process up to five tons of dry biomass per day (Figure 2). It operated as a dual fluidized bed gasification system, utilizing synthetic bed material to transfer heat from the combustion zone to the gasification zone.

Figure 2: Pilot-Scale Gasifier at The Woodland Biomass Research Center

Source: West Biofuels

In the gasification zone, steam was injected from the bottom of the gasifier to create a fluidized bed. This meant the steam lifted and mixed the bed material (like sand) and biomass particles, allowing them to behave like fluid. The biomass came into close contact with the hot bed material and steam, where it was heated to around 1472°F (800°C). At this high temperature, the biomass underwent thermochemical reactions and was converted into syngas—a mixture of H_2, CO, CO_2, CH_4, and other minor gases (ethylene (C_2H_4), ethane (C_2H_6)). The remaining solid material, called char, along with some bed material, was carried by gravity to the combustion zone.

In the combustion zone, air was injected to burn the char. This combustion generated heat, which reheated the bed material. The hot bed material was then lifted into a cyclone (a device that separates solids from gases) through a riser. In the cyclone, the bed material was separated from the flue gases (the gases produced during combustion). The reheated bed material was sent back to the gasification zone to continue the process, while the flue gases were directed to a flue gas treatment system. The flue gas treatment system first passed the flue gases through a particulate filter to remove dust and ash particles. Next, the gases flowed through an adsorber, which removed harmful pollutants like nitrogen oxides (NO_x), volatile organic compounds (VOCs), and sulfur dioxide (SO_2). This ensured that the flue gases were clean before being released into the atmosphere.

The raw syngas from the gasification zone also underwent conditioning to remove impurities, ensuring it was suitable for downstream applications. First, filtration removed particulate matter, such as dust and ash. Next, scrubbing with biodiesel eliminated tars and water-soluble impurities, such as ammonia and chlorine. Finally, the gas passed through an adsorption bed to remove sulfur compounds, such as hydrogen sulfide (H_2S). The resulting conditioned syngas was free from tars, particulate matter, sulfur compounds, chlorine, and ammonia. This made it ideal for use in catalytic systems and downstream gas separation.

Mixed Alcohol Synthesis

The synthesis reactor system was designed for pre-commercial catalytic process development and demonstration using biomass-generated syngas from the FICFB located on-site.[5] The proprietary reactor, designed by West Biofuels, was a fixed-bed system and contained a molybdenum sulfide catalyst for mixed alcohol synthesis. The reactor was designed to operate at pressures up to 172 bar and temperatures up to 662°F (350°C), with the capability to be upgraded to handle pressures up to 345 bar. It featured a two-inch internal diameter and a 20-foot length, providing a catalyst volume capacity of up to 10 liters (L). The system was designed to simulate a single catalyst tube of a commercial synthesis reactor, thereby maximizing confidence when scaling toward commercial applications. A 21-point profiling thermocouple was installed directly in the catalyst bed to measure temperature every 11 inches. Thermal management was accomplished via circulation of thermal heat transfer fluid. The automated control system regulated and monitored all process parameters during operation. Synthesis reactor system design parameters are summarized in Table 2. Gas Hourly Space Velocity (GHSV) is a key parameter in catalytic reactor design. It represents the volumetric flow rate of gas passing through a reactor per unit volume of catalyst per hour, with unit (per hour, 1/hour).

Table 2: Design Parameters of MAS Reactor System

Design Parameters	Range/Value
Temperature, ˚C	250 - 345
Catalyst Volume, Liter	10
Producer Gas Flow Rate, Standard liter per minute (SLPM)	212
Gas Hourly Space Velocity, 1/hour	1070
Liquid Flow Rate, L/hour	4.9

---

[5] Summers, Matthew, Matthew Hoffman, Chang-hsien Liao, Matthew Hart, Richard Seiser, Robert Cattolica, Reinhard Rauch, and Matthias Binder. West Biofuels. 2019. West Biofuels Fuel Ethanol & Value-Added Chemicals from Biomass Residues. California Energy Commission. Publication Number: CEC-600-2019-140.

Design Parameters	Range/Value
Condenser Temperature, °C	25
Number of Separator Stages	2
Number of Recycle Compressor Stages	4

Source: West Biofuels

Technical Approach

The MAS tests were conducted using on-site generated syngas and operated at higher pressures than those achievable in the laboratory.[6] Additionally, system degradation was monitored by analyzing performance variations over time-on-stream. The experimental design for the MAS pilot study is shown in Table 3, testing different combinations of temperature, pressure, Gas Hourly Space Velocity (GHSV), gas composition, H_2/CO ratio, and recycle rate to assess system performance.

Table 3: MAS Pilot Parametric Study Plan

Case #	Temperature, °C	Pressure, bar	GHSV,1/ hour	CO, mol%*	H_2, mol%	H_2/CO	Recycle Rate, %
1	270	100	1000	33.5	31.4	0.94	90
2	270	100	1000	33.5	31.4	0.94	75
3	270	140	1000	33.5	31.4	0.94	90
4	270	140	1000	33.5	31.4	0.94	75
5	330	100	1000	33.5	31.4	0.94	90
6	330	100	1000	33.5	31.4	0.94	75
7	330	140	1000	33.5	31.4	0.94	90
8	330	140	1000	33.5	31.4	0.94	75

* mol%: mole percent
Source: West Biofuels

Parameter testing of the synthesis reactor was conducted using captured gases generated by the FICFB system. Key process conditions, including temperature, pressure, and space velocity (flow rates), were set and automatically maintained by the control software throughout the test. The software also logged all set points and real-time measurements across the system. The gas composition of the input and output streams was analyzed on-site using Gas Chromatography (GC).

Gas analysis was performed periodically using GC sampling, while produced liquids were collected every hour and analyzed in batches. The duration of each test condition depended on the recycle rate, with conditions held until the system achieved steady performance, ensuring the generation of reliable data and product yields.

---

[6] Seiser Reinhard, and Nguyen An (2021) Production of Pipeline Grade Renewable Natural Gas and Value-Added Chemicals from Forest Biomass Residues_Mixed Alcohol/Renewable Natural Gas Parameter Test Report.

Sulfur study

Sulfur removal from the synthesis tail gas is essential before upgrading operations to protect equipment and meet gas purity standards. The study on sulfur removal technology followed the RG Test Plan with three key objectives:

- Determining the equilibrium breakthrough point for sulfur species.
- Confirming the accuracy of the design sizing for effective sulfur removal.
- Evaluating long-term removal performance in purifying the synthesis reactor tail gas.

For this project, a sulfur removal material was required to treat syngas containing up to 200 parts per million (ppm) of sulfur compounds, with a target output of less than 12 ppm total sulfur (including less than four ppm H_2S and less than five ppm mercaptan). After evaluating various materials, two sulfur removal absorbents were selected for testing:

- Unicat SR-112DMP: A mixed metal oxide, high surface area zinc oxide and manganese dioxide (MnO_2) based adsorbent with temperature operating range from ambient to 250 degrees Fahrenheit that is suitable for H_2S and light mercaptan capture.

- Unicat TSR-12 SF: A low-temperature desulfurization catalyst that uses a quad-metal promotion system, including copper oxide and iron oxide, manganese dioxide, and zinc oxide on activated carbon. It is specifically designed to remove trace amounts of H_2S, light mercaptans, dimethyl sulfide, carbon disulfide, carbonyl sulfide, and other trace contaminants. This catalyst operates effectively within a temperature range from ambient conditions up to 150 degrees Fahrenheit.

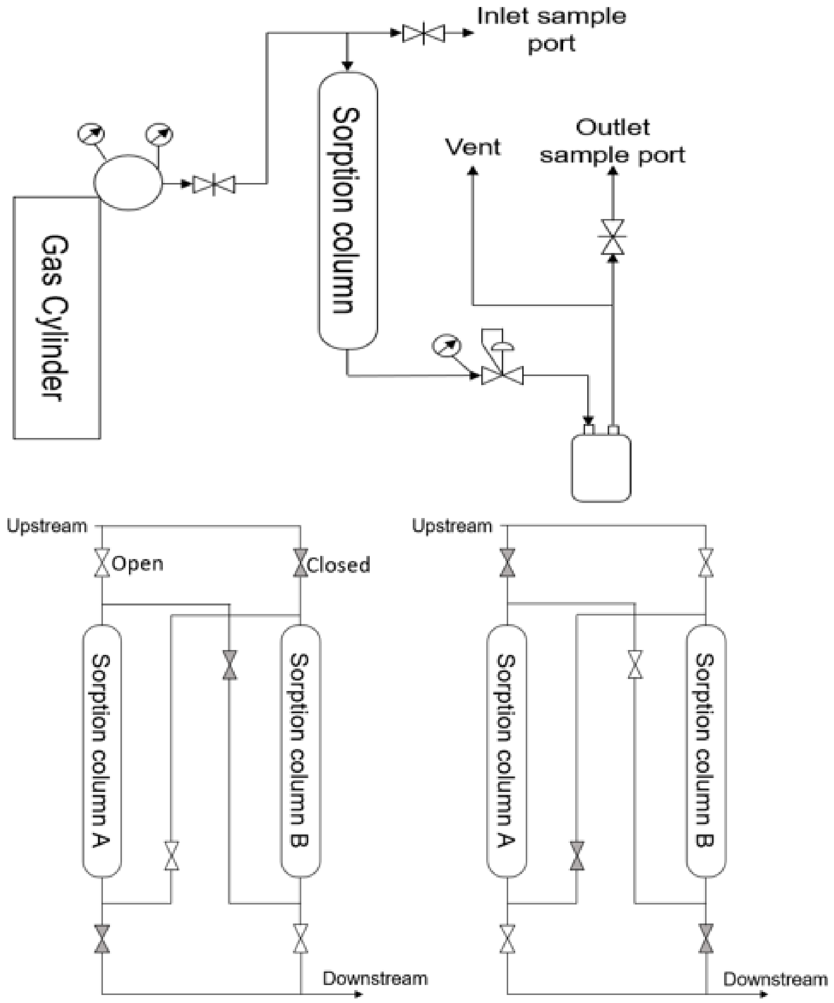
Sulfur Removal Process Description

The sulfur removal system consists of two sorption columns equipped with valves that allow either column to be used individually or both in series (Figure 3).

The system operates in an alternating lead-lag series, with the newest bed serving as a guard bed downstream of the active bed. When the upstream active bed is saturated, it is taken offline, and the guard bed then becomes the new active bed. After replacing the sorption material in the offline bed, it is brought back as the guard bed downstream of the current active bed. Bed saturation is monitored by measuring sulfur levels between the two beds, using Dräger tubes (high precision glass sampling tubes) with a detection limit of one ppm.

Two different three-foot-long sulfur sorption columns were fabricated from schedule 80, two-inch SS316 pipe to withstand operating pressures up to 172 bar and operate at a design space velocity of 2000 (1/hour) allowing SLPM of tail gas purification. Being a lead-lag arrangement, both columns were identically double packed to contain both adsorbents.

Figure 3: PFD of Sulfur Removal Study



Source: West Biofuels

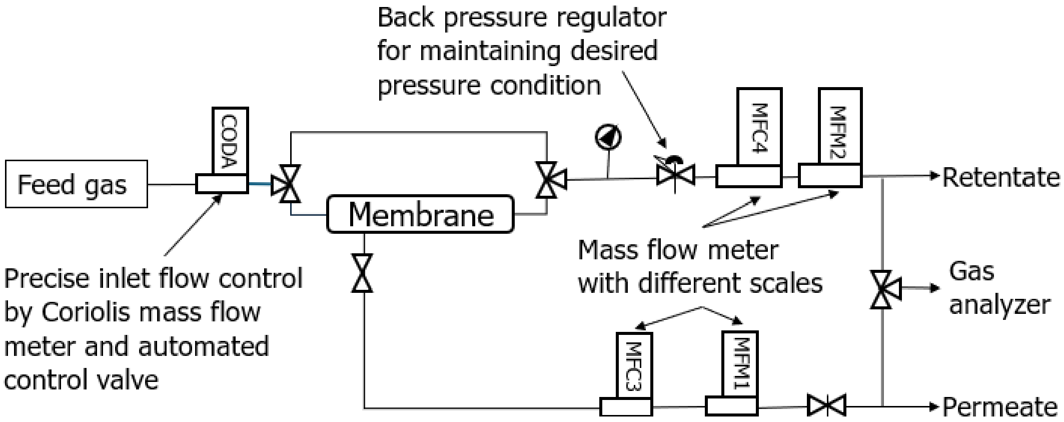
Modules Test Procedures

Membrane Separation Studies

Membrane technology offers an efficient gas separation process by selectively separating target gases via differing permeation through a material. When gas flows through the membrane system, it splits into two streams: retentate and permeate, based on their different permeation rates through the membrane material, driven by a pressure difference across the membrane. The components that pass through the membrane are called permeate while the components that are retained by the membrane are called retentate. Membrane separation efficiency and selectivity are primarily controlled by the membrane's pore size, structure, and material properties, as well as the operating conditions, such as temperature, pressure, and partial pressure differences of the components on either side of the membrane.

The diagram of the experimental setup for the membrane study is shown in Figure 4. Feed gas was introduced into the system with precise inlet flow control, managed by a Coriolis mass flow meter and an automated control valve. The gas then passed through a membrane designed for separation. A back pressure regulator was used to maintain the desired pressure conditions within the system. Mass flow meters with different scales were employed to measure flow rates accurately across varying ranges. Gas chromatography was used to analyze the gas composition from both retentate and permeate streams.

Figure 4: Flow Process Diagram for Membrane Module



Source: West Biofuels

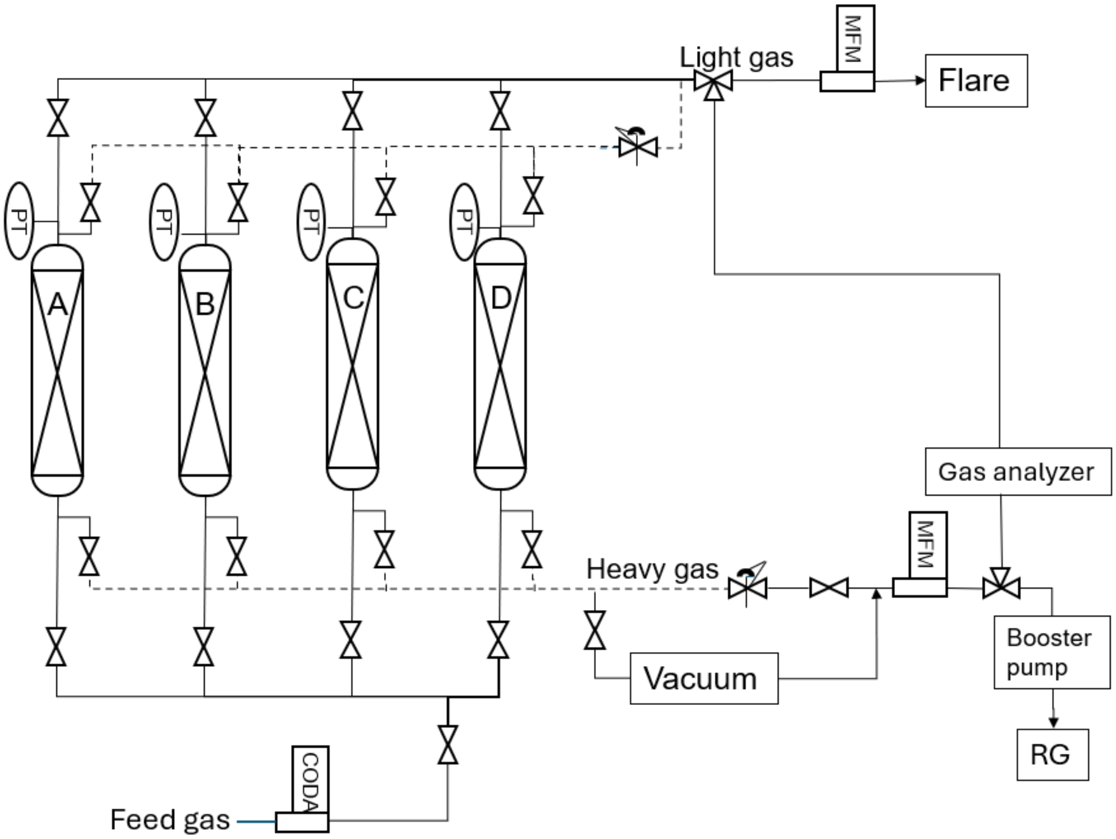
Pressure Swing Adsorption Studies

Pressure Swing Adsorption (PSA) is a separation technology in which at least two sorption units alternate between loading and unloading conditions through the control of operating pressure. Additional columns are typically employed to allow recovery of depressurization gases and improve process yields. When the active column reaches a set condition, typically time on stream or breakthrough concentration, the columns are switched. When inactive, the pressure of the pre-active column is reduced causing adsorbed gases to be released. The light gas stream (gas that is not adsorbed) flows continuously through the system and is separated from the heavy gas. This light gas typically includes less-adsorbable species such as hydrogen (H_2), which are collected or vented during the adsorption cycle. The purity of the heavy gas stream (gas that is adsorbed to sorbent) is maintained by cycling the process before the breakthrough of the desired species.

The behavior of the PSA process is affected by species partial pressure, temperature, residence time, and material properties. Pressure is the control variable of interest during the loading process. Temperature has minimal effect for the ambient operations of the proposed material when compared to the large pressure ranges under study. Residence time, a function of flowrate through the column, is fixed at the design value for all loading experiments.

Following an extensive literature review, a four-column PSA system (Figure 5) was implemented to offer improved separation performance and higher yields as the additional columns allowed for significant recycling of gases that would have been wasted. The designed four-column PSA system consisted of four identical columns filled with adsorbent material (activated carbon). The system operated cyclically, with each column alternating between four main phases: adsorption, depressurization, vacuum, and re-pressurization. During the adsorption phase, the feed gas mixture was introduced at high pressure, and target gas components were adsorbed by the material, while non-adsorbed gases passed through. The column was then depressurized, allowing the adsorbed gas to desorb; a vacuum phase followed to remove residual adsorbates and regenerate the adsorbent material; and finally, re-pressurization prepared the column for the next cycle. The columns operated in an overlapping manner to ensure continuous separation, with each undergoing a different phase at a given time. The system's valve controls, and vacuum controls, flow rates, and cycle duration, were programmed via LabVIEW software.

Figure 5: Four Column PSA Diagram



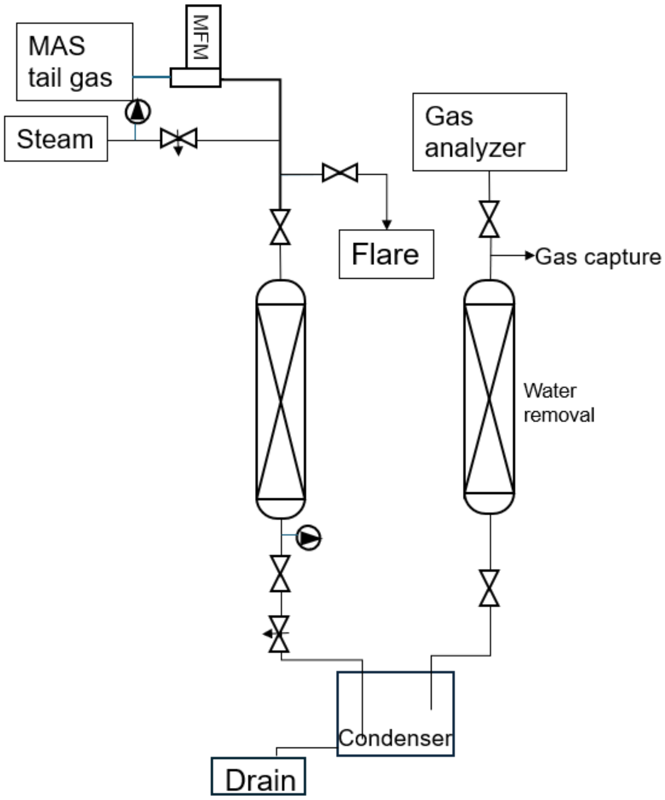
Source: West Biofuels

Water Gas Shift Studies

Based on the membrane and PSA separation results, it was found that CO could not be effectively separated from CH_4. To remove CO, the water gas shift (WGS) reaction was introduced. WGS is an essential industrial process for CO removal by transforming CO into CO_2 and H_2. The performance of the WGS reaction is influenced by factors such as temperature, catalyst activity, and gas composition. The goal is to maximize CO conversion while maintaining the balance of reaction kinetics and system efficiency, ensuring high-quality gas streams for downstream processes.

The PFD and actual assembled reactor for WGS reaction is shown in Figure 6. The reactor was loaded with 1858.8 grams of low-temperature shift catalyst from UNICAT Catalyst Technologies, LLC. The catalyst activation was completed by passing a carrier gas over the catalyst and introducing H_2 in a controlled manner to induce reduction. The bed temperature was heated and maintained within the range of 320°F (160°C) to 428°F (220°C) during activation. For the CO conversion of the gas, N_2 was introduced during reactor warm up. Reactor pressure was maintained at 2-3 bar. The gas introduction began when the reactor temperature reached 284°F (140°C), with its flow precisely controlled via a Coriolis flowmeter and metering valve, after which 5.5 bar steam was introduced.

Figure 6: The PFD of Water Gas Shift Reactor



Source: West Biofuels

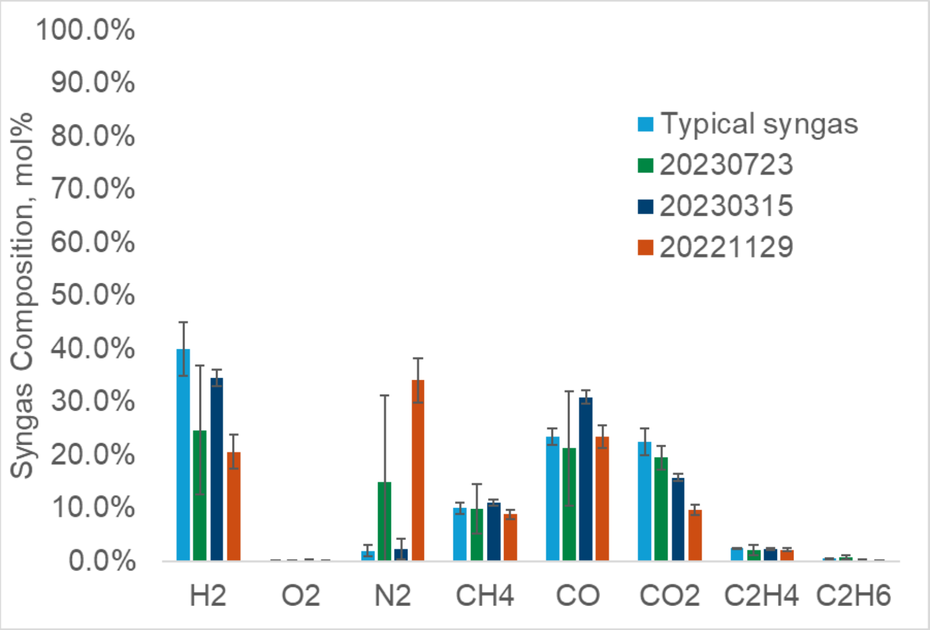
CHAPTER 3: Results

Gasifier Runs

The gasifier consistently produced syngas at rates exceeding the target of 25 SCFM, with recorded rates surpassing 70 SCFM. Over the course of 12 gasifier run campaigns, the system captured enough syngas to fill two 563 L vessels to 193 bar each and logged a total of 577 operational hours. Syngas composition varied based on operating conditions, with some runs exhibiting higher-than-expected N_2 content due to plugging of the biomass feeder. This is possibly because N_2 was injected into the biomass feed system (hopper), creating a blanket that prevents the entry of syngas. If the hopper or biomass feeder screw becomes plugged, it could disrupt the biomass supply to the gasifier. In this scenario, N_2 would continue to flow into the system, potentially diluting the syngas.

The gas compositions of syngas from different gasifier runs (dated 2022.11.29, 2023.03.15, and 2023.07.23, respectively) were compared to typical syngas composition in Figure 7. The term "typical syngas" refers to the expected composition of synthesis gas from biomass steam gasification under optimized conditions. Reference values for typical syngas compositions can be found in the report.[7]

Figure 7: Comparison of Typical Syngas Composition with Acquired Syngas



Source: West Biofuels

---

[7] Summers Matthew, Liao Chang-hsien, Cattolica Robert, Seiser Reinhard, Jenkins Bryan, Vergnani Paul, Weaver Christopher, and Hart Matthew. 2015. Demonstration of Advanced Biomass Combined Heat and Power Systems in the Agricultural Processing Sector. California Energy Commission. Publication number: CEC-500-2016-035.

Objectives Justification

- **Produce syngas from forest waste biomass at a rate of at least 25 SCFM.**

  Achieved. The syngas production rate was about 140 SCFM for a typical gasifier run.

- **Use Sierra Nevada Region HHZ Forest fuel hauled to the Woodland, California facility.**

  Achieved. The biomass was hauled from the Sierra Nevada Region higher hazard zone.

Challenges and Lessons Learned

- **Excessive Nitrogen Dilution from Biomass Feeder Plugging**

  The biomass feeder relied on N_2 injection to prevent syngas backflow; however, when the feeding screw became plugged, excessive N_2 entered the system. This resulted in high N_2 dilution in the captured syngas, reducing the heating value and affecting downstream processing efficiency. The issue highlighted the need for real-time monitoring of biomass flow and improved feeder design to prevent plugging.

- **Severe Tube Plugging in the Product Gas Heat Exchanger**

  During operation, significant plugging occurred in the heat exchanger tubes due to particulate accumulation and tar condensation, leading to reduced heat transfer efficiency and operational disruptions. This issue emphasized the need for enhanced gas cleaning upstream, improved heat exchanger design to mitigate fouling, and regular maintenance protocols to prevent severe blockages. Future designs should consider self-cleaning mechanisms or optimized operating temperatures to minimize tar deposition and particulate buildup.

Mixed Alcohol Synthesis Performance

The MAS reactor achieved 154 hours of operation, successfully converting syngas into mixed alcohols and methane-rich tail gas. Parametric study results are listed in Table 4 and analyzed based on specific performance parameters. High mass closure values (>91 percent) were achieved in most cases, indicating accurate measurements with minimal mass loss.

Table 4: Results of MAS Runs

No.	C_ rtr, %**	C_ sys, %***	Alcohol Productivity, g_liq/ L_cat/Nm^3	H_2*, %	O_2*, %	N_2*, %	CH_4*, %	CO*, %	CO_2*, %	C_2H_4*, %	C_2H_6*, %
1	0.99	0.91	6.66	28.01	0.13	2.72	14.65	31.01	19.24	1.24	0.58
2	0.98	0.94	6.29	31.01	0.14	2.96	12.83	31.12	17.14	1.75	0.43
3	0.99	0.96	7.15	27.12	<0.01	2.78	15.12	30.13	20.34	1.13	0.63
4	0.98	0.94	5.15	28.23	<0.01	2.92	15.23	29.14	20.92	1.21	0.63
5	0.99	0.94	9.13	22.15	0.12	8.83	16.32	25.23	22.64	0.81	0.78
6	0.99	0.96	5.78	24.31	<0.01	3.01	18.83	25.44	25.81	1.03	1.16

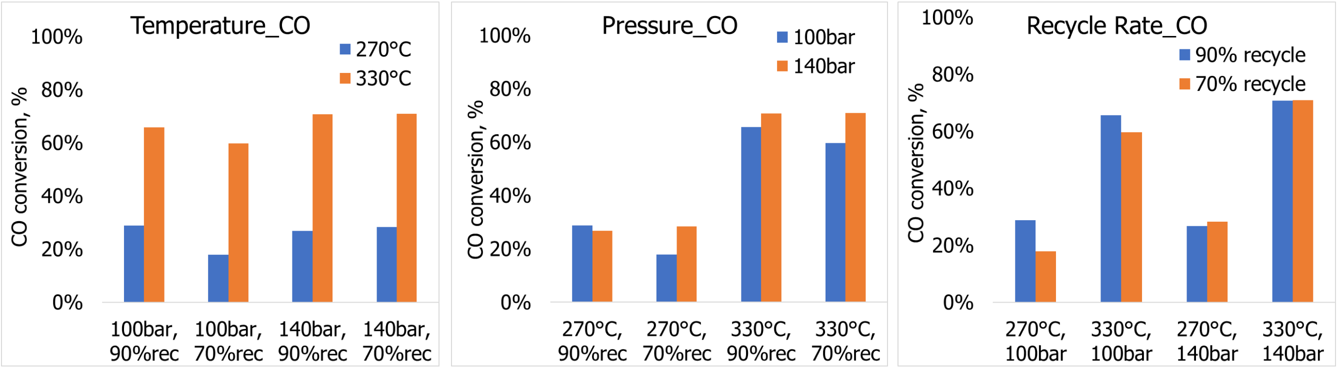
No.	C_ rtr, %**	C_ sys, %***	Alcohol Productivity, g_liq/ L_cat/Nm^3	H_2*, %	O_2*, %	N_2*, %	CH_4*, %	CO*, %	CO_2*, %	C_2H_4*, %	C_2H_6*, %
7	0.97	0.81	10.16	20.05	<0.01	5.84	19.32	24.21	25.74	0.89	1.05
8	0.98	0.92	5.55	22.14	0.24	4.01	19.72	22.25	27.43	1.07	1.2
Feed gas composition, %				33.89	<0.01	2.22	11.73	31.02	15.73	2.43	0.26

*Inlet Gas Composition
**C_rtr: Closure of reactor
***C_sys: Closure of system
Source: West Biofuels

CO Conversion

CO conversion increased with increasing temperature for all conditions. The CO conversion results aligned with the lab scale result in the parameter test report, which also demonstrated a significant difference between 518°F (270°C) and 626°F (330°C).[8] Higher pressure negatively impacted CO conversion across all cases, except in low-temperature, high-recycle scenarios. At low pressure, CO conversion decreased as the recycle rate increased, while at high pressure, the recycle rate had minimal impact on CO conversion (Figure 8).

Figure 8: CO Conversion Plots as Functions of Temperature, Pressure, and Recycle Rate



Source: West Biofuels

Production of Alcohols and Renewable Gas

Temperature, pressure, and recycle rate effects were all investigated against liquids, alcohol, and RG production. RG here is calculated as the CH_4 amount in the tail gas per unit of feed gas.

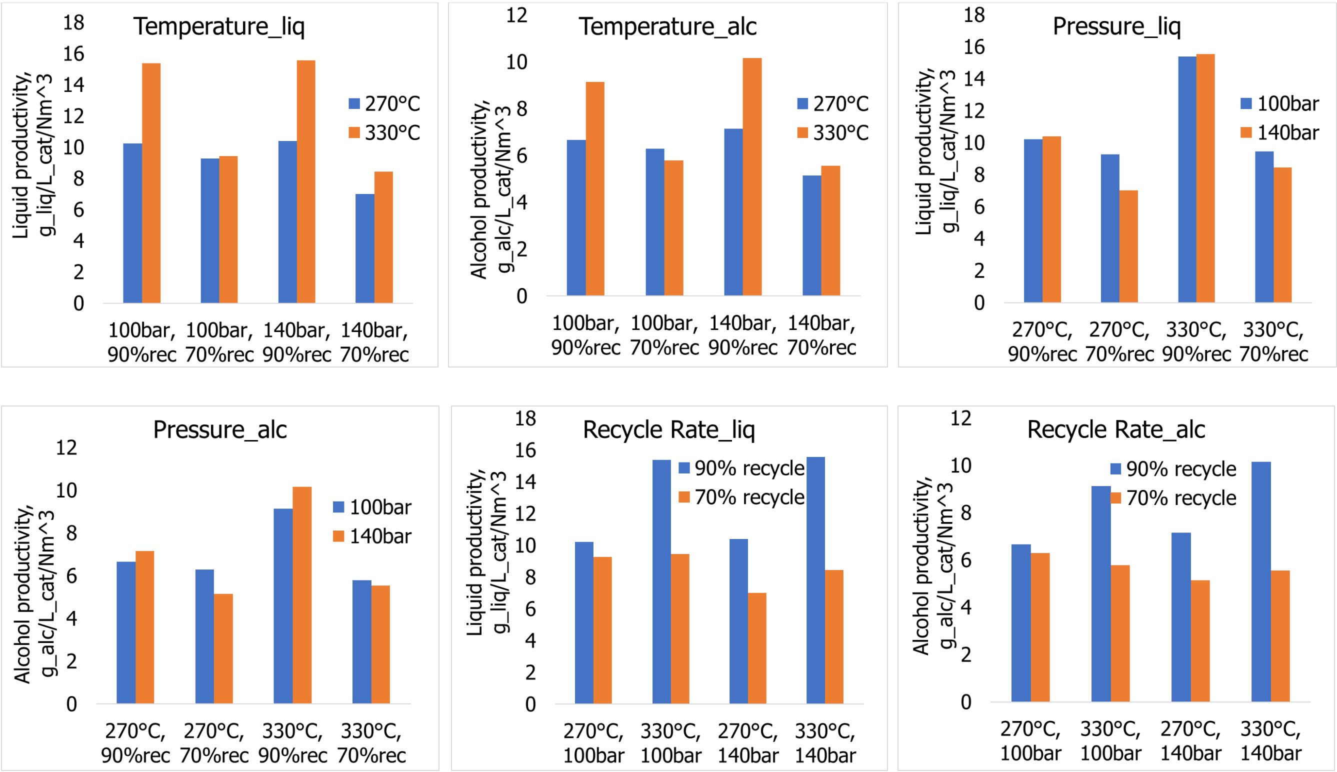
Both total liquid and total alcohol productivity increased during pilot testing as the temperature rose from 518°F (270°C) to 626°F (330°C), with the 90 percent recycle scenario showing a significantly greater increase compared to the 70 percent recycle scenario (Figure 9). Productivity, expressed in grams of alcohol per liter of catalyst per normal cubic meter of syngas (g_alc/L_cat/Nm^3), indicating the efficiency of syngas conversion in the reactor. In the

---

[8] Ibid

lab scale reactor (single pass, without recycling), higher temperatures were observed to reduce alcohol productivity.[9] At 100 bar and temperature of 518°F (270°C), the alcohol productivity ranged from 6-10 g_alc/L_cat/Nm³, which was slightly lower than the lab-scale tests simulating a 75 percent tail gas recycle, where productivity reached 15 g_alc/L_cat/Nm³. Similarly, at 100 bar and 626°F (330°C), the alcohol productivity ranged from 6-9 g_alc/L_cat/Nm³, compared to 13 g_alc/L_cat/Nm³ in the lab-scale tests with simulated 75 percent tail gas recycle. Overall, the pilot-scale MAS test results were consistent with the results observed in the lab-scale tests.

Figure 9: Effect of Temperature, Pressure, and Recycle Rate on the Productivity of Liquids and Alcohol



Source: West Biofuels

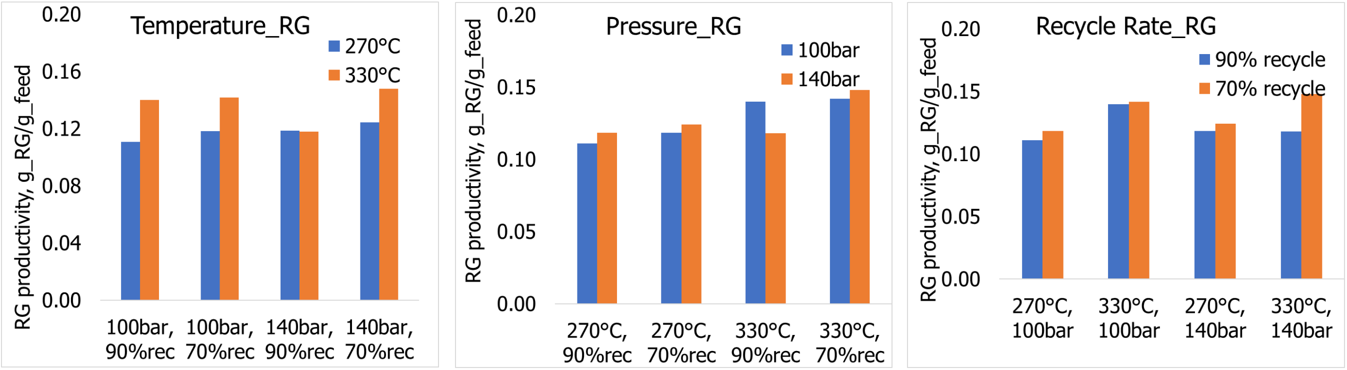
RG productivity in pilot scale testing increased significantly as temperature rose from 518°F (270°C) to 626°F (330°C), consistent with lab-scale findings indicating that higher temperatures in the laboratory reactor enhance RG productivity.[10] Higher pressure generally boosted the liquid and alcohol production across all cases, except for the condition with high temperature and a low recycling rate. Similarly, higher pressure improved RG production in most cases, except when both pressure and recycle rate were high. Increasing the recycling rate reduced both alcohol production and RG production.

---

[9] Ibid

[10] Ibid

Figure 10: Effect of Temperature, Pressure, and Recycle Rate on the Productivity of RG



Source: West Biofuels

Catalyst Degradation

The catalyst in the synthesis system was run for 154 hours total during testing. Catalyst degradation was evaluated by comparison of system performance against time-on-stream. No degradation in performance was detected in this period. Additional time-on-stream would be required to determine the degradation timeline for the catalyst. The catalyst can be regenerated so a few full cycles of degradation and regeneration should be completed. This could take thousands of hours and is outside the scope of the current project.

Key Findings

- CO conversion rates exceeded 70 percent under optimized conditions.
- Lower temperature favored mixed alcohol production, while increased temperature favored RG production.
- Alcohol productivity varied between 6–10 g/L_cat/Nm³.
- Recycle rates significantly influenced alcohol yields, with higher recycling leading to reduced alcohol output but increased RG production.

Objectives Justification

- **Achieve less than five percent degradation of system output and efficiency during the 500-hour test period.**

  While the goal was to run the pilot-scale system for 500 hours to check for less than five percent degradation, the test run was stopped after 154 hours. During this time, the system performed well, and no noticeable decline in output or efficiency was observed. However, running the reactor for the full 500 hours posed safety concerns. The reactor operates at high pressure and uses a molybdenum sulfide catalyst in a sulfur-rich environment, which can weaken the reactor walls over time. Since there was no long-term data on how the reactor would hold up, the risk of damage was too high to continue the test safely. Although the full test was not completed, the results so far show that the system works efficiently. Future studies should focus on testing reactor durability before committing to longer operational periods.

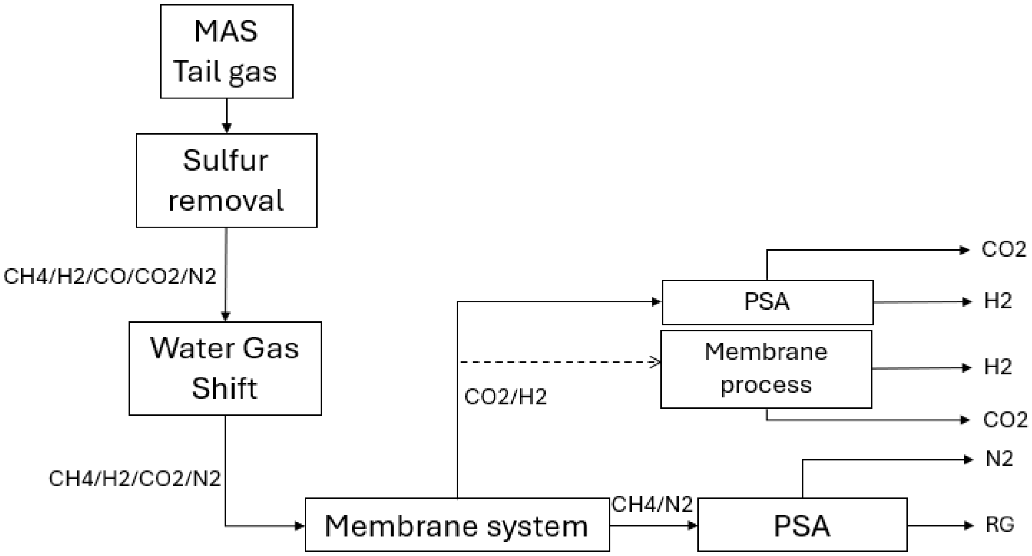
Challenges and Lessons Learned

- Reactor pressure limitations constrained operating flexibility. Sulfur based catalysts can degrade the reactor wall and make it vulnerable to high pressure.
- Early liquid withdrawal inconsistencies were resolved through system modifications. To resolve this issue, a redesigned liquid-gas separation unit was incorporated into the system. This two-stage unit includes a high-pressure dropout followed by a fine coalescing filter, ensuring efficient separation.
- Additional long-term catalyst stability testing is needed for commercialization.
- H_2/CO ratio smaller than one may lead to carbon deposition (coking).

Gas Upgrading and Separation

An integrated gas upgrading process was established based on the membrane and PSA separation results (Figure 11). The selected RG separation pathway begins with the MAS tail gas passing through a sulfur removal unit to eliminate sulfur, followed by a water-gas shift reactor to convert CO into CO_2. The resulting CO- and sulfur-free gas is then processed through a membrane to separate H_2 and CO_2, and finally through a PSA unit to remove N_2, producing a high-purity CH_4 stream. Due to the challenges of integrating all systems, each unit was operated individually, with the product gas collected at each stage and fed into the next to simulate the integrated process.

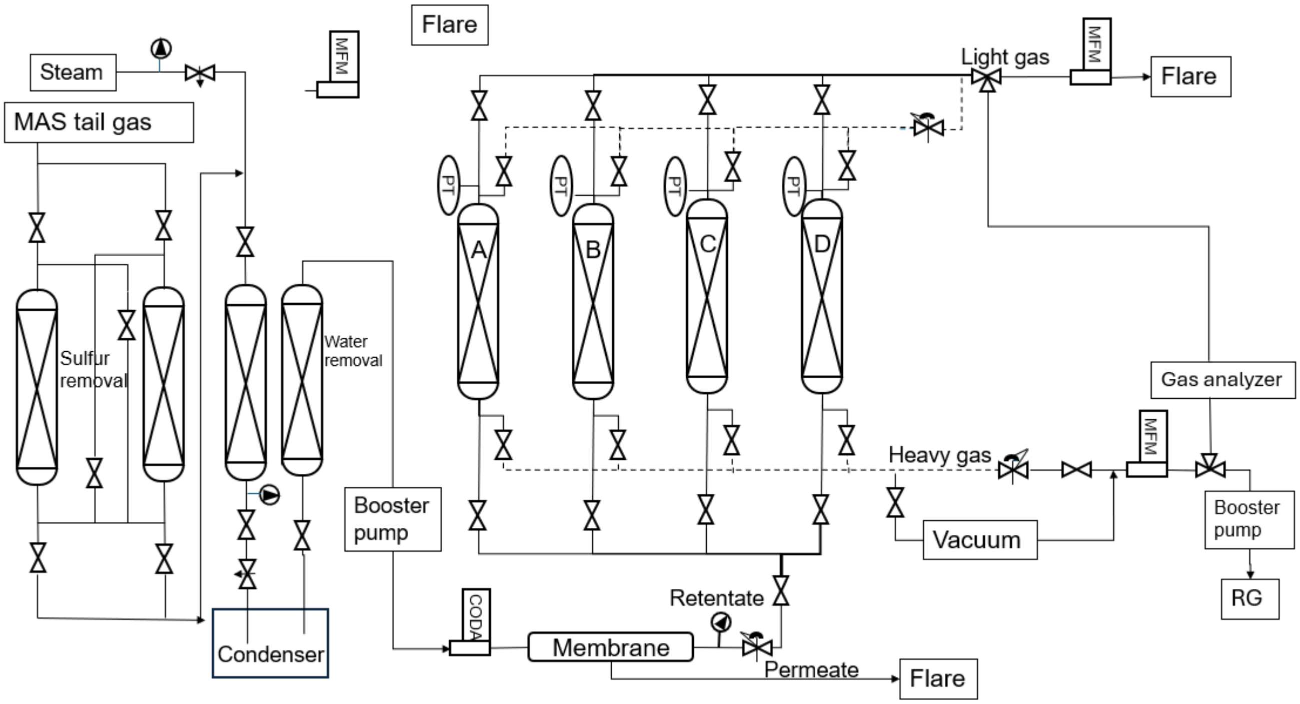
Figure 11: Technological Separation Pathways Towards Purified RG



Source: West Biofuels

The PFD illustrating the integrated system of gas separation, including sulfur removal, WGS, membrane, and PSA is provided in Figure 12.

Figure 12: PFD of Gas Separation Integrated System



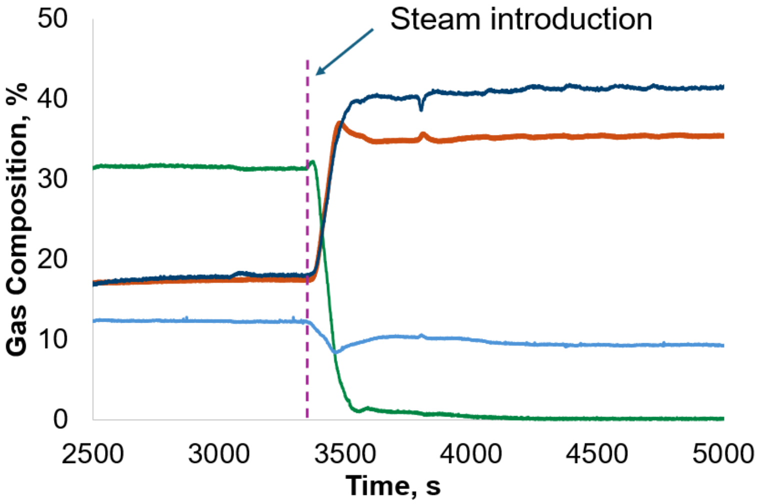
Source: West Biofuels

The result from the integrated separation runs using real syngas are presented in the following sections. The feedstock used was the syngas captured from the gasifier operation in July 2023, contains a substantial proportion of N_2.

Water Gas Shift Reactor

The gas composition before and after the steam introduction is shown in Figure 13. Once the steam was introduced, the WGS reaction began, leading to an immediate decrease in CO content. After some time, the CO concentration fell below 0.01 percent, achieving a CO conversion rate of more than 99 percent. The detailed gas composition of inlet and outlet gas streams for the WGS reactor is listed in Table 5. The CO-free gas was compressed and stored.

Figure 13: Gas Composition Before and After Steam Introduction During the Water-Gas Shift Reaction



Source: West Biofuels

Table 5: Gas Composition of Inlet and Outlet of WGS

Gas stream	H_2, %	O_2, %	N_2, %	CH_4, %	CO, %	CO_2, %	C_2H_4, %	C_2H_6, %
WGS inlet	18.43	0.46	22.83	12.08	29.07	16.57	<0.01	0.55
WGS outlet	37.08	0.24	19.35	9.70	0.08	31.46	<0.01	2.08

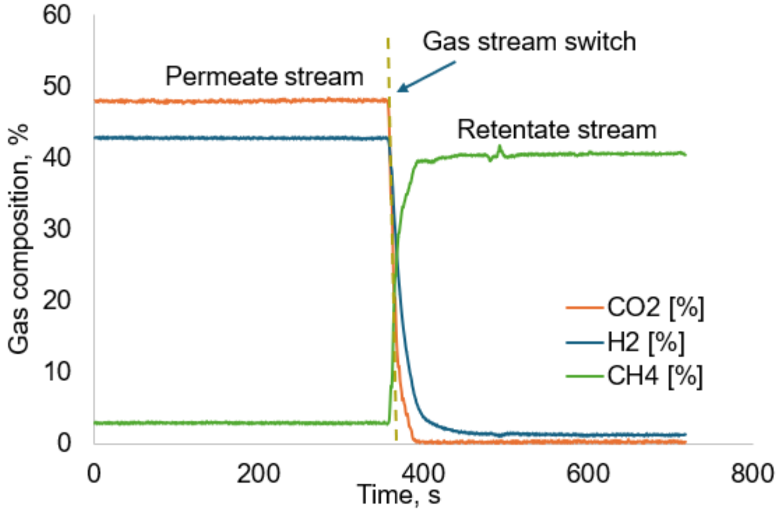
Source: West Biofuels

Membrane Separation

When the gas flows through the membrane system, it splits into two streams: retentate stream and permeate stream, based on their different permeation rates through the membrane material. The components that pass through the membrane are called permeate. The components that are retained by the membrane are called retentate.

In this case, WGS tail gas (CO-free) was used as the feed for the membrane unit, with an inlet gas flow rate of 26 SLPM. The system pressure was maintained at 12 bar, and CH_4, C_2H_6 and N_2 were enriched in the retentate stream from 10.7 percent to 33.1 percent, 1.8 percent to 9.2 percent and 12.7 percent to 55.8 percent, respectively (Figure 14). The detailed gas composition of the inlet and outlet gas streams is listed in Table 6.

Figure 14: Gas Composition of The Two Streams Exiting the Membrane



Source: West Biofuels

Table 6: Gas Composition of Inlet and Outlet Gas Streams of Membrane

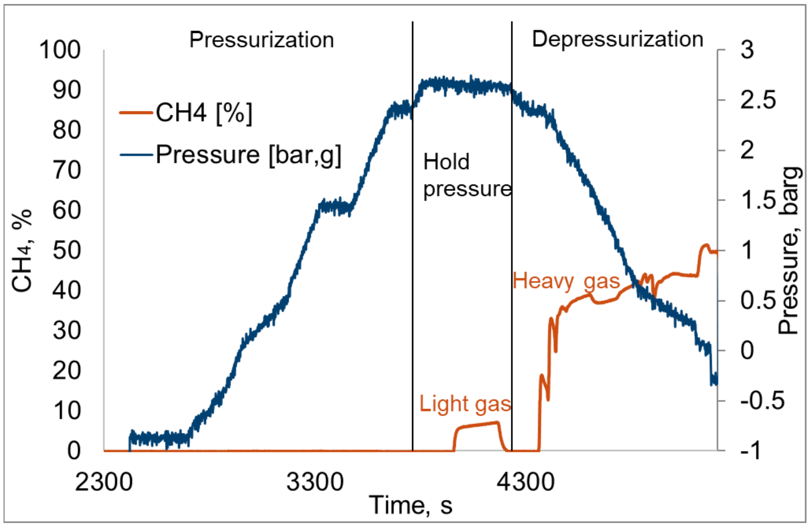
Gas stream	H_2, %	O_2, %	N_2, %	CH_4, %	CO, %	CO_2, %	C_2H_4, %	C_2H_6, %
Feed	37.08	0.24	19.35	9.70	0.08	31.46	<0.01	2.08
Retentate	0.02	0.25	55.03	34.77	0.15	0.28	<0.01	9.50
Permeate	43.14	0.00	9.37	3.38	0.05	43.72	<0.01	0.34

Source: West Biofuels

PSA Separation

The retentate stream exiting the membrane was used as the feed gas for the PSA unit. The CH_4 content in the light gas stream during depressurization and in the heavy gas stream during depressurization is depicted in Figure 15. CH_4 in the light gas stream stayed below 10 percent. During depressurization, CH_4 in the heavy gas stream was enriched over 40 percent. The result showed that PSA successfully concentrated CH_4 into the heavy gas stream (adsorbed phase), enriching it from 33 percent to over 40 percent. At the same time, the light gas stream (non-adsorbed phase) had a low CH_4 concentration (<10 percent), meaning most of the CH_4 was retained on the adsorbent during pressurization and later released in the heavy gas stream. The heavy gas captured in the Tedlar® bag was analyzed by GC and contained 0.3 percent H_2, 47.3 percent N_2, 43.5 percent CH_4, and 8 percent $C_2 H_6$ (Table 7).

Figure 15: Methane in Light and Heavy Gas Streams During Pressure Change



Source: West Biofuels

The gas composition of the CH_4 enriched gas stream and also CH_4 recovery rate after each purification step is listed in Table 7. The WGS reactor achieved complete CO removal, while the membrane effectively separated CO_2 and H_2 from the WGS tail gas. The primary challenge lies in the PSA separation of N_2 and CH_4. The syngas used for the integrated run had an abnormally high N_2 content compared to the typical three percent N_2 in a typical gasifier syngas. This N_2 level accumulated throughout the separation steps, resulting in a final PSA feed gas with more than 50 percent N_2, which posed a significant challenge for PSA separation. The reason for using high N_2 syngas is because the previously captured high quality syngas was all used for MAS runs and also PSA and membrane testing runs. The only syngas available was the high N_2 syngas which was captured in July 2023. Attempts to operate the gasifier after July 2023 were unsuccessful because the gasifier compressor was not functioning, preventing any further syngas capture.

Table 7: Gas Composition After Each Purification Step

Gas Species composition, mol%	Syngas, mol%	WGS_outlet, mol%	Membrane_ retentate, mol%	PSA_heavy gas, mol%
H_2	18.43	37.08	0.02	0.30
O_2	0.46	0.24	0.25	0.20
N_2	22.83	19.35	55.03	47.30
CH_4	12.08	9.70	34.77	43.50
CO	29.07	0.08	0.15	<0.01
CO_2	16.57	31.46	0.28	<0.01
C_2H_4	<0.01	<0.01	<0.01	<0.01
C_2H_6	0.55	2.08	9.50	8.01
CH_4 recovery, %		99%	85%	~70%

Source: West Biofuels

Since high-quality syngas was not available for an additional integration run to demonstrate the PSA's ability to enrich CH_4 to the desired pipeline quality, an alternative approach is to use a pre-mixed N_2 and CH_4 gas mixture that reflects the predicted gas composition. Given that the WGS stage fully removes CO, and the membrane efficiently separates CO_2 and H_2, the expected PSA inlet concentrations could be estimated based on the species concentrations from the WGS and membrane stages. The calculated results are presented in Table 8.

Table 8: Gas Composition Simulation of Each Separation Step

Gas Species composition, %	Syngas, mol %	Tail gas, mol %	WGS, mol %	Membrane retentate, mol%
H_2	34.60	14.50	25.90	<0.01
O_2	0.11	0.11	0.10	0.10
N_2	3.12	4.00	3.41	12.02
CH_4	11.02	26.62	22.62	78.11
CO	32.51	16.02	<0.01	<0.01
CO_2	16.41	36.71	44.74	<0.01
C_2H_4	2.01	0.11	<0.01	<0.01
C_2H_6	0.31	2.02	3.43	9.9
CH_4 recovery, %			99%	85%

Source: West Biofuels

If the actual MAS tail gas, as proposed in this project, is used, the PSA inlet gas should contain approximately 14 percent N_2, 80 percent CH_4, and 6 percent C_2H_6. To evaluate PSA performance under these conditions, a simulated gas mixture matching this composition was prepared and used for testing to determine whether high-purity CH_4 could be achieved. The four-bed PSA system was operated at 3.8 bar with a feed gas flow rate of eight SLPM, and the cycle time was set to 120 seconds (Table 9). During the five-hour run, approximately 10 bar gas was captured in a 47 L volume cylinder. The 91 percent closure indicated that the flow rate measurements and gas composition analysis were reliable, with only small deviations. The PSA system successfully enriched CH_4 from 80 percent to 88 percent and C_2H_4 from 7.2 percent to 8.6 percent, achieving an overall CH_4 recovery of 83 percent. Some air also entered the captured product gas due to a PSA valve leak, which was discovered after the PSA run. Since air contributed to the N_2 reading, the actual N_2 concentration in the product gas would be lower than three percent without this air intrusion.

Table 9: Steady State Performance of Four Bed PSA Cycle

Gas Stream	Gas flow rate, SLPM	N_2, mol%	CH_4, mol%	C_2H_4, mol%	CH_4 in the gas, SLPM
Feed gas	8.06	12.81	80.02	7.22	6.52
Product gas	6.07	3.92	88.12	8.64	5.31
Light gas	1.26	60.21	39.79	<0.01	0.53
Closure, %	90.9				
CH_4 recovery, %	82.8				

Source: West Biofuels

Overall, the CH_4 recovery through the separation train is 70 percent, by combining the recovery of 99 percent through WGS, 85 percent through the membrane, and 83 percent through PSA.

The overall process efficiency ranged from 26 percent to 36 percent, depending on the MAS operating conditions, where a higher CH_4 concentration in the MAS tail gas correlated with increased efficiency. The RG energy output varied between 51 percent and 75 percent, also depending on the MAS operating conditions.

Objectives justification

The test plan called for investigation of several main objectives, which are summarized and discussed:

- **Separate RG from other gas species.**

  The proposed separation train, which includes the WGS reactor, membrane, and PSA, successfully demonstrated its ability to enrich CH_4 at each stage of the process. This stepwise approach effectively separated CH_4 from other gas species, meeting the objective.

- **Demonstrate a pilot scale biomass-to-RG process including gasifier, catalyst reactor and gas separation process.**

  The project successfully demonstrated a pilot-scale process for converting biomass into RG, validating the performance and integration of each key component. To improve gas quality, the process was designed to first pass the MAS tail gas through a WGS reactor, which converts CO into CO_2. This step was necessary because existing separation technologies could not effectively remove CO from CH_4 and N_2. Next, the gas flowed into a membrane unit, which separated out H_2 and CO_2. Finally, a PSA system was used to remove N_2, leaving behind high-purity CH_4 that met the requirements for gas grid injection.

- **Utilize syngas for production of upgraded RG at a rate of at least 2.5 cubic feet per minute.**

  The objective of producing upgraded RG at a rate of at least 2.5 SCFM could not be met due to the limitations of the membrane unit. The membrane system purchased for this project was designed for smaller-scale operations and could not handle the larger feed gas flow required to achieve the targeted RG production rate. As a result, the membrane's limited capacity constrained the feed gas supply to the PSA unit, which directly impacted its ability to produce RG at the specified rate. Upgrading to a larger membrane system would address this limitation and enable the process to meet the objective in future operations.

- **Complete at least two eight-hour steady state operational periods with the full process. These tests were to include complete data collection of process parameters and performance.**

  The objective of achieving an eight-hour integrated steady-state run could not be met due to the unsafe operating situation of MAS reactor. However, each unit module of the system was tested separately. The MAS reactor and WGS reactor each operated independently for over 20 hours using the high N_2 content syngas which was produced on site in July 2023. The membrane separation unit ran for three hours, and the PSA system operated for five hours, with their shorter durations due to limited syngas availability. While an integrated run was not completed, the successful individual operations of each unit provide confidence that an integrated eight-hour run is achievable under the right conditions.

- **Complete more than 500 hours of testing producing RG from syngas.**

  Since producing RG involves several steps, each module of the system was tested separately to make sure it worked well on its own. The testing included 150 hours for membrane separation, 300 hours for PSA, 60 hours for the WGS reactor, and 154 hours for the MAS system. Altogether, these tests added up to more than 500 hours, meeting the goal.

- **Achieve an overall process efficiency of 55% with 60% of the total output energy (from both renewable gas and alcohol products) allocated to the renewable gas product.**

  The overall process efficiency was calculated as 36 percent. The 55 percent overall process efficiency target could not be met primarily due to limitations in both gasifier efficiency and downstream separation efficiency. The gasifier itself operated at only 63 percent efficiency, which inherently constrains the maximum possible overall efficiency. Additionally, the downstream separation train introduces further losses, with the best achievable efficiency reaching 56 percent. A key factor contributing to this limitation is that H_2, a potential energy carrier, is not counted as part of the output energy, reducing the reported efficiency. Furthermore, at the pilot scale, there is no gas recycling from the membrane and PSA units, leading to higher CH_4 losses. In contrast, industrial-scale systems can achieve over 90 percent CH_4 recovery, which would improve overall efficiency.

  The objective of at least 60 percent energy in the RG product was met under certain MAS operating conditions.

- **Confirmation of final product RG meeting pipeline quality RG specifications.**

  The final product RG's compliance with pipeline-quality specifications has been verified using an onsite GC. The GC was calibrated with certified calibration gas, ensuring accurate and reliable gas composition readings. These measurements confirm that the final product meets the required pipeline standards.

Proof of Compliance with Utility RG Specifications

The final product RG must meet acceptable quality standards for injection into the gas grid. Therefore, a review of major West Coast utilities' gas pipeline injection specifications is provided in Table 10. It also includes the simulated gas composition of renewable gas based on the integrated gas run and the PSA run. All key quality parameters of the produced gas, including H_2S, total sulfur, O_2, CO, hydrocarbon dew point, and higher heating value met the required RG quality standards. The gas composition aligned with the necessary specifications for safe and efficient injection into the natural gas pipeline, confirming its compliance with industry regulations.

Table 10: Renewable Gas Quality Specifications from Major West Coast Utilities

Parameters	SoCalGas Rule 30	PGE Rule 21	MAS Tail gas	Renewable Gas*
Temperature (˚C)	16-37	16-40	<30	16-20
H_2S (ppm)	4	4	~800	<1
Mercaptan (ppm)	5	8	~50	<1
Tot Sulfur (ppm)	12.6	17	~150	<1
H_2 (mol%)	<0.10	<0.10	20.50	<0.10
O_2 (mol%)	0.20	0.10	0.1	~0.1
CO_2 (mol%)	3.00	1.00	35.70	<0.2
CO (mol%)	< 0.03, may allow for higher	unspecified	22.70%	<0.10%
Inert (CO_2+N_2 and so forth)	4.00%	unspecified	----	<3%
Dew point temperature of hydrocarbons at 27.6 bar	<45F	<45F	----	<45F
CH_4 (mole%)	Balance	Balance	19.50%	~90%
Moisture (pounds per million standard cubic feet) @P< 55 bar	7	7	NA	NA
HHV (British Thermal Units per Standard Cubic Foot)	990-1150	1000**	~355	~1036

*Determined by receipt point
**Evaluated by PGE and depends on project and receipt point
---- Not applicable
NA: not analyzed
Source: West Biofuels

Key Project Milestones

Syngas Capture During Gasifier Run

Syngas capture during the gasifier run was a critical step in this project, as it provided captured feedstock for subsequent upgrading and separation processes. Maintaining a consistent gasifier output ensured a reliable and steady input for downstream processing, enhancing overall system efficiency and performance.

Mixed Alcohol Production from Syngas

The MAS reactor was tested for its ability to convert syngas into mixed alcohols, demonstrating successful synthesis. Reaction efficiency, alcohol yield, and catalyst performance were evaluated over an extended operational period. The results highlighted how different MAS operating conditions influenced the distribution of energy between RG and mixed alcohol production.

Sulfur Removal of MAS Tail Gas

Sulfur removal tests were conducted to prevent material poisoning in subsequent gas separation steps. The preliminary results indicated that the sulfur removal column successfully reduced the sulfur level from 200 ppm to 1 ppm.

Membrane Separation Demonstration

Membrane separation tests confirmed the membrane's ability to effectively separate H_2 and CO_2 from the MAS tail gas. This milestone validated the feasibility of using membrane technology for early-stage gas purification.

PSA Testing

PSA experiments using specialized activated carbon demonstrated that CH_4 could be enriched in CH_4/N_2 mixtures. This step was crucial in evaluating the PSA system's selectivity for CH_4 recovery.

Challenge in CO/N_2 Separation

Tests revealed that neither the membrane nor PSA could effectively separate CO from N_2 due to their similar properties. This challenge necessitated the addition of WGS to convert all CO to CO_2.

Integration of the RG Separation Simulation

The complete system, integrating the WGS reactor, membrane separation, and PSA, was finalized. To simulate the integrated process, syngas was sequentially processed through each unit, with each unit operating independently. The product gas from each stage was collected and fed into the next, ensuring a controlled and systematic evaluation of the overall separation pathway.

Air Emission Compliance

To assess the feasibility of scaling up the pilot-scale results to a commercial facility, this study evaluated the ability of a 100 MWth Mixed Alcohol Renewable Gas (MARG) plant to meet air emission requirements across air districts in the Sierra Nevada Region. The plant had air pollution stack emissions from the char combustor fluidized bed (CCFB). CCFB air pollution emissions are shown in Table 11. Emissions were based on the use of a baghouse for control of particulate matter with a diameter of 2.5 micrometers or smaller ($PM_{2.5}$) and Selective Non-Catalytic Reduction (SNCR) for control of NO_x.

A preliminary New Source Review permit analysis for the MARG indicates:

- **Best Available Control Technology (BACT).** Table 12 shows BACT thresholds for selected local Air Districts. Use of BACT was required for NO_x. SNCR will be considered BACT for NO_x for woody biomass combustors, as SCR is ruled out due to high cost, catalyst plugging and fouling concerns, and need for post PM control flue gas reheat. For PM, a baghouse is BACT.
- **Emission Reduction Credit (ERC) Offsets.** Table 12 shows ERC thresholds for selected local Air Districts. ERCs for NO_x will be required for some Districts (three tons where thresholds are 10 tons per year); other pollutant emissions were below ERC thresholds.
- **Air Toxics Risk.** Previous risk assessments from numerous comparable woody biomass combustors (with similar size, control and emission profiles, and nearby community receptors) indicated the MARG CCFB can meet Air District cancer risk threshold of less than 10 in one-million and hazard index (non-cancer) of less than one.
- **Local District Prohibitory Rules.** Review of several local Air Districts prohibitory rules indicated the MARG CCFB can meet all existing applicable rules.
- **Federal and State Rules.** Biomass boiler air toxics (40 CFR 63 Subpart JJJJJ) and solid waste incinerator new source (40 CFR 60 Subpart CCCC) requirements can be met, depending on biomass waste source type and boiler steam requirements. The MARG CCFB, with the above defined emissions and control profile can meet these requirements, if applicable.

In conclusion, the preliminary New Source Review permit analysis indicates that MARG is well-positioned to comply with air emission regulations across selected local Air Districts. The facility will require the implementation of BACT for NO_x and PM, with SNCR and a baghouse identified as suitable control measures.

Table 11: Air Pollution Emissions from MARG CCFB

Stack emissions	MW	Concentration ppm by volume on a dry basis	mg/dry standard cubic meter	Mass Emissions lb./hr	Mass Emissions lb./day	Mass Emissions tons/yr
CO_2	44	110,000	201,323	21821	523,702	90,797
CO	28	5	6	1	15	3
NO_x w/ Comb Control	46	50	96	10	249	43
NO_x w/ SNCR		15	29	3	75	13
NMOC	16	2	1	0	3	1
SO_2	64	25	67	7	173	30
$PM_{2.5}$	NA*	NA*	23	2	60	10

*Not applicable
Source: Placer County Air Pollution Control District

Table 12: Air District Thresholds for BACT And ERC Offsets

Air District	Placer	Shasta	San Joaquin
New Source Review Permit Rule	502	2.1	2201
BACT Thresholds (lb/day)			
NMOC	10	25	2
NO_x	10	25	2
SOx	80	80	2
$PM_{2.5}$	80	80	2
CO	500	500	2
Offset Thresholds (tons/year)			
NMOC	10	0	10
NO_x	10	0	10
SOx	27.5	0	27.5
$PM_{2.5}$	15	0	15
CO	99	0	100

Source: Placer County Air Pollution Control District

Greenhouse Gas Emission Impacts

To assess the greenhouse gas (GHG) emissions of a commercial MARG system, a 100 MWth facility was analyzed using the California Low Carbon Fuel Standard (LCFS) method. This approach considered emissions from fuel production activities, including biomass processing, transportation, upgrading, and distribution. However, CO_2 emissions from biomass combustion or fuel use were excluded, as they were considered biogenic and part of a closed carbon cycle.[11] The Carbon Dioxide Equivalent (CO_2e) emissions from each stage are detailed in Table 13. CO_2e is a metric used to compare the global warming potential (GWP) of different greenhouse gases by expressing their impact in terms of the equivalent amount of CO_2.

Table 13: Greenhouse Gas Emission of A 100MWth Plant

Greenhouse Gas Emission	kilograms CO_2e/hr
Biomass processing, grams CO_2e/hr	288
Biomass transporting, grams CO_2e/hr	368
Parasitic, grams CO_2e/hr	898
Alcohol Distribution for High Alcohol, grams CO_2e/hr	331
Alcohol Distribution for High RG, grams CO_2e/hr	57
Total for High Alcohol, grams CO_2e/hr	1886
Total for High RG, grams CO_2e/hr	1612

Source: NREL and West Biofuels

---

[11] California Air Resources Board. LCFS pathway certified carbon intensities. California Environmental Protection Agency. https://ww2.arb.ca.gov/resources/documents/lcfs-pathway-certified-carbon-intensities

The core mixed alcohol reactor system developed by West Biofuels can be operated in such a manner as to favor gaseous or liquid products with varying specificity depending on operating conditions. For the purposes of this analysis, two "bookend" scenarios were evaluated to highlight the dynamic ranges: (1) a high RG yield scenario; and (2) a high alcohol yield scenario. For the remainder of the report these two scenarios were denoted as the High RG and High Alc (Alcohol) cases. The carbon intensity ranged from 5-8 grams CO_2 equivalent/megajoule (g CO_2e/MJ) for both scenarios (Table 14), which is lower than that of other reported RG from biomass, which is 13 CO_2e/MJ.[12] Additionally, the carbon intensity of corn ethanol has been reported to range from 53.49 to 85.49 g CO_2e/MJ,[13] while pipeline natural gas typically ranges from 80 to 100 g CO_2e/MJ.

Table 14: Carbon Intensity Under Two Different Scenarios

Metric	High RG	High Alc
Energy in RG, MJ/Hr	136,800	24,120
Energy in alcohol, MJ/Hr	57,600	331,200
Carbon Intensity, g/MJ	8	5

Source: NREL and West Biofuels

Objectives Justification

- **Evaluate the ability for commercial-scale facilities to meet the air emission requirements of air districts across the Sierra Nevada Region based on the pilot-scale performance.**

  The analysis confirms that MARG complies with all relevant air emission standards, meeting the objective outlined in the study.

- **Demonstrate a Low Carbon Fuel Pathway carbon intensity less than 15 grams CO_2e per MJ of transportation fuel.**

  The two products achieved a carbon intensity of 4-8 g CO_2e/MJ, significantly below the 15 g CO_2e/MJ threshold.

Techno-Economic Modeling

The proposed integrated process will produce RG with a host of byproducts, including methanol, ethanol, n-propanol, and higher alcohols that can be used in the chemical and transportation fuel markets along with CO_2 that could be used for carbon sequestration. This variety of byproducts reduces the economic risk of the project and allows a commercial MARG facility to be market responsive and adjust product production towards an RG-focused production or alcohol-focused production, for example, to react to market demand over time.

---

[12] Ibid.

[13] Ibid.

The economic analysis presented in this report builds off prior established analysis models for mixed alcohol synthesis via biomass gasification,[14] and is informed by data provided by West Biofuels to achieve the following:

- An nth-plant techno-economic analysis for a commercial facility.
- The levelized cost of RG, showing pathways to reaching a range between $12 per MMBtu and $21 per MMBtu.
- Identification of critical production processes and equipment.
- Identification of operating and construction costs.

Total Capital Investment (TCI) is presented in Table 15 for a facility that consumes 2,000 bone dry tons per day.

Table 15: Total Costs Associated with Building Mixed Alcohol Production Plants for The High RG And High Alcohol Scenarios

Costs	High RG, MM $	High Alc, MM $
Total Direct (TDC)	258	241
Total Indirect (TIC)	155	144
Working capital	20	19
Total Capital Investment	434	405

Source: NREL and West Biofuels

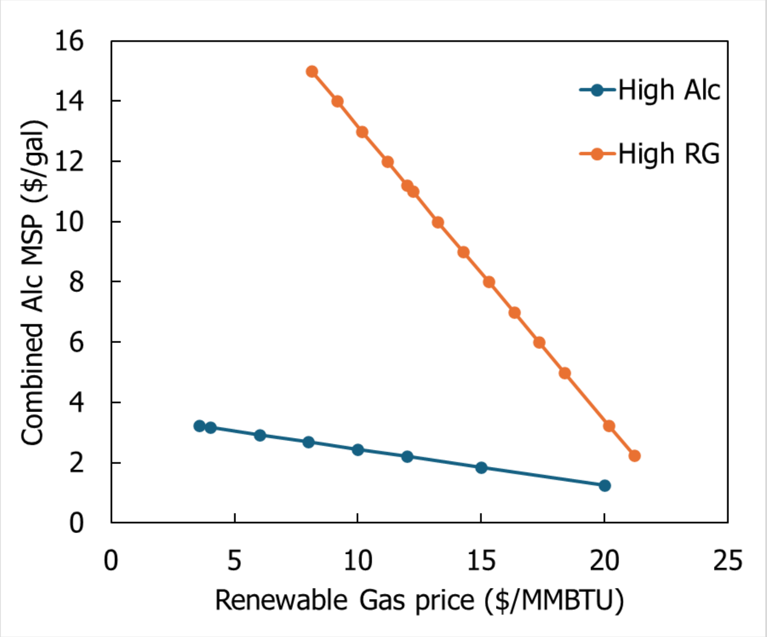
Once the capital and operating costs are determined, a minimum selling price (MSP) of the desired RG product was determined using a discounted cash flow rate-of-return analysis. The general method used is identical to that applied by Aden et al.[15] The MSP value represents the selling price of RG assuming a 30-year plant life and 40 percent equity financing with 10 percent internal rate of return and the remaining 60 percent debt financed at eight percent interest. The combined alcohol selling price is considered for high RG and high alcohol scenarios. In the high RG scenario, achieving an RG selling price below $12 per MMBtu requires an alcohol selling price of approximately $11 per gallon. While in the high alcohol scenario, an RG selling price below $12 per MMBtu can be achieved with an alcohol selling price of around $2.2 per gallon (Figure 16).

---

[14] Dutta Abhijit, Talmadge Michael, Hensley Jesse, Worley Matt, Dudgeon Doug, Barton David, and Groenendijk Peter, et al., Process Design and Economics for Conversion of Lignocellulosic Biomass to Ethanol. (2011) https://www.nrel.gov/docs/fy11osti/51400.pdf.

[15] Aden, A; Ruth, M; Ibsen, K; Jechura, J; Neeves, K; Sheehan, J; Wallace, B et al., 2002. Lignocellulosic Biomass to Ethanol Process Design and Economics Utilizing Co-Current Dilute Acid Prehydrolysis and Enzymatic Hydrolysis for Corn Stover. Report No. NREL/TP-510-32438. Golden, CO: National Renewable Energy Laboratory.

Figure 16: Sensitivity of the High Alcohol and High RG MSP to Different Combined Alcohol and RG Selling Prices



Source: West Biofuels

Across the High RG and High Alcohol scenarios, feedstock costs contribute to about 98 percent of the total variable operating costs and nearly 40 percent of the total product cost; thus, sourcing the lowest cost feedstocks should be one of the highest priorities.

Objectives Justification

- **Leverage by-products to achieve a wholesale cost of RG of $12 per MMBtu or lower.**

  Achieved. The High Alcohol scenario allows an RG price below $12 per MMBtu with an alcohol price of around $2.2 per gallon.

- **Demonstrate key financial metrics for a commercial plant, including a simple payback period of less than 15 years with a plant designed for 30 years of service.**

  Achieved. The calculation is based on a 10-year payback period with a facility designed for 30 years of service.

CHAPTER 4: Conclusion

This research project successfully demonstrated a novel and integrated pathway for converting forest biomass into mixed alcohols and RG, achieving the primary objectives of the project. By developing and testing a multi-step separation process involving a WGS reactor, membrane separation, and PSA, the project overcame significant challenges in separating complex gas mixtures, particularly the separation of CO and N_2 from CH_4. The integration of these technologies resulted in the production of high-purity RG that meets pipeline-quality RG standards, validating the effectiveness of the proposed system.

Key Achievements and Implications

- **Technological Advancements:** The project showcased the feasibility of converting multi-species tail gas into pipeline-quality RG through an innovative combination of a WGS reactor, membrane separation, and PSA. This approach not only addressed the technical challenge of separating CO and N_2 but also demonstrated the potential for scaling up the process for industrial applications.
- **Renewable Energy Production:** The successful conversion of forest biomass into mixed alcohols and RG highlights the potential of this pathway to contribute to renewable energy production. By utilizing biomass as a feedstock, the process aligns with global efforts to reduce reliance on fossil fuels and mitigate greenhouse gas emissions.
- **Environmental Benefits:** The project contributes to environmental sustainability by providing a pathway to produce renewable fuels from forest biomass, which can help reduce carbon emissions and promote the utilization of waste materials. The effective removal of impurities, like tars and particulate matter during syngas processing further underscores the environmental advantages of this system.
- **Economic and Policy Implications:** The findings of this research have significant implications for future energy markets and policy development. The ability to produce high-purity RG from biomass-derived syngas opens new opportunities for RG production, which can be integrated into existing natural gas infrastructure. Technoeconomic analysis demonstrates that the production cost of RG can be reduced to $12 per MMBtu, making it a competitive alternative to conventional natural gas. This could provide economic benefits to utility ratepayers, particularly in ratepayer-funded projects, by diversifying energy sources and reducing fossil fuel dependence.
- **Scalability and Future Research:** The results of this project lay the groundwork for future research and development in renewable energy technologies. Further studies could focus on optimizing the process for different feedstocks, scaling up the system for commercial deployment, and exploring additional applications for the integrated

separation train. The successful demonstration of the MAS process also highlights the potential for expanding its use in other renewable fuel production pathways.

Lessons Learned and Future Development Opportunities

The project provided valuable lessons that can inform future development and deployment of similar technologies:

- **Resilience and Adaptability in Research and Development Systems:** The project demonstrated the importance of resilience and adaptability when operating advanced research and development systems, particularly those with aging infrastructure or repurposed from previous projects. Significant challenges, such as equipment failures and system plugging, were overcome through repairs, upgrades, and process improvements, including rebuilding critical components and installing an evaporative cooling tower. However, some issues persist; notably, the bulk compressor remains unrepaired, awaiting rebuilding. These ongoing challenges highlight the need for robust maintenance protocols, operator training, and flexible system designs in future research and development projects. Lessons from troubleshooting and optimizing the gasification system provide a foundation for scaling up and improving similar systems, emphasizing the value of modular components and advanced monitoring to enhance efficiency and reduce downtime.
- **Integration of Technologies:** The successful integration of the WGS reactor, membrane separation, and PSA system demonstrated the importance of combining complementary technologies to address complex separation challenges. Future projects can build on this approach to optimize each step and improve overall efficiency.
- **Feedstock Flexibility:** While forest biomass was the primary feedstock tested, the lessons learned can be applied to other biomass sources, such as agricultural waste or municipal solid waste, expanding the potential applications of this technology.
- **Process Optimization:** The project highlighted areas for further optimization, such as reducing energy consumption in the PSA system and improving the durability of membranes under industrial conditions. These improvements could enhance the economic viability of the process.

Market Opportunities

The technology and knowledge developed through this project present significant market opportunities:

- **Renewable Gas Production:** The ability to produce high-purity RG from biomass-derived syngas aligns with growing demand for RG in sectors such as transportation, heating, and power generation. This creates opportunities for partnerships with utilities, energy companies, and RG producers.
- **Carbon Capture and Hydrogen Recovery:** Currently, CO_2 and H_2, which are selectively separated through membrane, are treated as waste, but both gases have

significant economic and environmental value. With proven separation technologies available for both CO_2 and H_2, industries have an opportunity to generate additional revenue, reduce waste, and contribute to the transition toward a low-carbon economy.

- **Sustainable Fuels Market:** The production of mixed alcohols and RG from biomass provides a pathway for entering the sustainable fuels market, which is increasingly driven by policies promoting renewable energy and reducing greenhouse gas emissions.
- **Rural Economic Development:** By utilizing forest biomass, this technology can support rural economies by creating new revenue streams for landowners and biomass suppliers, while also promoting sustainable land management practices and reducing wildfire risk.

GLOSSARY AND LIST OF ACRONYMS

Term	Definition
Alc	Alcohol, referring to any number of alcohols that are products of the Mixed Alcohol Synthesis process.
Best Available Control Technology (BACT)	Refers to the most effective emission control technology that is available for a specific source of air pollution, considering technological feasibility, cost, and environmental impact. It is determined on a case-by-case basis during the permitting process and aims to reduce emissions to the lowest possible level while considering economic and technical constraints. BACT is typically applied to new or modified facilities and is required to meet the air quality standards set by regulatory agencies like the U.S. Environmental Protection Agency (EPA) or local air districts.
CO_2	Carbon dioxide, a greenhouse gas that by definition has a global warming potential of 1.
Carbon Dioxide Equivalent (CO_2e)	A metric used to compare emissions of various greenhouse gases. It is the mass of carbon dioxide that produces the same estimated radiative forcing as a given mass of another greenhouse gas. Carbon dioxide equivalents are computed by multiplying the mass of the gas emitted by its global warming potential.
Carbon Intensity (CI)	The amount of carbon by weight emitted per unit of energy consumed. A common measure of carbon intensity is weight of carbon per British thermal unit (Btu) of energy. When there is only one fossil fuel under consideration, the carbon intensity and the emissions coefficient are identical. When there are several fuels, carbon intensity is based on their combined emissions coefficients weighted by their energy consumption levels.
CCFB	Char combustor fluidized bed, a process whereby char particles produced during combustion react with oxygen and other gases over a fluidized bed.
CH_4	Methane, a potent greenhouse gas with a global warming potential of 28-30 over 100 years.
CO	Carbon monoxide, a toxic, colorless and odorless gas that is a byproduct of incomplete combustion.
CSMs	Colorado School of Mines
Emission Reduction Credit (ERC)	A tradable certificate that represents a reduction in the emissions of a regulated pollutant, typically achieved through the implementation of emission control technologies or practices that lower air pollution. ERCs are generated by facilities or projects that reduce emissions below regulatory limits or baseline levels, and they can be used to offset emissions from other sources, allowing for compliance with air quality standards. ERCs are often used in air quality permitting to

Term	Definition
	satisfy offset requirements in areas with air pollution concerns, especially in nonattainment areas where pollutant levels exceed federal or state standards.
Fast Internally Circulating Fluidized Bed (FICFB)	A dual fluidized bed gasification system using a synthetic bed material to transfer heat from the combustion zone to the gasification zone. Biomass is fed into the gasification zone via a screw auger where it is thermochemically converted to producer gas through contact with the hot fluidized bed material and steam. The bed material and the remaining char are transported to the combustion side by gravity where air is injected, and the char is combusted to heat the bed material. The hot bed material is lifted up the riser with the combustion flue gases into a cyclone where the bed material and flue gases are separated. The reheated bed material is reintroduced into the fluidized bed gasification chamber while the flue gases continue through the flue gas treatment system. The producer gas, extracted on the gasification side, is conditioned to remove impurities before becoming available to an engine or catalyst system.
Gas Chromatograph (GC)	An analytical instrument used to separate and analyze chemical components in a complex mixture. It operates by passing a sample through a narrow, flow-through column in a gas stream. The different chemical constituents travel at varying rates based on their unique chemical and physical properties, allowing for their identification and quantification.
Gas Hourly Space Velocity (GHSV)	The ratio of gas flow rate (in standard condition) to the volume of the bed.
Greenhouse Gases (GHG)	Any gas that absorbs infrared radiation in the atmosphere. Greenhouse gases include water vapor, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), halogenated fluorocarbons (HCFCs), ozone (O_3), perfluorinated carbons (PFCs), and hydrofluorocarbons (HFCs).
GWP	Global warming potential, the measure of how much heat a gas is expected to trap in the atmosphere through the "greenhouse effect".
Higher Hazard Zone (HHZ) Forest Biomass	Refers to woody material, including dead trees, logging residues, and overgrown vegetation, collected from forest areas designated as HHZ due to their elevated wildfire risk.
H_2S	Hydrogen sulfide, a colorless gas that is highly toxic to humans, commonly found in fossil fuels.
MARG	Mixed Alcohol Renewable Gas, term of art for the technology involved in this project that generates mixed alcohols and renewable gas.
Mixed Alcohol	Mixed alcohol is a blend of alcohols, including methanol, ethanol, propanol, and butanol, using catalytic reactions under high

Term	Definition
	temperature and pressure. These mixed alcohols are blended into gasoline to improve octane rating and reduce emissions.
Mixed Alcohol Synthesis (MAS)	Converts syngas produced by the fast internally circulating dual fluidized bed gasifier into a mixture of alcohols via a catalytic process. The syngas is compressed and introduced to a patented fixed bed catalytic reactor containing a proprietary catalyst. Reactor temperature is maintained via a liquid thermal management system. The alcohol products are then collected for further processing into fuels, fuel additives, and chemicals.
Megawatt Thermal (MWth)	A unit of measurement used to express the thermal energy output of a system, such as a power plant, boiler, or gasifier. The "th" indicates that the measurement refers to thermal energy (heat) rather than electrical energy.
MJ	Megajoule, a unit of energy equivalent to one million joules.
MnO_2	Manganese dioxide, a mineral compound used to enhance combustion.
MM $	Million dollars
N_2	Nitrogen, an inert, colorless, odorless gas comprising 78% of the earth's atmosphere.
NO_x	Refers to a group of highly reactive gases that contain nitrogen and oxygen. The most common nitrogen oxides are nitric oxide (NO) and nitrogen dioxide (NO_2). NO_x is primarily produced during combustion processes, such as in vehicles, power plants, and industrial facilities. It is a significant air pollutant that contributes to the formation of smog, acid rain, and ground-level ozone, which can have harmful effects on human health, ecosystems, and air quality. Reducing NO_x emissions is a key focus of air pollution control strategies.
NREL	National Renewable Energy Laboratory
$PM_{2.5}$	Refers to fine inhalable particles that are 2.5 micrometers in diameter or smaller, which is about 30 times smaller than the width of a human hair. These tiny particles are a major component of air pollution and can be composed of a variety of substances, including dust, dirt, soot, and liquid droplets. $PM_{2.5}$ can originate from various sources, including vehicle exhaust, industrial processes, and biomass burning. Due to their small size, these particles can be inhaled deeply into the lungs, potentially causing serious health issues such as respiratory and cardiovascular diseases. Reducing $PM_{2.5}$ emissions is crucial for improving air quality and public health.
PGE	Pacific Gas and Electric Company
Placer County APCD	Placer County Air Pollution Control District
PPM	Parts per million, a measure of particle concentration.

Term	Definition
PSA	Pressure swing absorption, where adsorbent materials are used to capture specific gases from a mixture of gases.
TCI	Total capital investment, the total amount of funds needed to fund operations.
TDC	Total direct costs, comprising all expenses involved in the project.
TIC	Total indirect costs, all indirect costs involved in the project, including administration, materials, and labor.
UCSD	University of California, San Diego
UC Davis	University of California, Davis
RG	Renewable gas, biomethane derived from biomass.
Selective Non-Catalytic Reduction (SNCR)	A method used to reduce nitrogen oxide (NO_x) emissions from combustion processes. It involves injecting a reagent, typically ammonia (NH_3) or urea, into the flue gas stream at high temperatures (usually between 1562°F [850°C] and 2,012°F [1,100°C]). The reagent reacts with NO_x to form nitrogen (N_2) and water (H_2O), which are harmless. Unlike Selective Catalytic Reduction (SCR), SNCR does not require a catalyst but instead relies on the temperature and timing of the reagent injection to effectively reduce NO_x emissions. SNCR is often used in industries like power generation and biomass combustion where NO_x control is necessary, but the installation of a catalyst is not practical due to cost or other operational considerations.
SoCalGas	Southern California Gas Company
Standard Liter Per Minute (SLPM)	A unit of volumetric flow rate that measures the amount of gas flowing per minute under standard conditions of temperature and pressure (typically 0°C and one standard atmosphere of pressure [atm] or 77°F [25°C] and one atm, depending on the standard used). It is commonly used in gas flow measurements for scientific, industrial, and engineering applications.
SO_2	Sulfur dioxide, a colorless gas resulting from the burning of fossil fuels.
VOCs	Volatile organic compounds, chemicals that vaporize rapidly at room temperature, transitioning from liquid to gas.
WGS	Water gas shift reaction, where water and carbon monoxide react to produce carbon dioxide and hydrogen.

References

Aden, A; Ruth, M; Ibsen, K; Jechura, J; Neeves, K; Sheehan, J; Wallace, B et al., 2002. Lignocellulosic Biomass to Ethanol Process Design and Economics Utilizing Co-Current Dilute Acid Prehydrolysis and Enzymatic Hydrolysis for Corn Stover. Report No. NREL/TP-510-32438. Golden, CO: National Renewable Energy Laboratory.

Barsun Stephan, Ben Cheah, and Jean Shelton. 2023. Renewable Natural Gas in California. Characteristics, Potential, and Incentives: 2023 Update. California Energy Commission. Publication Number: CEC-200-2023-010.

Dutta Abhijit, Talmadge Michael, Hensley Jesse, Worley Matt, Dudgeon Doug, Barton David, and Groenendijk Peter, et al., 2011. Process Design and Economics for Conversion of Lignocellulosic Biomass to Ethanol. https://www.nrel.gov/docs/fy11osti/51400.pdf.

California Energy Commission. Supply and demand of natural gas in California. Energy Almanac. https://www.energy.ca.gov/data-reports/energy-almanac/californias-natural-gas-market/supply-and-demand-natural-gas-california.

California Energy Commission. Biomass energy in California. California Power Generation and Power Sources. https://www.energy.ca.gov/data-reports/california-power-generation-and-power-sources/biomass/biomass-energy-california.

California Air Resources Board. LCFS pathway certified carbon intensities. California Environmental Protection Agency. https://ww2.arb.ca.gov/resources/documents/lcfs-pathway-certified-carbon-intensities.

Seiser Reinhard, and Nguyen An. 2021. Production of Pipeline Grade Renewable Natural Gas and Value-Added Chemicals from Forest Biomass Residues_Mixed Alcohol/Renewable Natural Gas Parameter Test Report.

Summers Matthew, Liao Chang-hsien, Cattolica Robert, Seiser Reinhard, Jenkins Bryan, Vergnani Paul, Weaver Christopher, and Hart Matthew. 2015. Demonstration of Advanced Biomass Combined Heat and Power Systems in the Agricultural Processing Sector. California Energy Commission. Publication number: CEC-500-2016-035.

Summers Matthew, Matthew Hoffman, Chang-hsien Liao, Matthew Hart, Richard Seiser, Robert Cattolica, Reinhard Rauch, and Matthias Binder. 2019. West Biofuels Fuel Ethanol & Value-Added Chemicals from Biomass Residues. California Energy Commission. Publication Number: CEC-600-2019-140.

Project Deliverables

This project has produced a range of technical reports, analyses, and planning documents that support the development and validation of RG production from biomass-derived syngas. These deliverables provide detailed insights into system design, operational performance, and technical feasibility.

The key project deliverables include:

- Parameter Test Plan (draft and final)
- Parameter Test Report (draft and final)
- Design Basis Summary (draft and final)
- Construction Report (draft and final)
- Commissioning Plan (draft and final)
- Written Notification of Successful Commissioning (final)
- Long-Term Test Plan (draft and final)
- Long-Term Test Report (draft and final)
- RG Test Plan (draft and final)
- Proof of Compliance with Utility RG Specifications (draft and final)
- Kick-off Meeting Benefits Questionnaire
- Mid-term Benefits Questionnaire
- Final Meeting Benefits Questionnaire
- Initial Fact Sheet (draft and final)
- Final Project Fact Sheet (draft and final)
- Presentation Materials (draft and final)
- High Quality Digital Photographs
- Technology/Knowledge Transfer Plan (draft and final)
- Technology/Knowledge Transfer Report (draft and final)
- Production Readiness Plan (draft and final)

Project deliverables, including interim project reports, are available upon request by contacting pubs@energy.ca.gov.

CALIFORNIA
ENERGY COMMISSION

CALIFORNIA
NATURAL
RESOURCES
AGENCY

ENERGY RESEARCH AND DEVELOPMENT DIVISION

Appendix A: Process Efficiency and Energy Distribution Equations

March 2025 | CEC-500-XXXX-XXX

APPENDIX A:
Process Efficiency and Energy Distribution Equations

The equation for the overall process efficiency, $\eta_{overall}$, is given as:

$$\eta_{Gasifier} = \frac{\dot{\mathrm{E}}_{Syngas}}{\dot{\mathrm{E}}_{Biomass}} = \frac{\dot{\mathrm{m}}_{Syngas} \times GHV_{Syngas}}{\dot{\mathrm{m}}_{Biomass} \times GHV_{Biomass}}$$

$$\eta_{Train} = \frac{\dot{\mathrm{E}}_{RG+}\dot{\mathrm{E}}_{Alcohol}}{\dot{\mathrm{E}}_{Syngas}} = \frac{\dot{\mathrm{m}}_{RG} \times GHV_{RG} + \dot{\mathrm{m}}_{Alcohol} \times GHV_{Alcohol}}{\dot{\mathrm{m}}_{Syngas} \times GHV_{Syngas}}$$

$$\eta_{Overall} = \eta_{Gasifier} \times \eta_{Train}$$

The Equation for the energy distribution between RG and side products is as follows:

$$D = \frac{E_{RG}}{E_{RG} + E_{Alcohol}} = \frac{m_{RG} \times GHV_{RG}}{m_{RG} \times GHV_{RG} + m_{Alcohol} \times GHV_{Alcohol}}$$

Among them, $\dot{\mathrm{m}}_{Syngas}$, $\dot{\mathrm{m}}_{RG}$, and $\dot{\mathrm{m}}_{Alcohol}$ represent the production rates of syngas, biomass, RG, and mixed alcohol, respectively, with units in kg/hr. $\dot{\mathrm{m}}_{Biomass}$ represents the biomass feed in flow rate. GHV_{Syngas}, $GHV_{Biomass}$, $GHV_{Alcohol}$ and GHV_{RG} represent the gross heating value of syngas, biomass, mixed alcohol and RG, respectively, with units in MJ/kg. m_{RG} and $m_{Alcohol}$ represent the mass of products acquired during the certain time of the MAS run with units in kg.

CALIFORNIA
ENERGY COMMISSION

CALIFORNIA
NATURAL
RESOURCES
AGENCY

ENERGY RESEARCH AND DEVELOPMENT DIVISION

Appendix B: TEA Modeling Details

March 2025 | CEC-500-XXXX-XXX

APPENDIX B:
TEA Modeling Details

Table B-1: Total Installed Cost by Area for the High RG Case

Process Area	TPEC	Installation	TIC
Area A100: Feed Handling & Preparation	$107,540	2	$215,080
Area A200: Gasification	$19,279,394	2.31	$44,490,909
Area A300: Gas Cleanup	$1,301,400	2.31	$3,010,757
Area A400: Alcohol Synthesis	$27,710,608	2.11	$58,512,584
Area A500: Alcohol Separation	$3,769,485	1.71	$6,429,554
Area A1100: AGR & Methanation	$80,086,353	1.31	$105,670,111
Heat Integration and Pinch	$9,568,160	2.5	$23,928,501
Area A700: Steam System & Power Generation	$14,354,489	1.7	$24,464,907
Area A800: Cooling Water & Other Utilities	$3,248,847	2.22	$7,213,187
Totals	$159,426,278	1.72	$273,935,591
Other Direct Costs			
Warehouse			0
Site Development			9,690,300
Additional Piping			0
Total Other Direct Costs			9,690,300
Total Direct Cost (TDC)			**283,625,891**

Source: NREL

Table B-2: Indirect Costs and Total Capital Investment for the High RG Case

Indirect Costs	% of TDC	
Engineering (Proratable Expenses)	10.00%	$28,362,589
Construction (Home Office & Construction Fees)	20.00%	$56,725,178
Legal and Contractors Fees (Field Expenses)	10.00%	$28,362,589
Project Contingency	10.00%	$28,362,589
Other Costs (Start-Up, Permits, and so forth)	10.00%	$28,362,589
Total Indirect Costs (TIC)	**60.00%**	**$170,175,535**
Fixed Capital Investment Excluding Land (TDC + TIC)		**$453,801,426**
Working Capital	5.0% of FCI (ex Land)	$22,690,071
Total Capital Investment (TCI)		**$476,491,497**

Source: NREL

Table B-3: Total Installed Cost by Area for the High Alc Case

Process Area	TPEC	Installation	TIC
Area A100: Feed Handling & Preparation	$107,540	2	$215,080
Area A200: Gasification	$19,279,394	2.31	$44,490,909
Area A300: Gas Cleanup	$1,301,763	2.31	$3,011,463
Area A400: Alcohol Synthesis	$24,318,133	2.05	$49,839,785
Area A500: Alcohol Separation	$6,578,483	1.56	$10,243,814
Area A1100: AGR & Methanation	$63,810,517	1.37	$87,654,744
Heat Integration and Pinch	$9,512,880	2.5	$23,790,253
Area A700: Steam System & Power Generation	$18,129,280	1.66	$30,124,559
Area A800: Cooling Water & Other Utilities	$3,872,166	2.12	$8,196,230
Totals	**$146,910,157**	**1.75**	**$257,566,838**
Other Direct Costs			
Warehouse			0
Site Development			$8,769,842
Additional Piping			0
Total Other Direct Costs			$8,769,842
Total Direct Cost (TDC)			**$266,336,680**

Source: NREL

Table B-4: Indirect Costs and Total Capital Investment for the High Alc Case

Indirect Costs	% of TDC	
Engineering (Proratable Expenses)	10.00%	$26,633,668
Construction (Home Office & Construction Fees)	20.00%	$53,267,336
Legal and Contractors Fees (Field Expenses)	10.00%	$26,633,668
Project Contingency	10.00%	$26,633,668
Other Costs (Start-Up, Permits, and so forth)	10.00%	$26,633,668
Total Indirect Costs (TIC)	60.00%	$159,802,008
Fixed Capital Investment Excluding Land		$426,138,687
Working Capital	5% of FCI (ex Land)	$21,306,934
Total Capital Investment (TCI)		**$447,445,622**

Source: NREL

Table B-5: Variable Operating Costs for the High RG Case

Parameter	Quoted Price (Cents/Ton or Cents/kWh)	Year of Price Quote	2016 Cost (MM$/Year)
Feedstock, Catalyst and Chemicals			
Feedstock - Wood Chips	4426	2016	45.792

Parameter	Quoted Price (Cents/Ton or Cents/kWh)	Year of Price Quote	2016 Cost (MM$/Year)
Electricity	5.85	2016	-0.67
Magnesium Oxide (MgO)	36500	2004	0.016
Fresh Olivine	17290	2004	0.566
Tar Reformer Catalyst	4379658	2016	-
50 wt% Caustic	15000	2010	0.027
Boiler Chemicals	280000	1991	0.049
Cooling Tower Chemicals	200000	1999	-
Natural Gas for Reformer	23700	2016	-
Cooling Tower Makeup	19.96	2004	-
Boiler Feed Water Makeup	19.96	2004	0.041
Natural Gas for Gasifier	23700	2016	0
Diesel Fuel	80589	2007	0.296
LO-CAT Chemicals	160150	2009	0.018
DEPG Make-Up	26702	2010	0.052
Amine Make-Up	8000	2010	0.016
Waste Streams			
Sand and Ash Purge	3266	2004	0.483
WWT Cost	48.08	2004	0.026
Co-Product Credits	$/unit		
Methanol (gal)	1.06	2016	-0.9
Ethanol (gal)	2.19	2016	-4.23
Mixed Alcohol (GGE)	3.01	2016	-8.45
Total Variable Operating Cost			**33.13**

Source: NREL

Table B-6: Variable Operating Costs for the High Alcohol Case

Parameter	Quoted Price (Cents/Ton or Cents/kWh)	Year of Price Quote	2016 Cost (MM$/Year)
Feedstock, Catalyst and Chemicals			
Feedstock - Wood Chips	4,426	2016	45.792
Electricity	5.85	2016	-4.7
Magnesium Oxide (MgO)	36,500	2004	0.016
Fresh Olivine	17,290	2004	0.566
Tar Reformer Catalyst	4,379,658	2016	-
50 wt% Caustic	15,000	2010	0.027
Boiler Chemicals	280,000	1991	0.055
Cooling Tower Chemicals	200,000	1999	-
Natural Gas for Reformer	23,700	2016	-

Parameter	Quoted Price (Cents/Ton or Cents/kWh)	Year of Price Quote	2016 Cost (MM$/Year)
Cooling Tower Makeup	19.96	2004	-
Boiler Feed Water Makeup	19.96	2004	0.014
Natural Gas for Gasifier	23,700	2016	0
Diesel Fuel	80,589	2007	0.296
LO-CAT Chemicals	160,150	2009	0.042
DEPG Make-Up	26,702	2010	0.025
Amine Make-Up	8,000	2010	0.007
Waste Streams			
Sand and Ash Purge	3,266	2004	0.483
WWT Cost	48.08	2004	0.02
Co-Product Credits	$/unit		
Methanol (gal)	1.06	2016	-11.987
Ethanol (gal)	2.19	2016	-
Mixed Alcohol (GGE)	3.01	2016	-41.287
Renewable Gas (MMBtu)	3.56	2016	-13.646
Total Variable Operating Cost			-24.27

Source: NREL

Table B-7: Fixed Operating Costs for the High RG Case

Parameter	2016 Cost (MM$ / Year)
Total Salaries	3.08
Overheard and Benefits	2.78
Maintenance	13.61
Insurance & Taxes	3.18
Total Fixed Operating Cost	**22.65**

Source: NREL

Table B-8: Fixed Operating Costs for the High Alc Case

Parameter	2016 Cost (MM$ / Year)
Total Salaries	3.08
Overheard and Benefits	2.78
Maintenance	12.78
Insurance & Taxes	2.98
Total Fixed Operating Cost	21.62

Source: NREL