Energy Research and Development Division

FINAL PROJECT REPORT

Modular Biomass Power Systems to Facilitate Forest Fuel Reduction Treatment

California Energy Commission

Gavin Newsom, Governor

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PREFACE

The California Energy Commission's Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solution, foster regional innovation and bring ideas from the lab to the marketplace. The California Energy Commission and the state's three largest investor-owned utilities – Pacific Gas and Electric Company, San Diego Gas and Electric Company and Southern California Edison Company – were selected to administer the EPIC funds and advance novel technologies, tools and strategies that provide benefits to their electric ratepayers.

The Energy Commission is committed to ensuring public participation in its research and development programs which promote greater reliability, lower costs and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

Modular Biomass Power Systems to Facilitate Forest Fuel Reduction Treatment is the final report for the research and development project (contract number EPC-14-024) conducted by West Biofuels. The information from this project contributes to the Energy Research and Development Division's EPIC Program.

All figures and tables are the work of the author(s) for this project unless otherwise cited or credited.

For more information about the Energy Research and Development Division, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-327-1551.

ABSTRACT

This research and development project aimed to evaluate modular gasification for use across California's forested landscape to promote and support sustainable fire-safe management activities. Research activities were conducted at the Woodland Biomass Research Center in Woodland, California through a collaboration between West Biofuels, University of California San Diego, and University of California Davis with additional support from TSI Consultants on forest resource analysis.

The research program included extensive feedstock testing and resource analysis, gasifier system testing and demonstration, and internal combustion engine testing using biomass-derived producer gas. The project team used data collected throughout the testing phases to evaluate the techno-economic feasibility of various gasification system schemes, identify opportunities for structural and operational improvements, and define best practices to improve the performance and reduce the cost of community-scale gasification.

The results of the research identified critical challenges with the original CircleDraft gasification design when used with traditional forest residue. These challenges are a direct result of the feedstock processing used in fire-safe management activities across the western United States. In addition, the resulting syngas did not meet gas quality targets and was difficult to synchronize with an engine generator system. The team found an alternative gasification approach using rotary processing technology already commonly used in the forest products industry with challenging biomass feedstock. This rotary gasification system coupled with a thermal oil heater and organic rankine cycle turbine generator resulted in a superior approach in terms of overall energy cost and system capacity factor. Coupled with site optimization and biochar marketing, the resulting energy costs are in the range of currently available power purchase prices from California utility companies. These research breakthroughs resulted in process improvements to ready a new technology for commercialization in California forest communities, as well as a deeper understanding of best practices applicable to community-scale forest biomass projects across California.

Keywords: biomass, gasification, forest, fire-safe management, SB 1122, community-scale

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EXECUTIVE SUMMARY

Introduction

California is home to 33 million acres of forest lands, all of which face a number of threats. However, the greatest threat is not loss of forest due to harvesting and the lack of subsequent regrowth, but rather from serious catastrophic events such as large wildfires and land use change to agricultural and residential uses. While the causes of catastrophic wildfires are actively debated, the impacts of these severe events indisputably threaten power lines, hydroelectric generation facilities, watersheds and water storage facilities, roadways, and most importantly communities and human lives.

This research project focused on developing a modular technology solution and business strategy to improve community engagement in the sustainable collection, transportation, management, and power generation from forest residue to reduce forest fire risk. The project sought a technological solution to support California's policy goals for healthy forest management, protection of electricity infrastructure, and production of renewable electricity.

Project Purpose

Biomass gasification technology, in which solid organic material is converted to a combustible gas, is new to the California marketplace. The development of gasification technology was spearheaded in Europe and throughout the developing world where electricity is scarce and biomass availability is high. European technologies were designed to have high levels of automation and high efficiency using carefully processed wood chips from plantation forests as a feedstock. This ecosystem led to the growth and development of fluidized bed systems that can convert highly-uniform feedstock to a high-quality producer gas for use in high-efficiency internal combustion engine. Conversely, technologies from developing world economies have focused on low levels of automation and the production of a crude producer gas product that can run in early to mid-20th century engines. Neither of these technology pathways fit the California economy where environmental standards and labor costs resemble the European markets, but feedstock availability and low power prices represent the developing country markets.

West Biofuels works towards a modular solution tailored specifically for the biomass widely available across the forested landscapes of California. This research sought to identify technologies that can operate reliably and consistently thereby creating and sustaining jobs in rural areas, producing renewable electricity, and contributing to the healthy management of the forest.

Project Process

The research project had four main technical tasks:

1. Feedstock testing: The project team conducted (a) feedstock testing to understand the principal types of forest material available in California; (b) an analysis of the state's

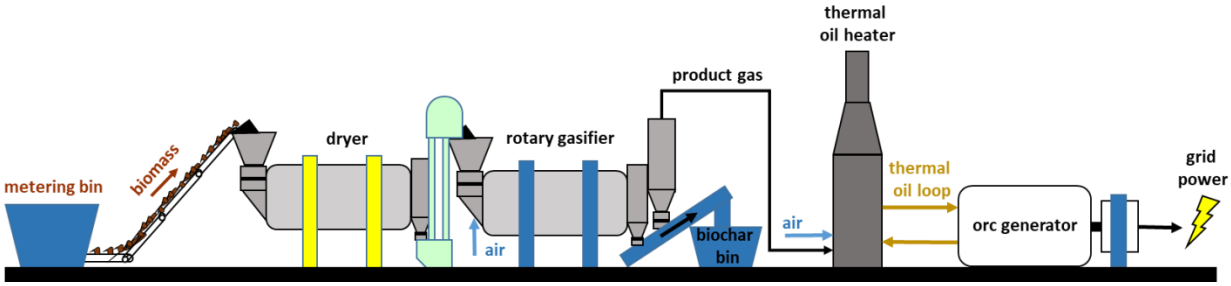
vegetation cover and ownership types to understand regional availability; (c) testing and analysis of commonly available feedstock types to determine typical feedstock characteristics; and (d) a statewide study of processing infrastructure to understand the types of equipment commonly used in the field to process biomass. This testing and analysis provided important insights into the physical characteristics of the feedstock.

2. Gasifier testing: West Biofuels tested the CircleDraft gasifier to evaluate its ability to effectively and consistently use common California feedstocks. The tests used a commercial demonstration-scale gasification system located at West Biofuels. The project team collected and analyzed producer gas and biochar (a co-product of gasification that can be used as a soil amendment) to determine the gas composition and quality.
3. Generator testing: West Biofuels tested the producer gas generated by the CircleDraft system in a Caterpillar internal combustion engine generator. The project team conducted engine testing to determine operational performance, maintenance requirements, and air emissions. The team also tested an alternative generation system that had potential for superior performance.
4. Feasibility study: West Biofuels conducted a feasibility study to determine the potential business case and economic viability of the systems developed during the gasifier and generator testing. The feasibility study evaluated grid interconnection pathways, the Biomass Market Adjusting Tariff (also known as BioMAT, the state's feed in tariff program for biomass projects), environmental compliance, greenhouse gas lifecycle, and potential candidate sites for deployment.

Project Results

The project yielded important results that did not support the initial hypothesis that the CircleDraft gasification was appropriate for the California market. However, the project did result in the development of a more robust modular system that addressed critical process challenges with the initial system including material flow issues associated with forest material, associated producer gas output and quality fluctuations, and high engine generator maintenance requirements. The new system configuration selected is shown in Figure ES-1.

Figure ES-1: Final Technology Configuration Selected for Forest Biomass



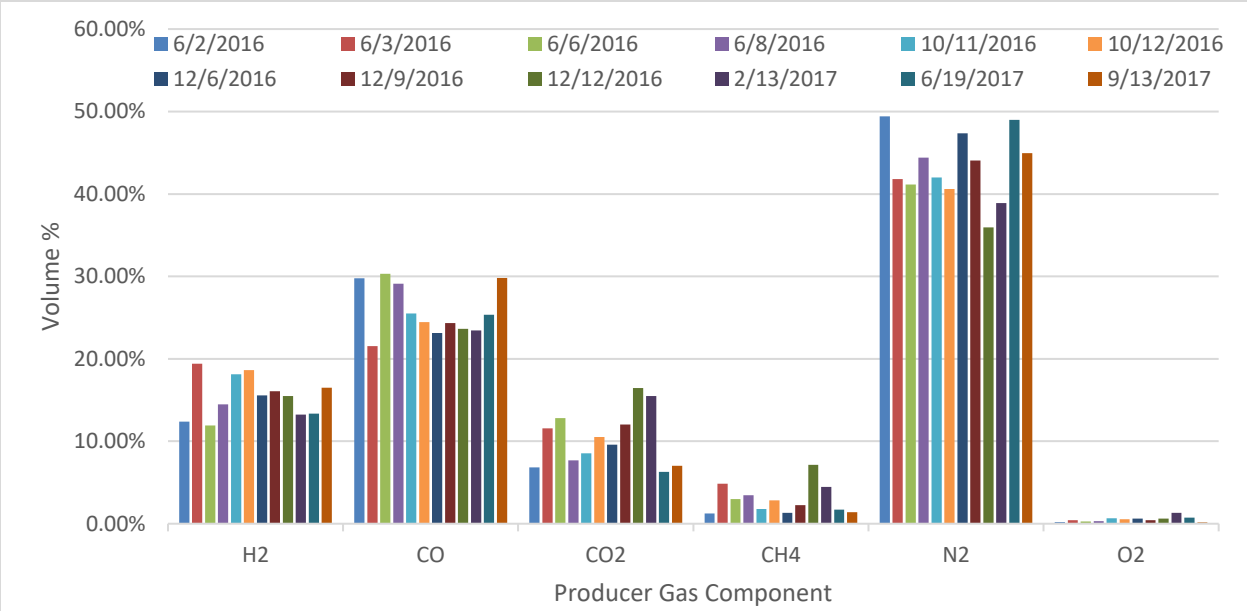
Source: West Biofuels

West Biofuels analyzed four different system configurations to reach the final technology selection.

- System 1: Metering bin, dryer, CircleDraft gasifier, product gas scrubber, gas engine.
- System 2: Metering bin, dryer, torrifier, CircleDraft gasifier, product gas scrubber, gas engine.
- System 3: Metering bin, dryer, torrifier, CircleDraft gasifier, thermal oil heater, Organic Rankine Cycle generator.
- System 4: Metering bin, dryer, rotary gasifier, thermal oil heater, Organic Rankine Cycle generator.

The four systems used two different gasification systems; System 1 – System 3 focused on the CircleDraft gasification system and System 4 focused on a rotary gasification system. The majority of the gasifier testing occurred on the CircleDraft gasification system, which was the focus of the research project. Figure ES-2 shows a summary of the average gas data from each of the gasifier tests.

Figure ES-2: Producer Gas Data from CircleDraft Tests



Source: West Biofuels

During producer gas sampling, the research team measured tar levels in the raw gas and the treated gas (through the product gas scrubber). The scrubber system demonstrated a high level of efficiency and reduced tar contamination by more than 90 percent for the majority of the constituents measured. However, the overall tar loading was higher than predicted and above target levels for use in an internal combustion engine. In response to this challenge, West Biofuels evaluated two systems with a thermal oil heater and Organic Rankine Cycle generator, which offers greater flexibility to producer gas specifications (System 3 and System 4). Using a thermal oil heater and Organic Rankine Cycle generator, West Biofuels was able to evaluate a

rotary gasifier system, which has the potential to be lower cost than the CircleDraft system and produce a higher energetic content in the gas. Table ES-1 compares the producer gas generated by these two gasifier systems.

Table ES-1: Producer Gas Comparison (System 3 and System 4)

Parameters	Units	CircleDraft Gasifier w/ Torrefied Wood @5%mc	Rotary Gasifier w/Wood @10%mc	Rotary Gasifier w/Wood @10%mc and Air Injection
Producer Gas Composition				
CO	(dry vol%)	29.8%	37.5%	21.0%
H2	(dry vol%)	16.5%	0.4%	0.3%
CH4	(dry vol%)	1.4%	5.6%	2.3%
N2	(dry vol%)	45.0%	0.3%	37.3%
CO2	(dry vol%)	7.0%	54.2%	34.8%
C2H4	(dry vol%)	0.0%	0.1%	1.0%
C2H6	(dry vol%)	0.1%	0.3%	0.0%
Producer Gas Higher Heating Value (HHV)	(MJ/kg)	5.9	4.0	2.7
Mass/Energy				
Producer Gas Generation	(mass% of dry input)	52%	27%	45%
Vapors Production*	(mass% of dry input)	2%	42%	38%
Biochar Production	(mass% of dry input)	16%	31%	17%
Producer Gas + Vapors HHV	(MJ/kg)	6.1	13.0	10.7
Biochar HHV	(MJ/kg)	24.3	21.6	24.0
Producer Gas + Vapors Energy	(MJ/kg of dry input)	11.3	9.6	12.1
Process Thermal Efficiency		***0.56***	***0.53***	***0.64***

Source: West Biofuels

Using the data collected for gas production, West Biofuels evaluated the economic performance of the four systems. West Biofuels modeled a baseline scenario and conducted sensitivity analysis showing that capacity factor (the ratio of potential to actual power output) and biochar price were the most important economic model factors. The baseline scenario did not include any by-product value for biochar. A summary of the baseline results is presented in Table ES-2.

Table ES-2: Baseline Economic Model Results

	System 1	System 2	System 3	System 4
LCOE ($/MWh)	$403	$310	$317	$242

Source: West Biofuels

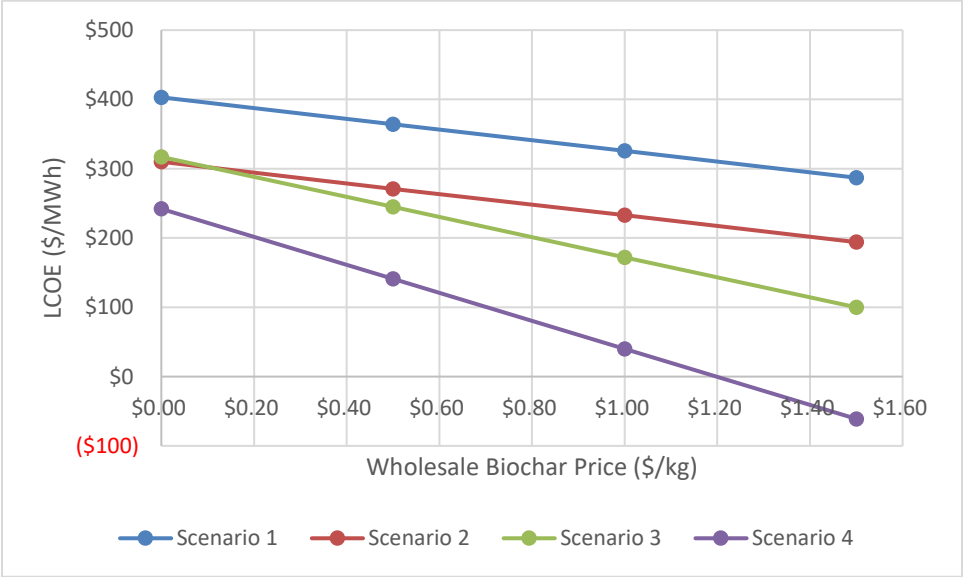
The selected technology has an overall lower system efficiency; however, the increased up-time and co-product production resulted in a more favorable business case and economic analysis. Promisingly, the business case and production readiness of the final technology configuration are ready for commercial production. Supported by the BioMAT program, the availability of long-term revenue should be sufficient to attract external investment in forest biomass projects.

Benefits to California

A significant portion of the state's electrical infrastructure is located in forested regions, including critical transmission and distribution lines and hydropower assets. Forest fires are a significant threat to this critical infrastructure. Electricity ratepayers can benefit from community-scale forest gasification technologies because of the ability to more proactively manage the forested landscape.

Unlike traditional direct combustion technologies, gasification technology offers an important co-product: biochar. As the biochar market establishes in California, the potential to generate renewable power that is cost competitive with intermittent renewables like solar or wind increases. Figure ES-3 shows the impact of biochar on the levelized cost of electricity (the average price an asset needs to break even over its lifetime). With a market hovering above $1.00 per kilogram (kg) at the time of this report, long-term production of high-quality biochar could have a substantial impact, reducing electricity generation prices to $40 per megawatt-hour (MWh).

Figure ES-3: Biochar Sensitivity

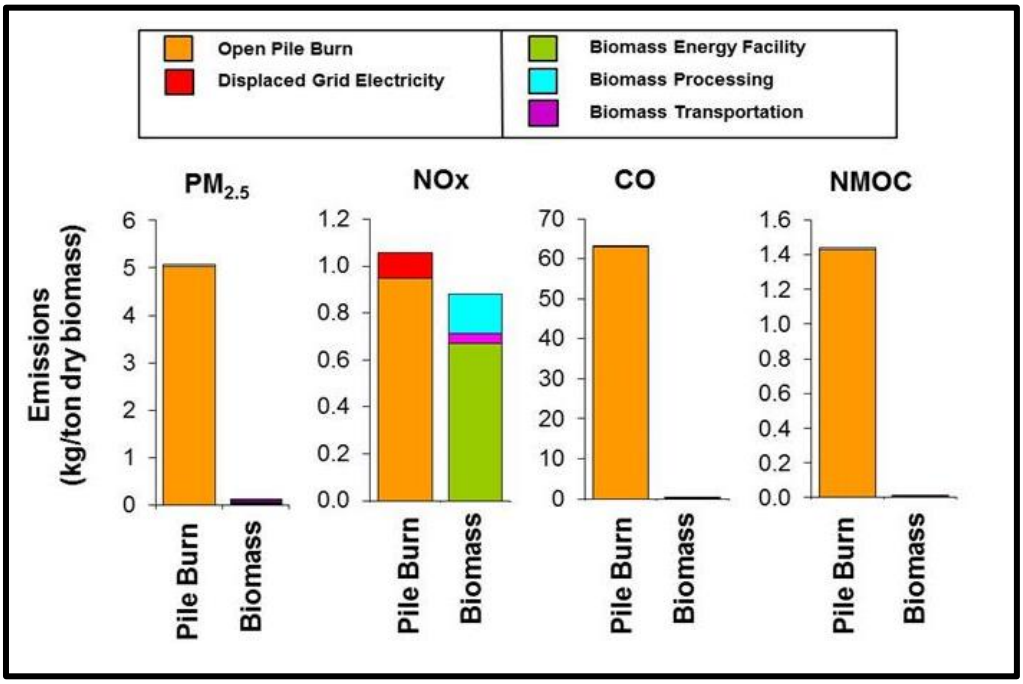


Source: West Biofuels

The proliferation of biomass energy will provide important air emissions and greenhouse gas emissions reductions. Emission reductions are generated from utilization of biomass for renewable electricity instead of open pile burning (business as usual). Figure ES-4 shows the air emissions savings and Table ES-3 shows the greenhouse gas savings.

Lastly, the project team evaluated the greenhouse gas benefits for each of the systems. System 4 had the greatest greenhouse gas reductions over all the systems studied (Table ES-3).

Figure ES-4: Pile and Burn versus Controlled Emissions



Source: Placer County Air Pollution Control District, 2018

Table ES-3: Net Greenhouse Gas Lifecycle Emissions

	System 1	System 2	System 3	System 4
Construction Emissions (MT CO2e/yr)	8.25	8.25	8.25	8.25
Project Emissions (MT CO2e/yr)	19,623	28,402	56,648	54,757
Mobile Emissions (MT CO2e/yr)	926	926	926	1,389
Gross Emissions (MT CO2e/yr)	**20,557**	**29,336**	**57,582**	**56,154**
Avoided Pile & Burn (MT CO2e/yr)	10,405	14,591	30,038	29,035
Avoided Mastication (MT CO2e/yr)	8,935	12,529	25,794	24,932
Sequestered Carbon (MT CO2e/yr)	3,005	4,213	8,674	10,951
Gross Savings (MT CO2e/yr)	**22,345**	**31,333**	**64,506**	**64,918**
Net Lifecycle (MT CO2e/yr)	**-1,788**	**-3,005**	**-6,924**	**-8,764**

Source: West Biofuels

Technology Transfer

The project team shared the technology and knowledge developed through the implementation of this project with other technology experts, other researchers, and the larger community of engaged forest communities, forest-focused agencies and non-profits, and the wood products industry. The researchers conducted different outreach activities, such as Conference Presentations; Annual Project Review Meetings; Open House for the Public, and Technology Presentations to Community and Industry.

The project team attended technical conferences and presented the status and results of the project with other subject matter technical experts in the area of thermochemical conversion of biomass for energy. These are national and international gatherings of experts in this field where there is an opportunity to transfer knowledge to others and help spread the technology

and efforts of California to improve technology. These meetings are also a chance for the project team to keep informed on other efforts that may be beneficial and complementary to this project. The team gave more than two technical conference presentations per year during the course of the project. For instance, some of the conference were tcbiomass2015, European Biomass Conference, and Exhibition (EUBCE), and tcbiomass2017.

Researchers also gave technology presentations to industry, government, and community members interested in the CircleDraft technology and addressing forest-source residue management. These presentations took place at the project site and at other locations on an invited basis. These presentations are opportunities to transfer information about the project and CircleDraft technology to a wider audience. The team gave at least five of these presentations per year during the course of the project.

Conclusions and Next Steps

Based on the characteristics of the California forest resource, the most promising regions for forest biomass energy projects included the Sierran and Interior regions and specific sites were identified showing good attributes for forest bioenergy project development. The current equipment inventory available for processing and delivery of forest thinning residues can produce a good particle size and low ash content biomass suitable for gasification.

The CircleDraft gasifier coupled with an engine generator was not a viable option for power production from California forest biomass. The project team encountered problems with bridging and channeling (which affects the feedstock fuel flow) in the gasifier, inconsistency and quality problems with the gas, maintenance challenges with the engine generator system, and overall costs exceeding market prices for biopower. To address these shortcomings, the team developed an alternative technology approach including a rotary gasifier/thermal oil heater/Organic Rankine Cycle. This new gasifier approach maintained better material flow and precise temperature control with continuous and consistent gas delivery to the heater system without requiring any costly gas cleanup. The maintenance cost and downtime of the Organic Rankine Cycle generator system is minimal, making the overall cost of power within the range of power purchase contracts available in the state. The research showed that community-based projects with this technology would enable better local forest management, reduced pollutant emissions from burning, and greenhouse gas emissions benefits.

West Biofuels next step is a commercial demonstration of this technology in a California forest sector community. The team is developing a 3 megawatt forest biopower facility in the Northern Sierra region in collaboration with one of the site owners identified in this project. This is likely to be the first demonstration of this technology in California and the team hopes this facility will lead to many more community-based biopower plants in the future sprinkled in the California forest regions. The team also recommends future funding of a study to track the longer-term performance record of community-scale forest bio-power systems in other parts of the world, funding further analysis of the electrical grid in forest community areas to identify site locations with favorable attributes for the grid, and funding market development activities for biochar.

CHAPTER 1: Introduction

Relevance to California

California is home to 33 million acres of forest lands, all of which face a number of threats. However, the greatest threat is not loss of forest due to harvesting and the lack of subsequent regrowth but conversion to non-forests from serious catastrophic events such as large wildfires and land use change to agricultural and residential uses. While the cause of catastrophic wildfire is an actively debated topic, the impacts of these severe events indisputably threaten electrical infrastructure (for example, transmission and distribution lines) and hydroelectric generation facilities, watersheds and water storage facilities, roadways, and most importantly communities and human lives.

Community-scale bioenergy provides an opportunity to support local and sustainable fire management activities that can protect these important resources. Defined by California State Senate Bill (SB) 1122 (Rubio, 2012) and later amended by California State Assembly Bill (AB) 1923 (Wood, 2016), community-scale facilities are designed to have a net generating capacity of no more than 5 megawatts (MW) to serve onsite load with up to 3MW of exporting capacity as a distributed energy resource. Community-scale bioenergy allows local outlets for the material collected as a by-product of existing and planned fire safe management activities (for example electric line clearing, forest thinning in the wildland-urban interface, road maintenance).

Gasification Basics

To facilitate community-scale bioenergy in California, West Biofuels is committed to advancing biomass gasification solutions that can be developed to meet local needs, utilize the local workforce, and produce revenue-generating co-products that can drive down the long-term price of electricity production. Gasification technology is a thermo-chemical process by which feedstock—in this case sustainable wood residue—is placed in a high-temperature, low-oxygen environment forcing the release of volatile gases and leaving behind a basic carbon structure.

The volatile gases, known as producer gas or syngas in the literature,[1] can be collected and conditioned for a variety of uses include heat production, electricity generation with an internal combustion engine, organic Rankine cycle engine or steam turbine, advanced transportation fuels, and biochemicals. For community-scale gasification projects, the primary energy products are heat and power. The basic carbon material that remains after gasification is called biochar. Unlike ash, biochar is a complex and highly porous structure that can be used in agricultural applications to improve crop production through water and fertilizer retention in the root zone and in industrial applications as filtration.

[1] Syngas traditionally refers to the reactive part of the volatile gases, primarily carbon monoxide and hydrogen. Producer gas is a more inclusive term encompassing all gas collected in the gasification process including syngas, other inert gases, primarily carbon dioxide and nitrogen, and contaminants, collectively referred to as tars.

Research Scope

West Biofuels, in partnership with the University of California (UC) San Diego, TSS Consultants, CLERE Inc., the Soper Company, and the Placer County Air Pollution Control District, sought to advance the knowledge and best practices for forest biomass utilization in community-scale gasification applications in California. To do so, West Biofuels conducted a series of tests and data analysis:

1. Feedstock Testing: This step focuses on developing a better understanding of specific characteristics of wood residue generated from sustainable forest management activities. Existing literature is focused on biomass combustion and lacks important information about the physical and chemical characteristics of this biomass feedstock. The project team conducted a thorough high-level evaluation of feedstock availability by region in California. This data is intended to be used by prospective developers to better identify and prepare for the specific feedstock varietals that are most abundant in the region, which is a function of vegetation cover and land ownership patterns. West Biofuels specifically tested feedstock provided by Soper Company from the Central Sierra Nevada range to further evaluate the properties associated with some of the most common feedstock types across the state.
2. Gasifier Testing: West Biofuels hosts the Woodland Biomass Research Center and operates two pilot-scale gasification facilities. The Woodland Biomass Research Center is a collaboration between West Biofuels, UC San Diego, and UC Davis and is one of North America's premier gasification test facilities. This project focused on the existing 0.5MW fixed-bed CircleDraft gasification, originally developed by INSER S.P.A. (Italy). This gasifier type has potential for modular construction and deployment, important for reducing costs over time. The gasifier testing program involved hundreds of hours of gasifier testing to evaluate system performance, specifically producer gas and biochar production.
3. Engine Testing: At the community-scale size, the most complex yet most efficient way to convert producer gas to electricity is through an internal combustion engine. A consistent and high-quality producer gas is required to effectively use an internal combustion engine. Based on the findings of the gasifier testing stage, an engine test plan was developed to understand the impacts of producer gas utilization in the engine. Data is focused on operational performance and maintenance requirements.
4. Feasibility Study: Based on the data collected from the first three phases, a feasibility study was conducted to identify regulatory, technical, and economic barriers and opportunities for community-scale development across the state. The feasibility study evaluates the economic potential of the gasification system and locations that may be suitable for further deployment of the technology.

To evaluate the success of the research program, West Biofuels developed a comprehensive list of quantifiable and measurable objectives.

The objectives were to:

- Design, build, and install a system to process incoming forest-sourced feedstock to create a uniform feedstock without fines, overs, or inorganic material (for example, rock and dirt).[2] Targets, after processing, include:
    - Total Inert Content <5 percent
    - Ash Characteristics: Melting point greater than 900˚C
    - Particle Size: <1 percent 3-inch and over, <5 percent fines (Less than ¼ inch)
    - Moisture Content: Less than 25 percent
    - Higher Heating Value (HHV): Greater than 7,500 British thermal units (Btu)/dry pound
- Test the gasifier to determine operating conditions (for example temperature, flow rates, grate speed) for optimized efficiency and producer gas quality. Targets for efficiency and producer gas quality include:
    - Thermal Efficiency: >70 percent
    - Throughput Rate: > 900 dry pounds per hour
    - Producer Gas Energy Content: > 150 Btu per cubic foot
    - Tar Content: < 20 mg per normal cubic meter (Nm3)
    - Tar Dew Point: < 15˚C
    - Particulates: < 5 mg per Nm3 and less than 1 micron
    - Hydrogen Sulfide: < 50 parts per million (ppm)
    - Biochar Production: > 72 dry pounds per hour
    - Biochar Quality: Meets or exceeds International Biochar Initiative (IBI) Biochar Standards
- Install and test an internal combustion engine generator under various operational settings to identify the optimal configuration for producer gas fuel. Targets include:
    - Electrical Efficiency: > 35 percent
    - Combined Heating Power (CHP) Efficiency: > 75 percent
    - Oil Change Frequency: >750 hours
    - Generator Fault Frequency: <1 fault per 250 hours
    - Operating Speed: 1,000 revolutions per minute (RPM) to 2,000 RPM
    - Equivalence Ratio: < 0.55
    - Compression Ratio: > 11:1
- Demonstrate emission controls that meet California Air Resources Board (CARB) and Regional Air District standards. Targets include:

[2] Fines and overs refer to materials of a certain particle size.

    - Nitrogen Oxide (NOx): < 0.07 pounds per megawatt-hour (MWh)
    - Carbon Monoxide (CO): < 0.1 pounds per MWh
    - Volatile Organic Compounds (VOC): < 0.02 pounds per MWh
    - Particulate Matter (PM): < 0.31 pounds per MWh
- Research the potential to site modular community-scale biomass gasification projects in the forest/urban interface factoring grid infrastructure and high fire risk areas. Research includes:
    - Identify 10 high-priority locations in the forest/urban interface.
    - Cost/Benefit analysis of feedstock transportation or plant replication/relocation.
    - Assess environmental impacts of modular power system.
    - Greenhouse gas (GHG) life cycle analysis utilizing forestry waste to generate electricity.
    - Identify opportunities and challenges for modular community-scale deployment that are part of the SB 1122 Renewable Market Adjusting Tariff programs and Utility Power Purchase Agreements.
- Assess production readiness and perform economic analysis to evaluate feasibility for deployment of modular bioenergy technology. Targets include:
    - Deployment capacity ramping from 3 MW to 20 MW per year.
    - SB 1122 competitive Levelized Cost of Energy (LCOE) of $124.66 per MWh.
    - Support 4.9 local renewable energy jobs per MW.
    - Support 700 acres per year of forest treatment/thinning projects per MW.

CHAPTER 2:
Feedstock Testing

Feedstock Characterization

Feedstock characterization is critical to understand what types of feedstock are available across California's forested landscape. A statewide evaluation was conducted and includes:

- An overview of forest types in California.
    - A statewide forest land cover classification scheme customized from existing vegetation mapping systems.
- An overview of landownership patterns in California.
    - A statewide land ownership classification system integrating state, federal, and private industrial forest landownership data.
- Development of forest land cover classes and landownership spatial databases for mapping and GIS analysis.
- Development of a regional approach to facilitate analyses of forest land cover class, landownership, and forest management practices for nine forested regions in California.
- Description of Forest Management Practices (FMP) typical in each of the defined regions.
- Identification of sample forest feedstock from four distinct forest management sites within the reach of Soper Company, the project's primary feedstock supplier. Sample feedstock will be chosen to be representative of the diversity of forest biomass throughout California.
    - Description of the FMP occurring at each of the four selected sites including: geography and topography; forest type; management objectives; management practices; and actual yield.

Overview of California Forests

Three vegetation and land cover classifications schemes were examined and evaluated for their suitability to meet the project's objectives:

- The California Wildlife Habitat Relationship (CWHR); State of California
- Vegetation Classification and Mapping (CALVEG); U.S. Forest Service (USFS)
- Landscape Fire and Resource Management Planning Tools (LANDFIRE), U.S. Geological Survey (USGS)

The CWHR is a vegetation classification system developed for the California natural resource agencies by the Department of Fish and Wildlife.[3] It is the vegetation mapping system used by

[3] *A Guide to Wildlife Habitats of California.* 1988. Edited by Kenneth E. Mayer and William F. Laudenslayer, Jr. State of California, Resources Agency, Department of Fish and Game, Sacramento, CA. 166 pp. Also: https://www.dfg.ca.gov/biogeodata/cwhr/wildlife_habitats.asp.

the California Department of Forestry and Fire Protection (CAL FIRE) in their Fire and Resource Assessment Program (FRAP). CAL FIRE has recently released a revised 2015 version of the CWHR, geodatabase name FVEG_15_1.[4] CWHR has a total of 59 vegetation classes across the state with 27 forest classes for tree-dominated habitats. CALVEG was developed by the USFS, Region 5, Resource Management division, using remote sensing classification, photo editing, and field based-observations. The state is divided into 11 regions and has a total of over 300 vegetation classes. LANDFIRE was developed by the USGS and is a national-scale vegetation cover mapping system. It was mapped using landscape models based on field reference data, satellite imagery, biophysical gradient layers, and classification and regression trees. The existing vegetation type (EVT) data layer represents the current distribution of the terrestrial ecological systems classification developed by NatureServe for the western Hemisphere.[5] The forest agencies developed CWHR and CALVEG specifically and solely for the state of California, and offered higher spatial accuracy than the LANDFIRE national dataset.

- CWHR vegetation classes were used as the basis for the forest land cover classes and 17 forest classes were defined.[6]
- CALVEG provided the regional framework, and nine regions as delineated by CALVEG were adopted for the regional analyses.

Classification and Description of Forest Land Cover Classes

For simplicity, the research team combined the original 27 CWHR tree-dominated habitats and re-classed into 17 forest land cover classes based on relevance for forest woody biomass production (Table 1). For example, Blue Oak–Foothill Pine and Blue Oak Woodland were combined into the single Blue Oak Woodland–Foothill Pine designation.

- NotifS: The team designated forest types that they deemed inconsequential as potential sources of woody biomass material as “NotifS”. For example, Desert Riparian and Eucalyptus were re-classed and designated NotifS (Table 1).
- Non Forest: The team classed shrub-dominated and herbaceous dominated vegetation classes, aquatic habitats, and agricultural lands as Non-Forest (Table 2).

Stand descriptions for the 17 forest land cover classes are included in Table 3. Each stand description provides ecological information, including dominant and co-dominant tree species, type of site, where generally found, and elevation zone.

[4] http://frap.fire.ca.gov/data/frapgisdata-sw-fveg_download.php

[5] http://www.natureserve.org/publications/usEcologicalsystems.jsp

[6] There is a crosswalk for vegetation classes from CWHR to CALVEG. It was not used in this report, but could be available for additional analyses

Table 1: Forest Land Cover Classes with California Wildlife Habitat Relationship Vegetation Type

Forest Land Cover Class	Original CWHR Vegetation Type/s	Primary Species**
Aspen	Aspen	Aspen, Willows, Alders
Blue Oak Woodland-Foothill Pine	Blue Oak-Foothill Pine; Blue Oak Woodland	Foothill Pine, Blue Oak, Interior Live Oak, Blue Oak, Interior Live Oak, California Buckeye
Coastal Oak Woodland	Coastal Oak Woodland	Coast Live Oak, Engelmann Oak, Island Oak
Douglas Fir	Douglas Fir	Douglas Fir, Tanoak, Ponderosa Pine
Eastside Pine	Eastside Pine	Ponderosa Pine, Jeffrey Pine, White Fir
Jeffrey Pine	Jeffrey Pine	Jeffrey Pine, Ponderosa Pine, Sugar Pine
Juniper – Pinyon Juniper	Juniper Pinyon-Juniper	Juniper Species, White Fir, Jeffrey Pine, Pinyon Species, Mountain Mahogany Species
Klamath Mixed Conifer	Klamath Mixed Conifer	White Fir, Douglas Fir, Ponderosa Pine
Lodgepole Pine	Lodgepole Pine	Lodgepole Pine, Aspen, Mountain Hemlock
Montane Hardwood-Conifer	Montane Hardwood-Conifer	Ponderosa Pine, Incense Cedar, California Black Oak
Montane Hardwood	Montane Hardwood	Canyon Live Oak, California Black Oak, Oregon White Oak
Ponderosa Pine	Ponderosa Pine	Ponderosa Pine, Jeffrey Pine, Douglas Fir
Redwood	Redwood	Redwood, Grand Fir, Sitka Spruce
Red Fir	Red Fir	Red Fir, White Fir, Lodgepole Pine
Subalpine Conifer	Subalpine Conifer	Engelmann Spruce, Subalpine Fir, Mountain Hemlock
Sierran Mixed Conifer – White Fir	Sierran Mixed Conifer White Fir	Douglas Fir, Ponderosa Pine, White Fir, Sugar Pine
NotifS	Closed-Cone Pine-Cypress; Desert Riparian; Eucalyptus; Joshua Tree; Montane Riparian; Palm Oasis; Valley Oak Woodland; Valley Foothill Riparian	

* Forest types that were deemed inconsequential as potential sources of woody biomass material were designated as "NotifS". For example, Desert Riparian and Eucalyptus were re-classed and designated NotifS.
**These are the primary species of the vegetation type as referenced in CWHR documentation. See footnote 1.

Source: West Biofuels, LLC

Table 2 shows non-forest classification. The team classified shrub-dominated and herbaceous dominated vegetation classes, aquatic habitats, and agricultural lands as non-forest.

Table 2: CWHR Vegetation Types Re-classed as Non-Forest

Forest Land Cover Class	Original CWHR Vegetation Type
Non-Forest	Alpine Dwarf-Shrub
	Alkali Desert Scrub
	Bitterbrush
	Chamise-Redshank Chaparral
	Coastal Scrub
	Desert Scrub
	Desert Succulent Shrub
	Desert Wash
	Low Sage
	Mixed Chaparral
	Montane Chaparral
	Sagebrush
	Annual Grass
	Fresh Emergent Wetland
	Pasture
	Perennial Grass
	Saline Wetland
	Wet Meadow
	Estuarine
	Lacustrine
	Marine
	Riverine
	Cropland
	Dryland Grain Crops
	Deciduous Orchard
	Evergreen Orchard
	Irrigated Grain Crops
	Irrigated Row and Field Crops
	Irrigated Hayfield
	Orchard - Vineyard
	Rice
	Urban
	Vineyard

Source: West Biofuels, LLC

Table 3: Forest Land Cover Classes with Forest Stand Description

Forest Land Cover Class	Forest Stand Description[7]
Aspen	Mature stands of quaking aspen usually have relatively open canopies, often shared with other deciduous trees and a few conifer species, typically pines. Aspen stands in California occur primarily at higher elevations (6,500 to 9,850 feet) near seeps, streams, and meadows on the eastern slopes of the Sierra Nevada and Cascade Ranges. Zonally, they are found within the Red Fir, Mixed-Conifer, and Lodgepole Pine habitats.
Blue Oak Woodland-Foothill Pine	Generally these woodlands have an overstory of scattered trees, although the canopy can be nearly closed on better quality sites. The canopy is dominated by broad-leaved trees 16 to 50 feet tall, commonly forming open savanna-like stands on dry ridges and gentle slopes. Blue oak is the dominant species, comprising 85 to 100 percent of the trees present. It is generally found at elevations from 500 to 2,000 feet at the northern end of its range and on the western slopes of the Sierra Nevada, from 250 to 3,000 feet in the Central Coast Range, and from 550 to 4,500 feet in the Transverse and Peninsular Ranges.
Coastal Oak Woodland	Coastal Oak Woodlands are extremely variable. The overstory consists of deciduous and evergreen hardwoods (mostly oaks) sometimes mixed with scattered conifers. In the North Coast Range and south to Sonoma County, coast live oak often does not dominate. From Sonoma County south, the Coastal Oak Woodlands are usually dominated by coast live oak. In many coastal regions, coast live oak is the only overstory species. Most Coastal Oak Woodlands are comprised of medium to large trees with few seedlings and saplings, especially in heavily grazed areas. Coastal Oak Woodlands occur in the coastal foothills and valleys from Trinity to Humboldt counties and south through the coastal regions of the Northern and Southern Coast Ranges, the Transverse and Peninsular range of Southern California. They occur at elevations from just above sea level near the immediate coast to about 5,000 feet in the interior regions, especially in Southern California.
Douglas Fir	This forest type forms a complex mosaic of forest expression due to the geologic, topographic, and successional variation typical within its range. Typical aggregations include a lower overstory of dense, sclerophyllous, broad-leaved evergreen trees (tanoak, Pacific madrone) up to 114 feet tall, with an irregular, often open, higher overstory of tall needle-leaved evergreen trees (Douglas fir) up to 295 feet. Douglas Fir occurs in the North Coast Range from Sonoma County north to the Oregon border and in the Klamath Mountains of California and Oregon. This forest type usually occurs at elevations from 500 to 2,000 feet in the Coast Range and from 1,000 to 4,000 feet in the Klamath Mountains. It can occur at higher elevations if plentiful precipitation is present.
Eastside Pine	Ponderosa pine is the dominant tree with less representation by Jeffrey pine, Lodgepole pine, white fir, incense cedar, Douglas Fir, California black oak, and western juniper. Eastside Pine forests are found on coarse, well-drained basaltic soils, in a drier, colder setting than the Ponderosa Pine forest. Eastside Pine occurs from about 4,000 to 6,500 feet elevation.
Jeffrey Pine	The structure of the Jeffrey Pine forest varies over its distribution. A single tree layer is characteristic of Jeffrey Pine stands on moderately dry sites, giving an impression of openness, limited leaf area, light, and heat. On moist and mesic sites a second tree layer exists which is composed of deciduous hardwood species, whereas on dry sites evergreen hardwood species form the second tree layer. Jeffrey Pine occurs in a variety of physical settings throughout its extensive range. Jeffrey Pine ranges from 500 to 9,500 feet.

[7] Referenced from the Guide to Wildlife Habitats of California. 1988.

Forest Land Cover Class	Forest Stand Description[7]
Juniper – Pinyon Juniper	The Juniper-Pinyon Juniper forest type can be characterized as open woodlands with dense aggregations of junipers, and stands of pinyon pine mixed with juniper (primarily found east of the Sierra Nevada). Juniper-Pinyon Juniper can be adjoining a number of other forest types, including Eastside Pine, Jeffery Pine, Sierra Mixed Conifer-White Fir, Ponderosa Pine, and Montane Hardwood Conifer. Elevation range of this forest type is significant with juniper dominated ranging from 300 to 10,000 feet. Elevations for pinyon-juniper dominated areas vary with latitude. In the Sierra Nevada region, it ranges from 6,000 to 9,000 feet and in the southern portions of the state such as the San Jacinto and Santa Rosa Mountains, 3,500 to 5,500 feet.
Klamath Mixed Conifer	Klamath Mixed Conifer forest type is typically composed of tall, dense to moderately open, needle-leaved evergreen forests with patches of broad-leaved evergreen and deciduous low trees and shrubs. The overstory layer is characterized by a mixture of conifers. This forest type is normally found between 4,500 and 6,900 feet and is restricted to the Klamath Region of Northern California and Southwestern Oregon.
Lodgepole Pine	Lodgepole Pine typically forms open stands of similarly sized specimens in association with few other species and with a sparse understory. Lodgepole pine overwhelmingly dominates this forest type. Typically the Lodgepole Pine zone is found above Red Fir and below the Subalpine Conifer habitat. Well-developed Lodgepole Pine forests are found above 5,900 feet elevation in the Northern Sierra and above 7,900 feet in the south.
Montane Hardwood-Conifer	Montane Hardwood-Conifer forest includes both conifers and hardwoods often as a closed forest. To be considered this forest type, at least one-third of each of the trees must be conifer or broad-leaved. This diverse forest type consists of a broad spectrum of mixed, vigorously growing conifer and hardwood species. Typically, conifers to 200 feet in height form the upper canopy and broad-leaved trees 30 to 100 feet in height comprise the lower canopy. Montane Hardwood-Conifer occurs throughout California. Elevations range from 1,000 to 4,000 feet in the north to 2,000 to 5,800 feet in the south.
Montane Hardwood	A typical Montane Hardwood forest is composed of a pronounced hardwood tree layer, with an infrequent and poorly developed shrub stratum, and a sparse herbaceous layer. Montane Hardwood ranges throughout California mostly west of the Cascade-Sierra Nevada crest. East of the crest, it is found in localized areas of Placer, El Dorado, Alpine, and San Bernardino Counties. Elevations range from 300 feet near the Pacific Ocean to 9,000 feet in Southern California.
NotifS	Forests not of interest for feedstock.
Ponderosa Pine	The Ponderosa Pine forest type includes pure stands of ponderosa pine as well as stands of mixed species in which at least 50 percent of the canopy area is ponderosa pine. Tree spacing in ponderosa pine stands varies from open patchy to extremely close. Ponderosa Pine habitat is found on suitable mountain and foothill sites throughout California except in the immediate area of San Francisco Bay, in the North Coast area, south of Kern County in the Sierra Nevada and east of the Sierra Nevada Crest. Elevational ranges include 800 to 5,000 feet in the Northern Sierra Nevada and Cascades, 4,000 to 6,900 feet in the central and southern Sierra Nevada and 4,300 to 7,000 feet) in the Transverse and Peninsular Ranges, although it may be found as low as 3,500 feet in moist South Coast sites.
Redwood	The Redwood Forest is a composite name for a variety or mix of conifer species that grow within the coastal influence zone within 30 to 35 miles from the coast. Redwood becomes dominant along coastal areas approximately 2 to 10 miles from the ocean. Redwood is a self-perpetuating forest type, with or without fire as a disturbance. After disturbance (usually logging, fire, or flooding), succession proceeds rapidly. Elevations where the forest type can be found range from sea level to over 3,000 feet.

Forest Land Cover Class	Forest Stand Description[7]
Red Fir	Red Fir stand structure is typified by even-aged groups of trees (established within 20-year spans) that cover several to thousands of square yards. The cause of this pattern is probably a history of recurrent lightning fires, wind throws, and insect outbreaks acting to kill groups of trees. Mature Red Fir stands normally are monotypic, with very few other plant species in any layer. Red Fir occurs on frigid soils of the higher mountains of Northern California. At lower elevations Red Fir intergrade with white fir-dominated mixed conifer stands on drier sites and with Lodgepole pine-mountain meadow stands on moist sites. Red Fir is distributed in an elevational band from about 6,000 to 9,000 feet.
Subalpine Conifer	Typically, Subalpine Conifer forests are open with needle-leaved evergreen trees of low to medium stature and typically occupy extremely harsh environments. Subalpine Conifer intergrades with Lodgepole Pine, Jeffrey Pine, and Red Fir forests at lower elevations. Subalpine Conifer is generally distributed at high elevations in all significant mountain ranges of California. It is well represented in the north, with a range from about 7,000 to 9,500 feet and in the Sierra Nevada, ranging from 9,000 to 11,000 feet. Although sparsely represented in Southern California it can occur, typically within a range of 9,500 to 11,200 feet.
Sierran Mixed Conifer – White Fir	The Sierran Mixed Conifer – White Fir habitat is an assemblage of conifer and hardwood species that forms a multilayered forest. Historically, burning and logging have caused wide variability in stand structure, resulting in both even-aged and uneven-aged stands. Forested stands form closed, multilayered canopies with nearly 100 percent overlapping cover. The forest type adjoins Ponderosa Pine at lower elevations and drier slopes, and White Fir and Red Fir at higher elevations. The Sierran Mixed Conifer forest type generally forms a vegetation band ranging 2,500 to 4,000 feet in the north to 4,000 to 10,000 feet in the Southern Sierra Nevada. The White Fir forest type is characterized by nearly monotypic even-aged overstory. Mature white fir stands, normally monotypic, with more than 80 percent occurring as white fir, are found throughout California, from the Klamath Mountains along the North Coast to the South Coast mountain ranges, and in interior ranges. In the Klamath Mountains, the Cascades, and the Sierra Nevada, White Fir occurs between Mixed Conifer and Red Fir. In the Transverse and Peninsular Ranges and in the mountain ranges of interior Southern California, White Fir intergrades at lower elevations with Mixed Conifer and is replaced at higher elevations by Lodgepole Pine. Elevation of White Fir habitat varies with latitude. In the Klamath Mountains of Trinity and Siskiyou Counties, White Fir occurs 4,500 to 5,500 feet; from 5,000 to 6,000 feet in the Cascade and Warner Mountains; at about 5,500 feet in the Southern Sierra Nevada; above 6,000 feet throughout the Transverse and Peninsular Ranges; and between 6,000 and 7,000 feet in the southern interior ranges.

Source: West Biofuels, LLC

Forest Land Ownership and Jurisdiction

California forests occur in a mosaic on public lands, private lands, and tribal lands. Forested public lands can be under the jurisdiction of the state or federal government, each of which has multiple management agencies. The researchers combined three separate land ownership/jurisdiction spatial databases for this project to develop a statewide land ownership map.

The CAL FIRE FRAP land ownership and jurisdiction spatial database, California Multi-Source Land Ownership, 2013 version 2_2 was the primary source for the statewide description of land

ownership of federal and state lands.[8] The USGS National Atlas of the United States, 2014 version 1, served as the source for federal wilderness lands and Native American lands.[9]

Private timberland information is difficult to obtain. Typically, projects will map all forestlands and then assume any forested land not under federal or state jurisdiction is by default in private ownership. However, non-industrial timberlands and smaller family-owner forests provide little forest residue for biomass power. A newly developed CAL FIRE FRAP spatial database of industrial forests that identifies contiguous and non-contiguous forest acreage in which the owner possesses greater than 5,000 acres. For this study, the researchers incorporated these industrial forest lands into the final land ownership classification as displayed in Table 4.

Table 4: Land Ownership Classes

Land Ownership Class Name	Ownership Included and Original Ownership Name/s	Original Data Source
Bureau of Land Management	U.S. Bureau of Land Management	CAL FIRE FRAP Ownership 2013
California State Lands	CA Department of Parks and Recreation, CA Department of Fish and Game, other State lands	CAL FIRE FRAP Ownership 2013
Conservancy and Trusts	Non-Profit Conservancy and Trust	CAL FIRE FRAP Ownership 2013
Department of Defense	U.S. Department of Defense	CAL FIRE FRAP Ownership 2013
Local Government	Local Government	CAL FIRE FRAP Ownership 2013
National Park Service	U.S. National Park Service	CAL FIRE FRAP Ownership 2013
Native American Lands	Tribal Lands	USGS National Atlas 2014
Other Federal Lands	U.S. Bureau of Reclamation, U.S. Fish and Wildlife Service, other Federal lands	CAL FIRE FRAP Ownership 2013
USDA Forest Service	U.S. Forest Service	CAL FIRE FRAP Ownership 2013
Industrial Forest	Private forest land > 5000 acres owned	CAL FIRE FRAP
Bureau of Land Management (BLM) Wilderness	Each Wilderness Area is listed by name	USGS National Atlas 2014
USFS Wilderness	Each Wilderness Area is listed by name	USGS National Atlas 2014
NPS Wilderness	Each Wilderness Area is listed by name	USGS National Atlas 2014

Source: West Biofuels, LLC

[8] http://frap.fire.ca.gov/data/frapgisdata-sw-ownership13_2_download.php.

[9] http://www.usgs.gov/newsroom/article.asp?ID=3814#.Vgnbhk2FOQE.

Regional Approach to Statewide Analysis

The USFS performed an extensive review of land cover and delineation of naturally occurring vegetation zones across the state. The result is the CALVEG zone map used in this analysis.

The nine zones used for regional analyses are shown in Figure 1: North Coast West, North Coast Mid, North Coast East, North Interior, North Sierran, South Sierran, Great Basin, Central Coast and South Coast. Two CALVEG zones have minimal forested lands and were not included in the report: Central Valley and South Interior.

Figure 1: CALVEG Zones

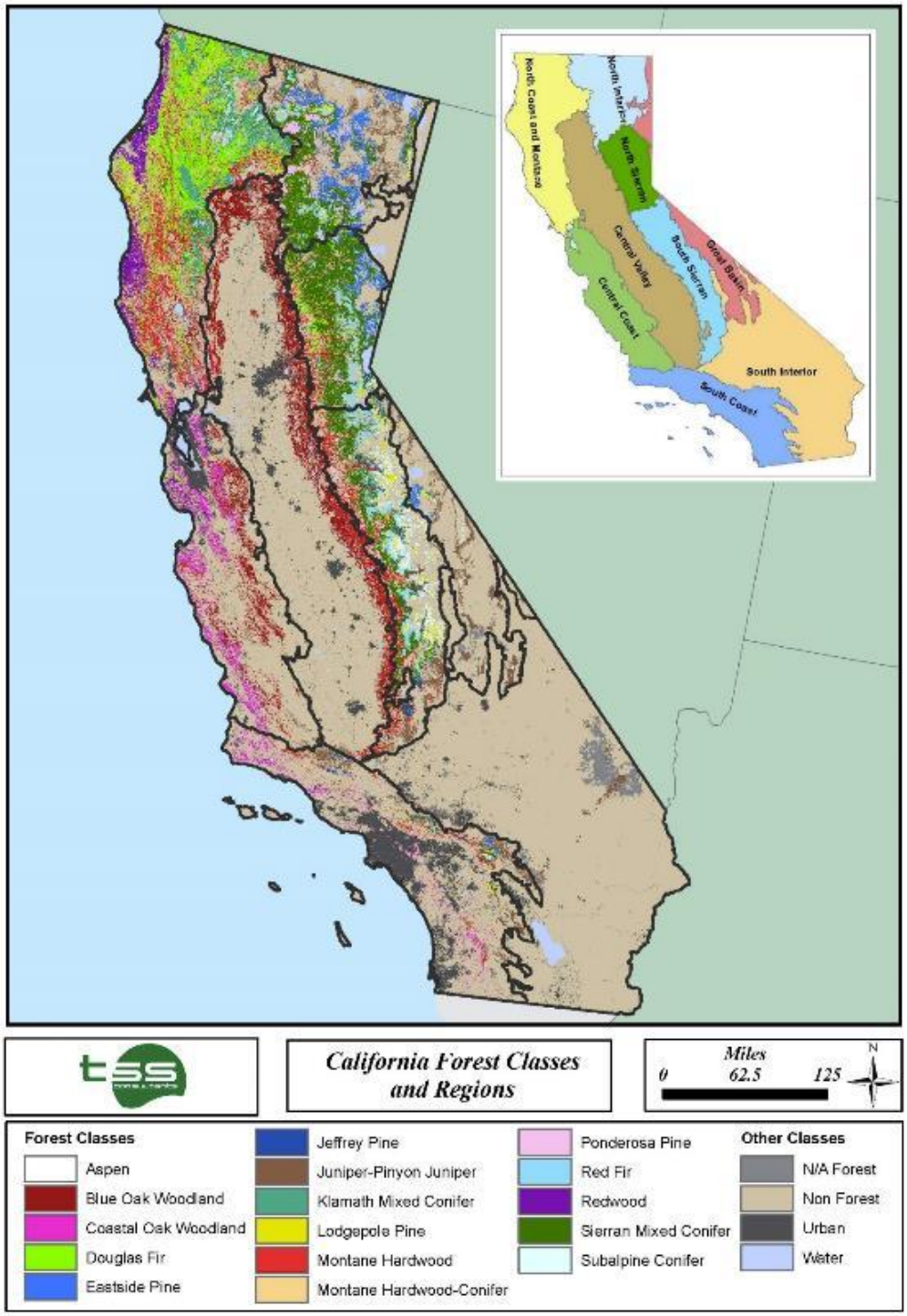
Source: West Biofuels, LLC

In this report, the terms “zones” and “regions” are considered synonymous and used interchangeably; for example, the South Sierran Zone is equivalent to the South Sierran Region.

The nine regions are the underlying structure of this report. Forest land cover classes and land ownership was mapped for each region using GIS, ESRI ArcMap 10. In addition, FMP analysis

was conducted for each region. Statewide forest land cover classes and statewide land ownership and jurisdiction are mapped in Figure 2 and Figure 3.

Figure 2: California Statewide Forest Land Cover Classes and Regions



Source: West Biofuels, LLC

Figure 3: California Statewide Land Ownership and Regions

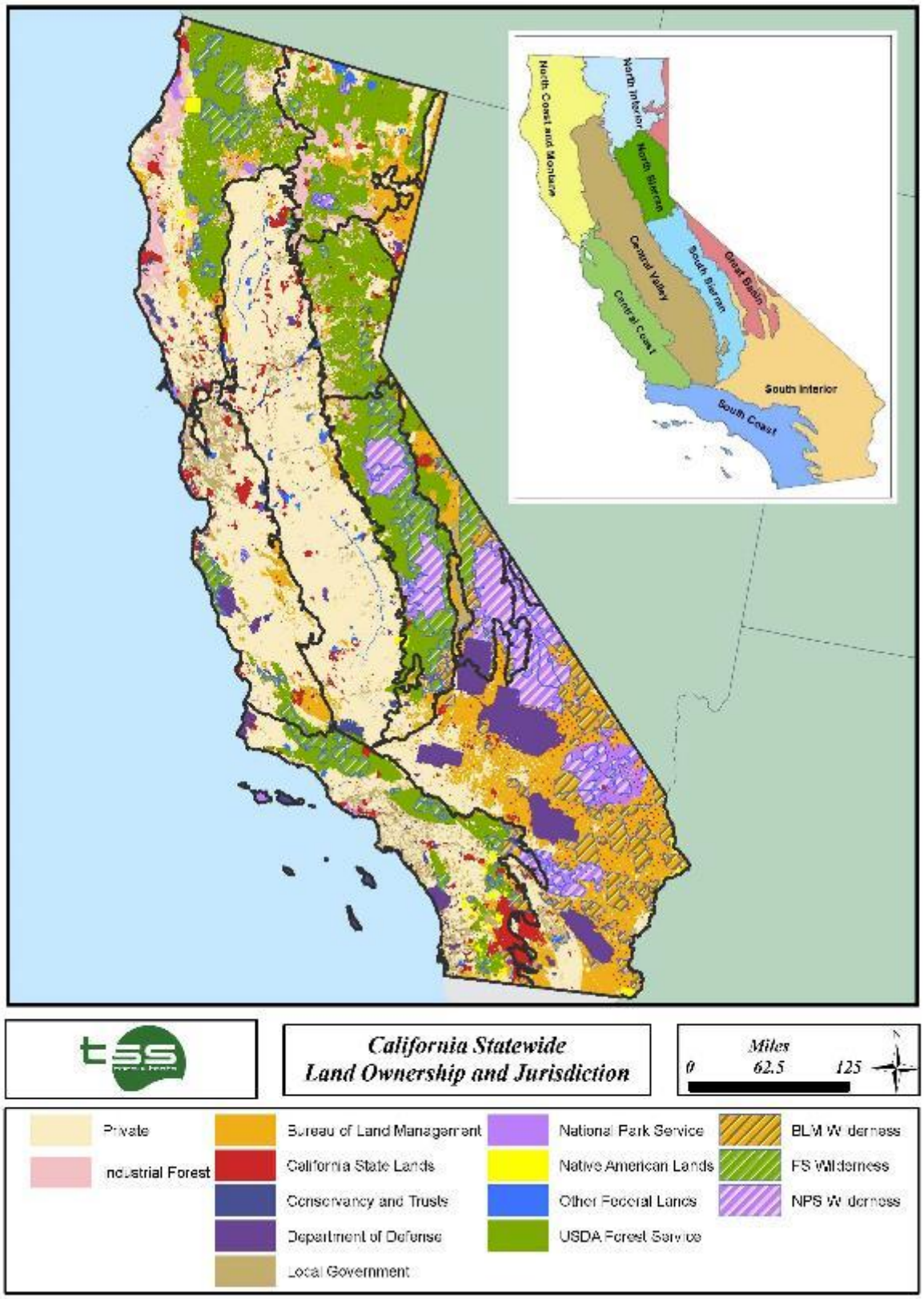


Figure 4: California Statewide High Hazard Zone Maps

Source: West Biofuels, LLC

Maps and Analyses of the Nine Regions

Statewide forest land cover classes and statewide land ownership and jurisdiction are mapped in Figure 2 and Figure 3. This data is also mapped for each of the 9 regions (Figure 5 through Figure 22). Each region has maps showing:

- Forest Land Cover Classes
- Land Ownership and Jurisdiction

In addition to the maps, each region has accompanying tables with the aerial extent of forest and land ownership classes, Table 5 through Source: West Biofuels, LLC

Table 40. The researchers calculated gross acreages using GIS data. This report does not assess technical availability for the use of any given acreage for biomass collection. Local feedstock supply studies should be conducted for any project considering siting a biomass facility. Each region has tables showing acreage of:

- Forest Land Cover Classes
- Land Ownership Classes

- Designated Wilderness Areas
- Dominant Forest Classes by Land Ownership

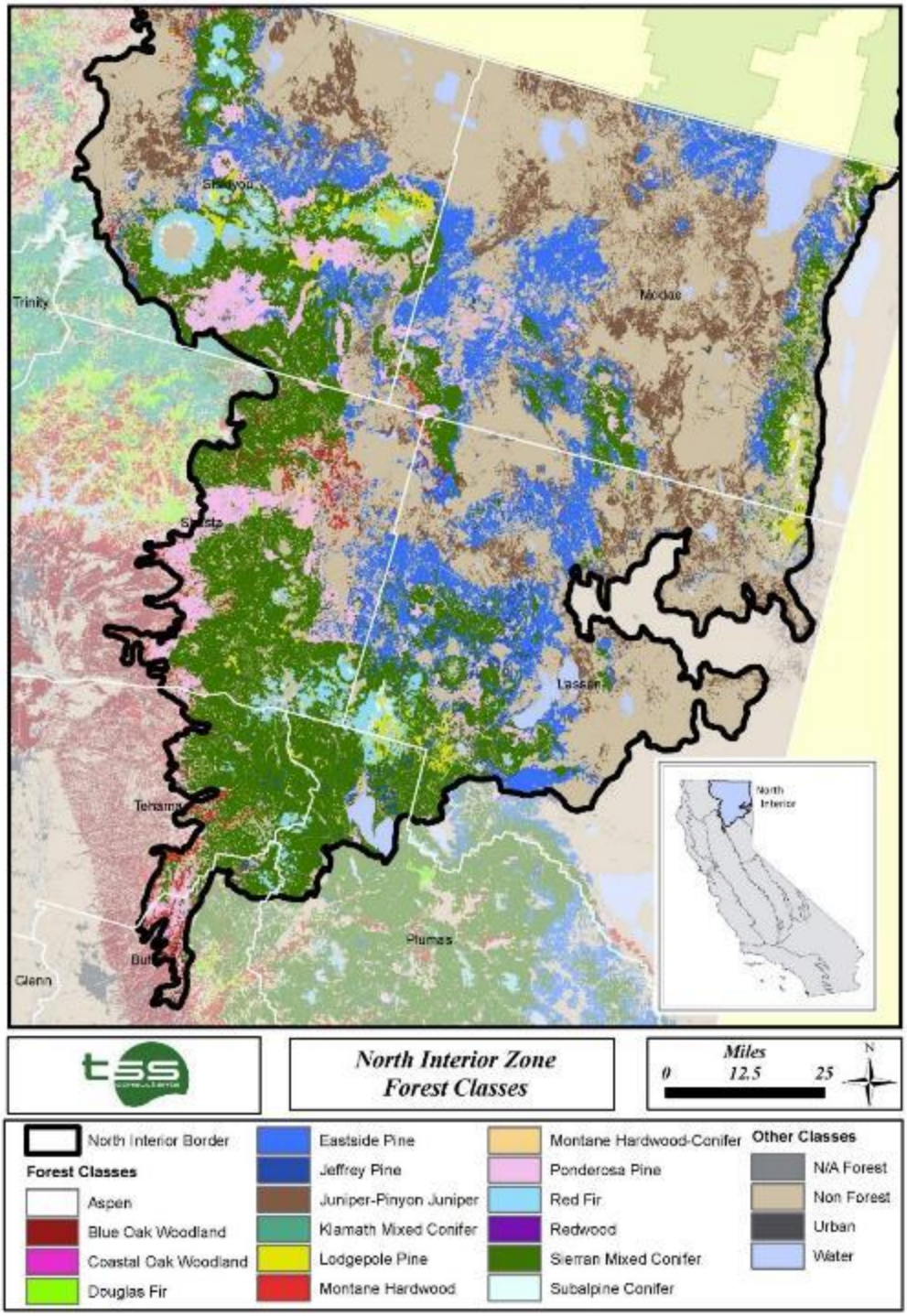
Given the large amount of data, the top five forest classes by region and top three land ownerships statewide are analyzed. This is indicated graphically by grey shading in the forest cover class and land ownerships tables. The study then used the five largest forest cover classes in the Dominant Forest Classes by Land Ownership table. The regional analysis provides a comprehensive statewide picture of forest resources, their distribution and jurisdiction. The forest type regions are presented in the following order (generally north to south):

- North Interior
- North Sierran
- South Sierran
- Great Basin
- North Coast East
- North Coast Mid
- North Coast West
- Central Coast
- South Coast

Northern Interior

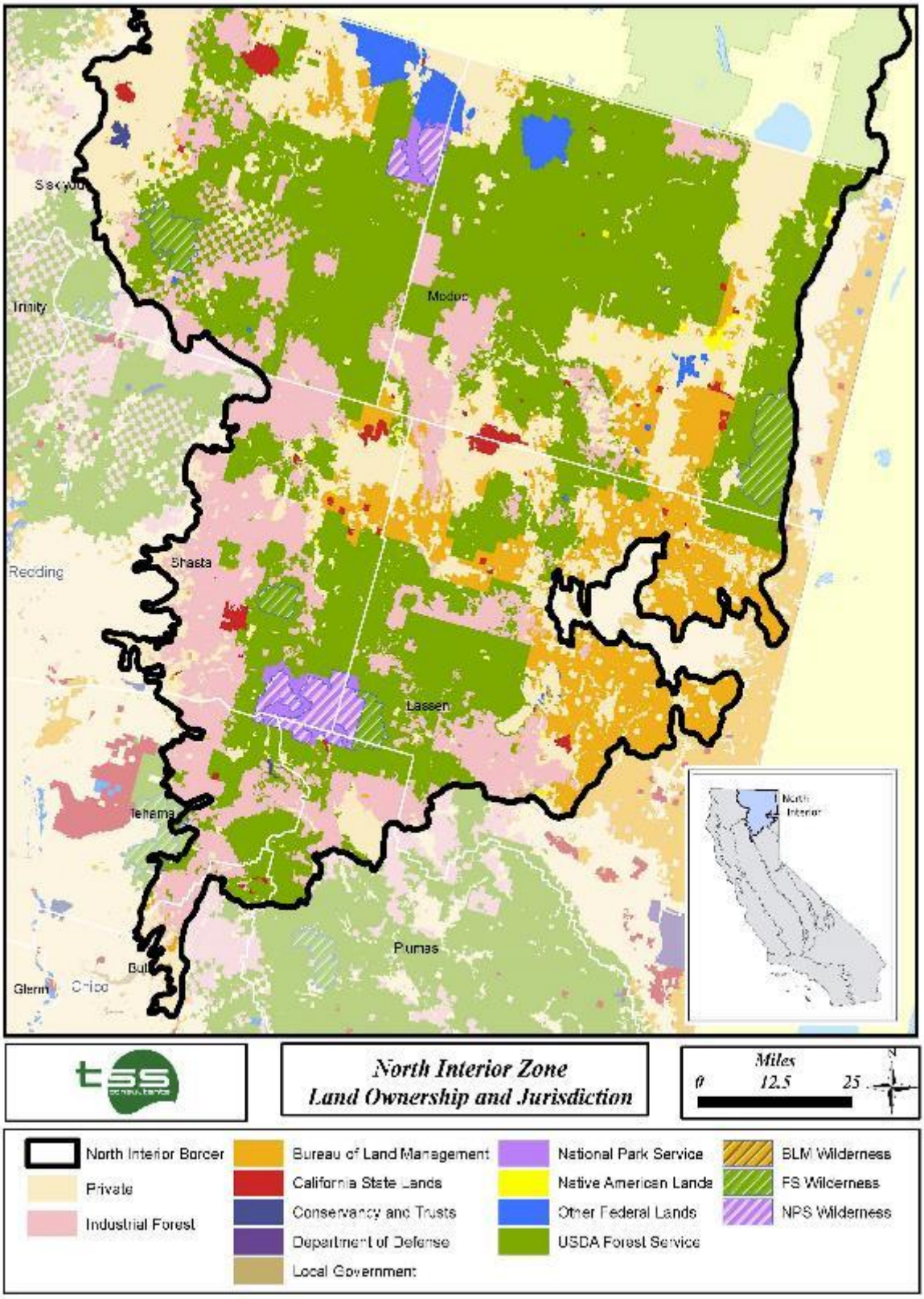
The Northern Interior region consists of the Cascade Mountain range and primarily includes Shasta, Modoc, Lassen, and Siskiyou Counties. Figure 5 and Figure 6 identify the forest class and landownership patterns in the region.

Figure 5: North Interior Forest Classes



Source: West Biofuels, LLC

Figure 6: North Interior Land Ownership and Jurisdiction



Source: West Biofuels, LLC

Table 5 through Table 8 summarize the data presented in the maps.

Table 5: North Interior Forest Land Cover

Forest Classes	Acres	Percent
Aspen	8,879	0.11%
Blue Oak Woodland-Foothill Pine	24,159	0.31%
Douglas Fir	830	0.01%
Eastside Pine	847,069	10.94%
Jeffrey Pine	61,856	0.80%
Pinyon Juniper	697,262	9.01%
Klamath Mixed Conifer	308	0.00%
Lodgepole Pine	82,683	1.07%
Montane Hardwood	88,212	1.14%
Montane Hardwood-Conifer	53,557	0.69%
Ponderosa Pine	462,161	5.97%
Red Fir	179,369	2.32%
Sierran Mixed Conifer-White Fir	1,647,054	21.28%
Subalpine Conifer	25,801	0.33%
N/A Forest	21,265	0.27%
Non Forest	3,324,046	42.95%
Urban	14,095	0.18%
Water	201,633	2.60%
Total	**7,740,239**	**100.00%**

Source: West Biofuels, LLC

Table 6: North Interior Land Ownership

Land Ownership	Acres	Percent Public Land
Bureau of Land Management	809,557	17.75%
California State Lands	75,264	1.65%
Conservancy and Trusts	7,076	0.16%
Local Government	2,970	0.07%
National Park Service	154,127	3.38%
Native American Lands	17,397	0.38%
Other Federal Lands	129,173	2.83%
USDA Forest Service	3,366,555	73.79%
Public Lands Total	4,562,119	100.00%
Private Industrial Forest Total	1,348,889	
Region Total	7,740,239	

Source: West Biofuels, LLC

Table 7: North Interior Wilderness Area

Land Ownership	Wilderness Areas	Acres
USDA Forest Service		**151,317**
	Lassen National Forest	43,592
	Modoc National Forest	69,664
	Shasta National Forest	38,060
National Park Service		**106,260**
	Lassen Volcanic National Park	78,157
	Lava Beds National Monument	28,103
Wilderness Total		**257,577**

Source: West Biofuels, LLC

Table 8: North Interior Dominant Forest Classes by Land Ownership

Forest Class	USFS		BLM		Industry		Total
	Acres	%	Acres	%	Acres	%	Acres
Sierran Mixed Conifer-White Fir	773,530	52%	11,689	1%	708,393	47%	1,493,612
Eastside Pine	558,411	74%	33,355	4%	162,210	22%	753,976
Pinyon Juniper	276,504	60%	178,740	39%	3,172	1%	458,416
Ponderosa Pine	200,021	50%	3,669	1%	194,229	49%	397,919
Red Fir	116,647	83%	152	0%	24,407	17%	141,206

Source: West Biofuels, LLC

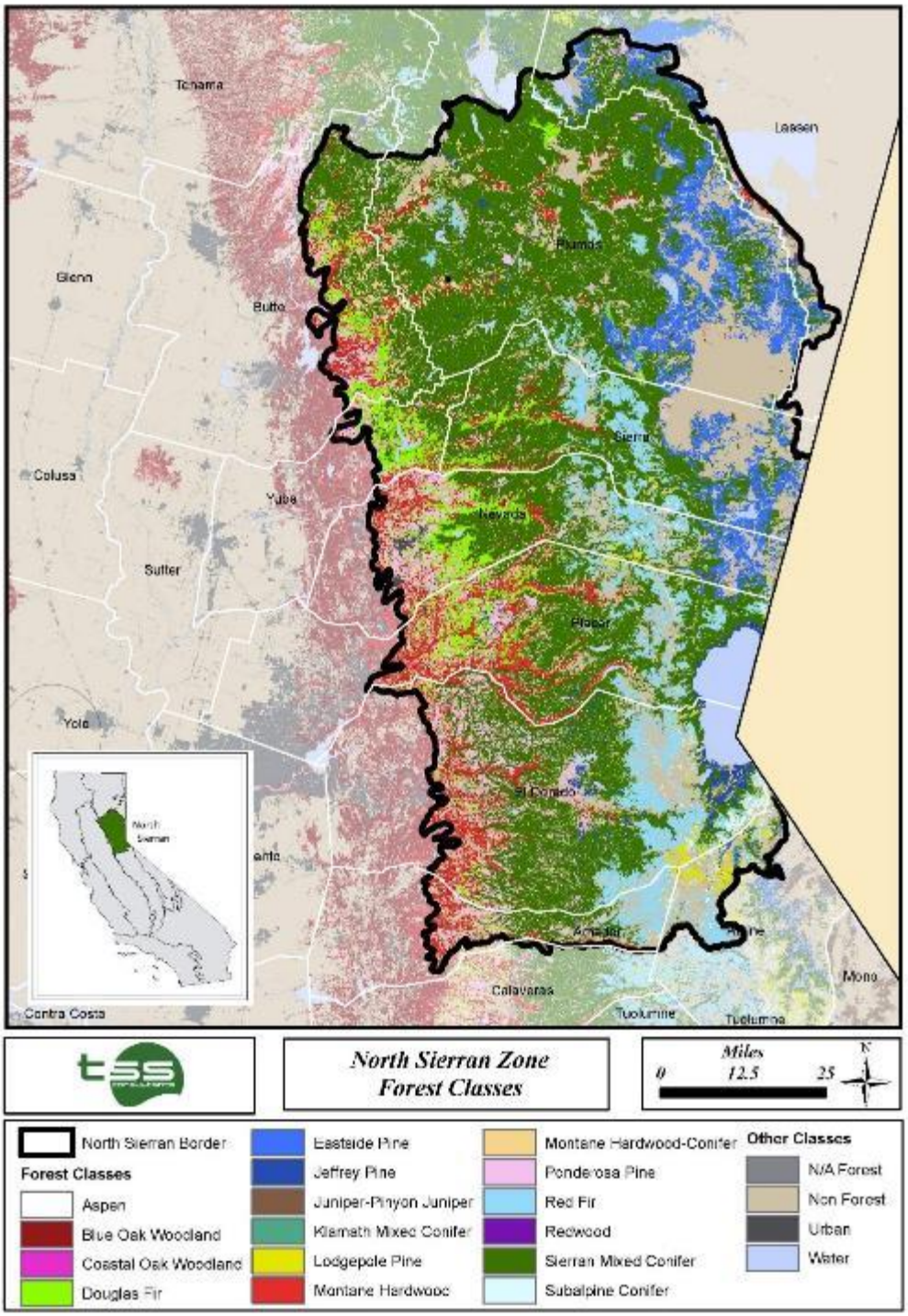
The western mountainous areas of the North Interior Region are largely Sierran Mixed Conifer interspersed with Ponderosa Pine in lower elevations. The eastern side is Eastside Pine.

Public lands dominate in this region and are almost 60 percent of the land base total. The majority of forested land is held by the USFS. Sierran Mixed Conifer-White Fir and Eastside Pine dominate the USFS holdings. BLM forested land is almost exclusively in Pinyon Juniper. However, there is also a significant amount of private industrial forest in this region; over 1.3 million acres. Privately-owned forests are mostly Sierran Mixed Conifer-White Fir and Ponderosa Pine.

Northern Sierran

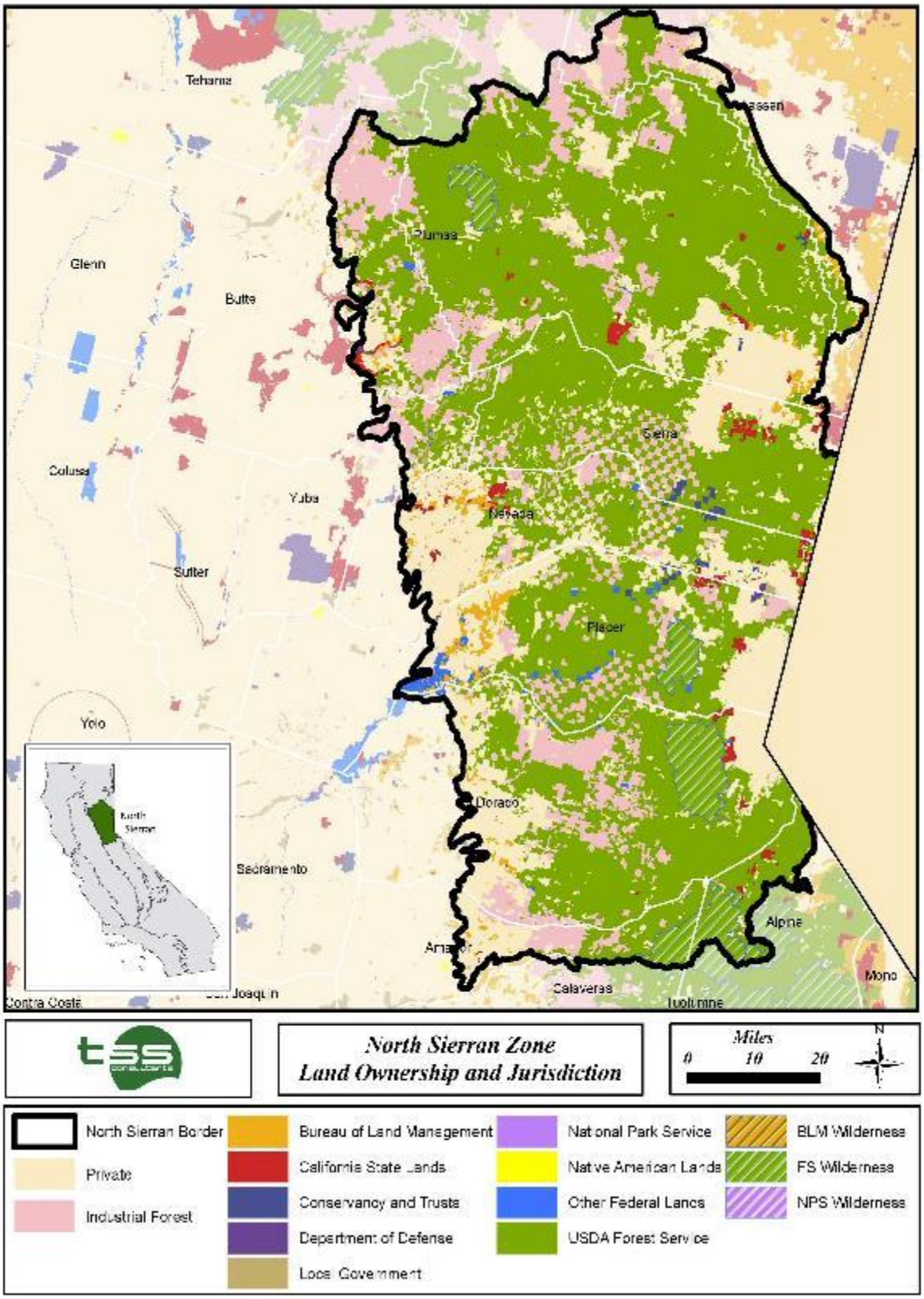
The Northern Sierran region consists of the northern section of the Sierra Nevada range and includes several counties running north and south between Plumas to Amador counties. Figure 7 and Figure 8 identify the forest class and landownership patterns in the region.

Figure 7: North Sierran Forest Classes



Source: West Biofuels, LLC

Figure 8: North Sierran Land Ownership and Jurisdiction



Source: West Biofuels, LLC

Table 9 through Table 12 summarize the data presented in the maps.

Table 9: North Sierran Forest Land Cover

Forest Classes	Acres	Percent
Aspen	3,092	0.06%
Blue Oak Woodland-Foothill Pine	14,204	0.29%
Coastal Oak Woodland	198	0.00%
Douglas Fir	169,243	3.40%
Eastside Pine	291,983	5.86%
Jeffrey Pine	53,491	1.07%
Juniper-Pinyon Juniper	1,258	0.03%
Lodgepole Pine	38,467	0.77%
Montane Hardwood	330,877	6.64%
Montane Hardwood-Conifer	224,645	4.51%
Ponderosa Pine	255,636	5.13%
Red Fir	303,073	6.08%
Sierran Mixed Conifer-White Fir	2,061,241	41.37%
Subalpine Conifer	27,241	0.55%
N/A Forest	34,220	0.69%
Non Forest	994,768	19.97%
Urban	29,460	0.59%
Water	149,415	3.00%
Total	**4,982,511**	**100.00%**

Source: West Biofuels, LLC

Table 10: North Sierran Land Ownership

Land Ownership	Acres	Percent Public Land
Bureau of Land Management	79,522	2.57%
California State Lands	55,180	1.78%
Conservancy and Trusts	15,345	0.50%
Department of Defense	2,623	0.08%
Local Government	9,271	0.30%
Native American Lands	991	0.03%
Other Federal Lands	29,363	0.95%
USDA Forest Service	2,905,038	93.79%
Public Lands Total	3,097,334	100.00%
Private Industrial Forest Total	699,032	
Region Total	4,982,511	

Source: West Biofuels, LLC

Table 11: North Sierran Wilderness Area

Land Ownership	Wilderness Areas	Acres
USDA Forest Service		**178,270**
	Eldorado National Forest	126,295
	Plumas National Forest	24,419
	Stanislaus National Forest	78
	Tahoe National Forest	26,043
	Toiyabe National Forest	1,434
Wilderness Total		**178,270**

Source: West Biofuels, LLC

Table 12: North Sierran Dominant Forest Classes by Land Ownership

	USFS		BLM		Industry		Total
Forest Class	**Acres**	**%**	**Acres**	**%**	**Acres**	**%**	**Acres**
Sierran Mixed Conifer-White Fir	1,391,499	77%	3,193	0%	422,767	23%	1,817,459
Montane Hardwood	119,212	71%	19,230	11%	29,023	17%	167,465
Red Fir	248,035	89%	13	0%	30,210	11%	278,258
Eastside Pine	205,533	91%	2,722	1%	18,172	8%	226,427
Ponderosa Pine	87,699	58%	9,224	6%	54,764	36%	151,687

Source: West Biofuels, LLC

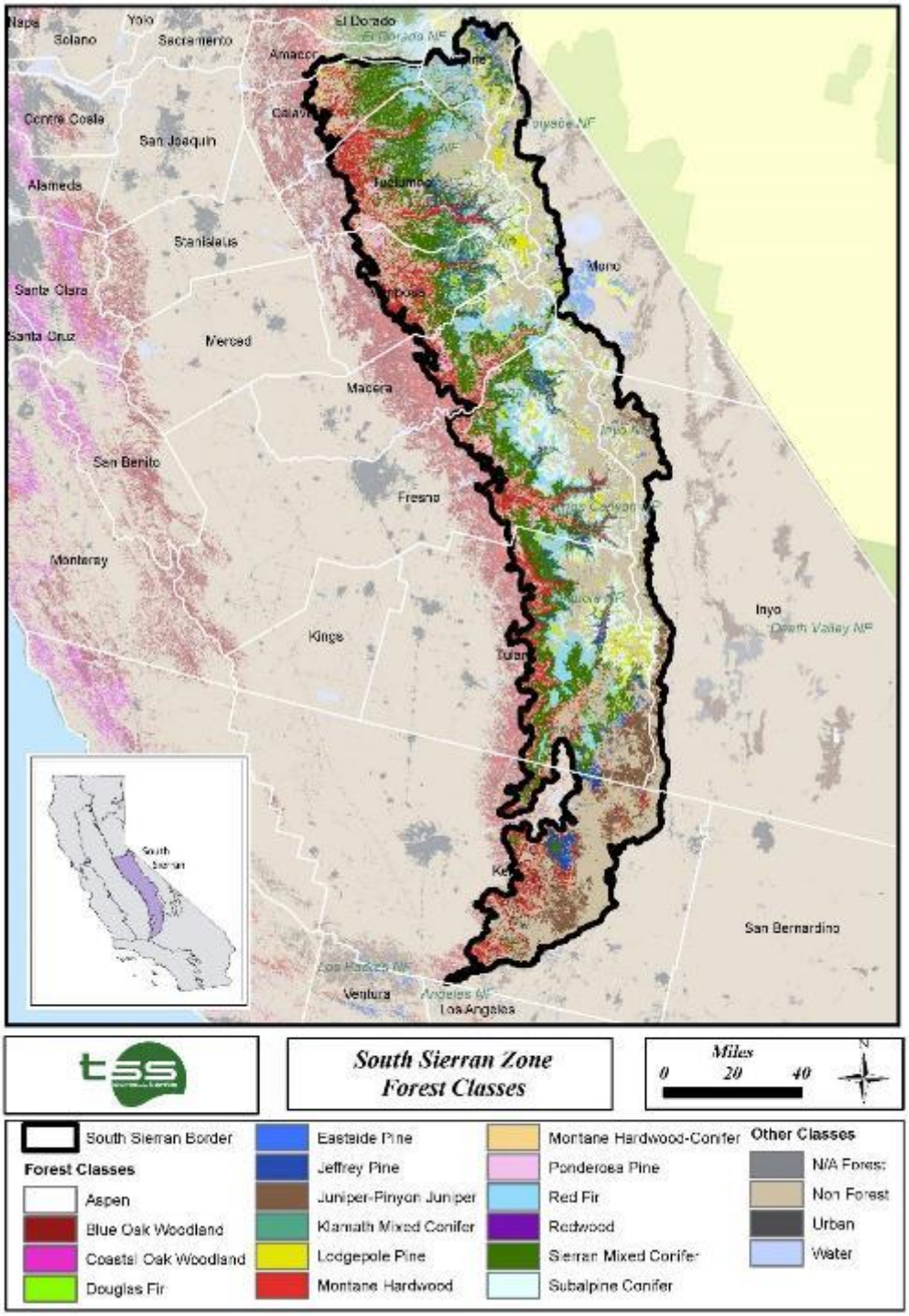
The North Sierran region is dominated by Sierran Mixed Conifer forests with Red Fir and Eastside Pine on the eastern slopes of the Sierra Nevada range. Lower elevations on the western slope have Douglas Fir or Ponderosa Pine forests.

Over 62% of the region is public land, most of which is managed by the USFS. Almost 70% of the USFS holdings are Sierra Mixed Conifer-White Fir forests. BLM lands are not a large portion of the region. Industrial forests are Sierran Mixed Conifer-White Fir forest, or tend to occur at lower elevations with Ponderosa Pine or Montane Hardwood forests.

Southern Sierran

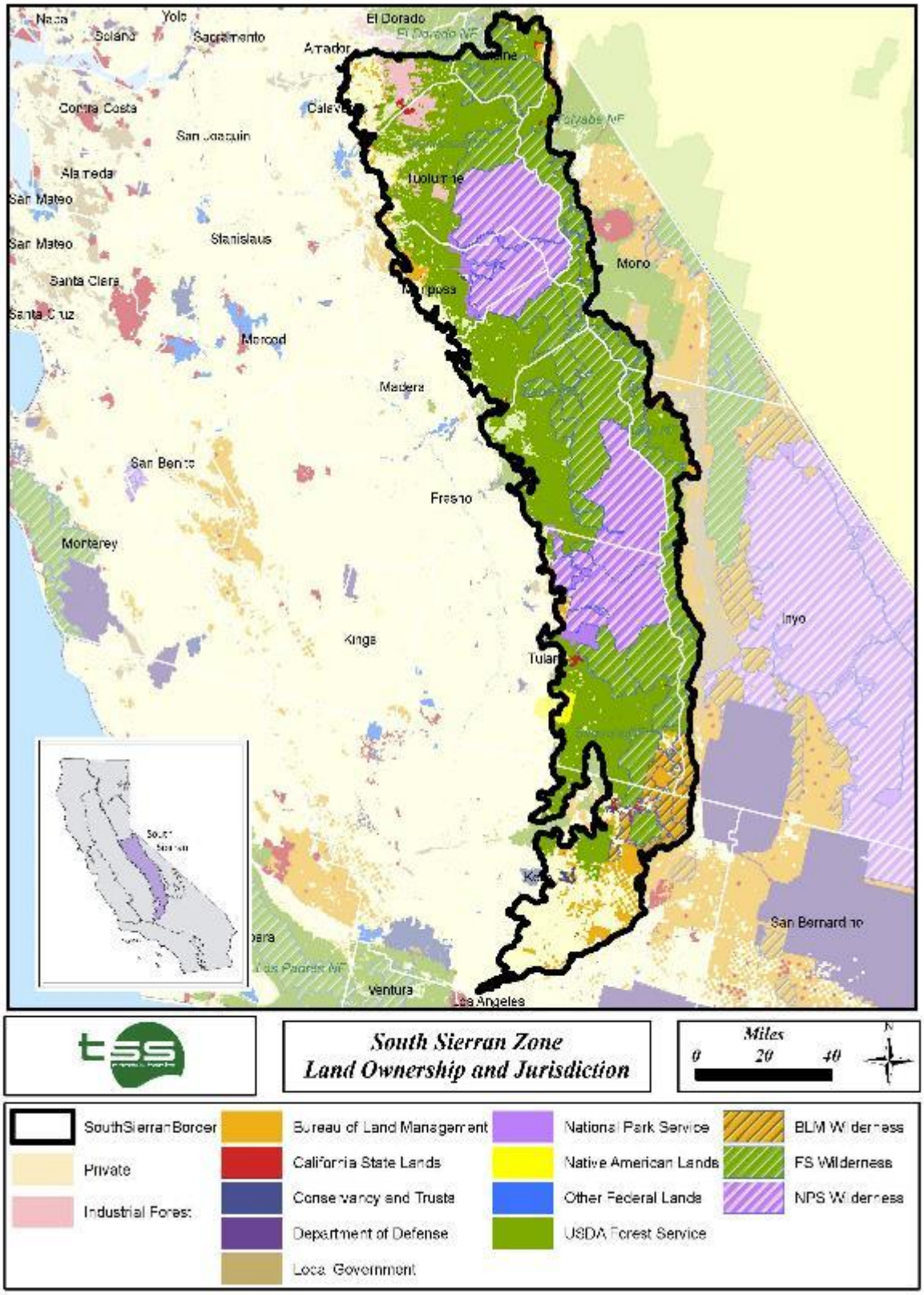
The Southern Sierran region encompasses the southern Sierra Nevada range extending from Calaveras County to Kern County. Figure 9 and Figure 10 identify the forest class and landownership patterns in the region.

Figure 9: South Sierran Forest Classes



Source: West Biofuels, LLC

Figure 10: South Sierran Land Ownership and Jurisdiction



Source: West Biofuels, LLC

Table 13 through Table 16 summarize the data presented in the maps.

Table 13: South Sierran Forest Land Cover

Forest Class	Acres	Percent
Aspen	28,825	0.37%
Blue Oak Woodland-Foothill Pine	105,660	1.36%
Douglas Fir	7,096	0.09%
Eastside Pine	43,598	0.56%
Jeffrey Pine	207,032	2.66%
Juniper-Pinyon Juniper	348,340	4.48%
Lodgepole Pine	270,539	3.48%
Montane Hardwood	651,272	8.38%
Montane Hardwood-Conifer	244,604	3.15%
Ponderosa Pine	246,133	3.17%
Red Fir	504,015	6.49%
Sierran Mixed Conifer-White Fir	1,236,245	15.91%
Subalpine Conifer	658,024	8.47%
N/A Forest	77,249	0.99%
Non Forest	3,060,581	39.40%
Urban	9,907	0.13%
Water	69,773	0.90%
Total	**7,768,895**	**100.00%**

Source: West Biofuels, LLC

Table 14: South Sierran Land Ownership

Land Ownership	Acres	Percent Public Land
Bureau of Land Management	544,382	8.21%
California State Lands	32,529	0.49%
Conservancy and Trusts	11,785	0.18%
Local Government	18,394	0.28%
National Park Service	1,614,138	24.35%
Native American Lands	28,008	0.42%
Other Federal Lands	3,834	0.06%
USDA Forest Service	4,375,390	66.01%
Public Lands Total	6,628,461	100.00%
Private Industrial Forest Total	143,547	
Region Total	7,768,895	

Source: West Biofuels, LLC

Table 15: South Sierran Wilderness Area

Land Ownership	Wilderness Areas	Acres
Bureau of Land Management		**214,098**
	National Monument / Conservation Area	214,098
USDA Forest Service		**1,956,957**
	Eldorado National Forest	155
	Inyo National Forest	643,557
	Sequoia National Forest	315,881
	Sierra National Forest	582,442
	Stanislaus National Forest	217,979
	Toiyabe National Forest	196,943
National Park Service		**1,497,804**
	Kings Canyon National Park	450,521
	Sequoia National Park	354,061
	Yosemite National Park	693,223
Wilderness Total		**3,668,860**

Source: West Biofuels, LLC

Table 16: South Sierran Dominant Forest Classes by Land Ownership

	USFS		BLM		Industry		Total
Forest Class	Acres	%	Acres	%	Acres	%	Acres
Sierran Mixed Conifer-White Fir	791,655	89%	3,894	0%	92,207	10%	887,756
Subalpine Conifer	368,904	100%	25	0%	0	0%	368,929
Montane Hardwood	334,209	88%	39,116	10%	4,585	1%	377,910
Red Fir	388,590	100%	-	0%	1,335	0%	389,924
Juniper-Pinyon Juniper	120,961	53%	105,665	47%	0	0%	226,626

Source: West Biofuels, LLC

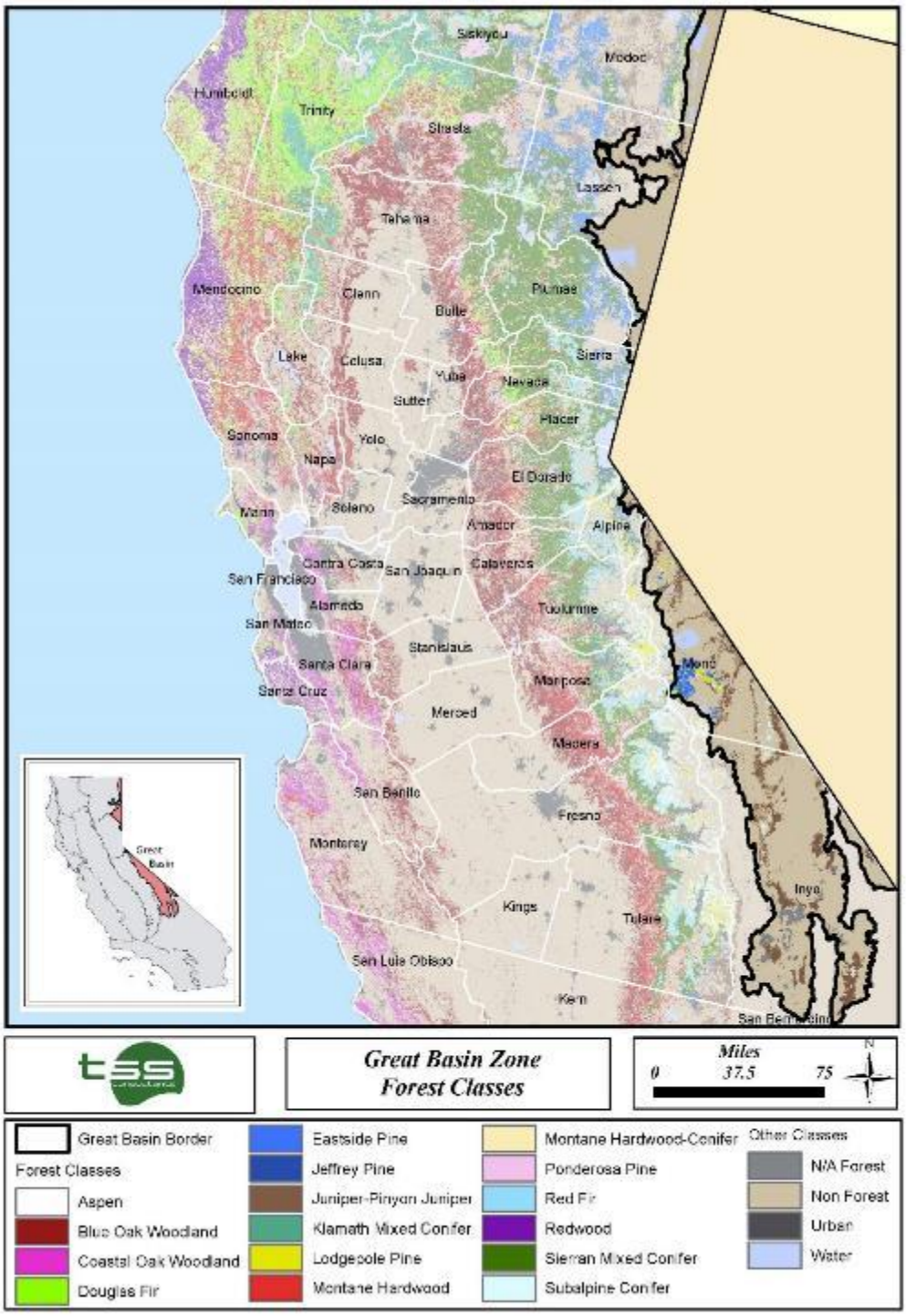
The dominant forest types in the South Sierran, like the North Sierran, are Sierran Mixed-Conifer, Red Fir, high elevation Subalpine Conifer and low elevation Montane Hardwood.

Public lands dominate the region. Most forest land is under the jurisdiction of the USFS, and there are several large wilderness areas within the region (for example, Yosemite, Kings Canyon, and Sequoia National Parks are in this zone). The eastern portion of the region is managed by the BLM, with forested acreage in Pinyon-Juniper. Private industrial lands are very limited in the South Sierran region.

Great Basin

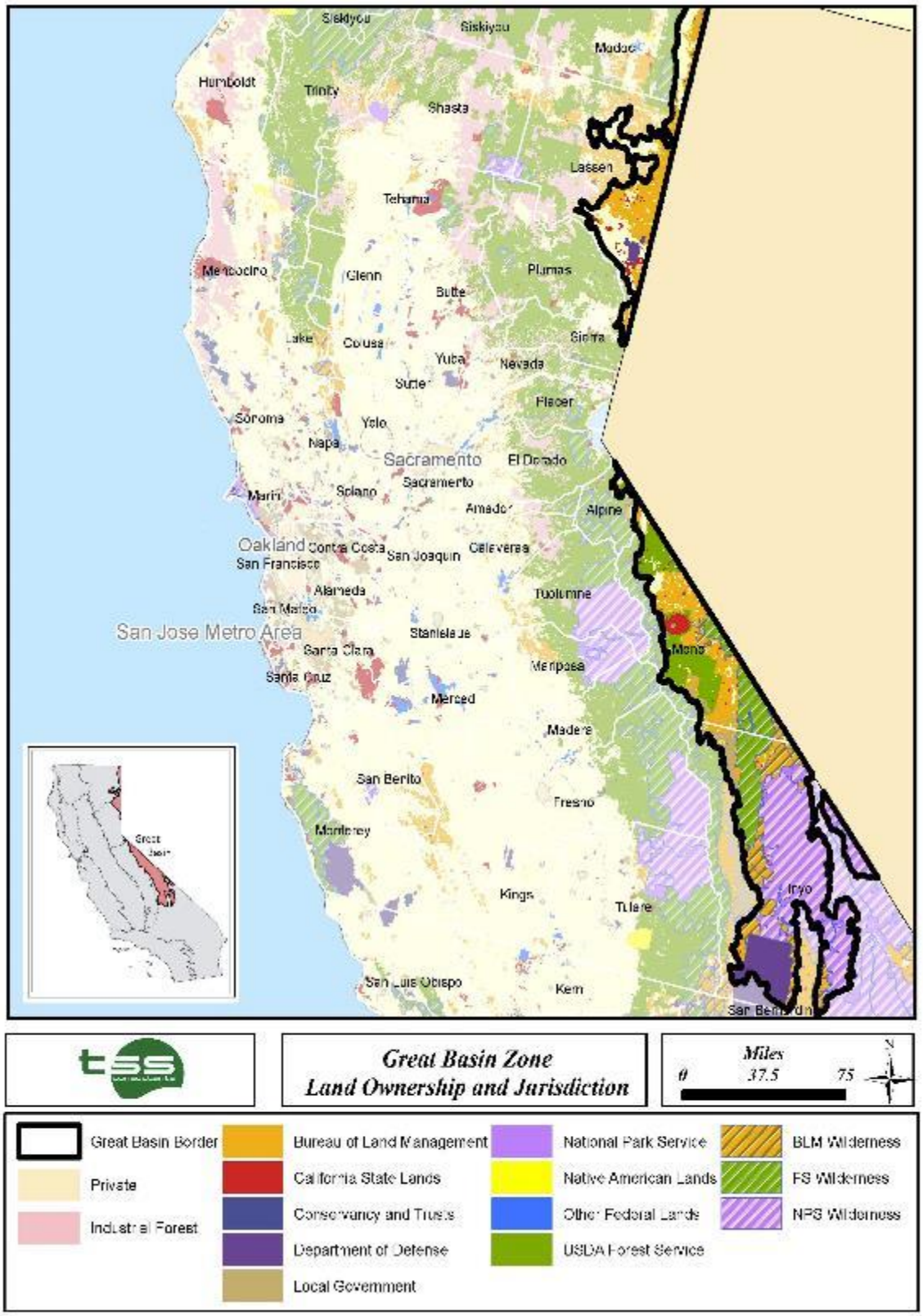
The Great Basin region covers the east side of the Sierra Nevada and Cascade range, consisting of Mono and Inyo counties along with the eastern parts of Modoc and Lassen counties. Figure 11 and Figure 12 identify the forest class and landownership patterns in the region.

Figure 11: Great Basin Forest Classes



Source: West Biofuels, LLC

Figure 12: Great Basin Land Ownership and Jurisdiction



Source: West Biofuels, LLC

Table 17 through Table 20 summarize the data presented in the maps.

Table 17: Great Basin Forest Land Cover

Forest Classes	Acres	Percent
Aspen	16,889	0.28%
Eastside Pine	79,574	1.33%
Jeffrey Pine	903	0.02%
Pinyon Juniper	574,939	9.62%
Lodgepole Pine	25,171	0.42%
Montane Hardwood	541	0.01%
Montane Hardwood-Conifer	3,128	0.05%
Red Fir	1,311	0.02%
Sierran Mixed Conifer-White Fir	9,651	0.16%
Subalpine Conifer	33,078	0.55%
N/A Forest	145,913	2.44%
Non Forest	4,895,336	81.94%
Urban	14,042	0.24%
Water	174,017	2.91%
Total	**5,974,557**	**100.00%**

Source: West Biofuels, LLC

Table 18: Great Basin Land Ownership

Land Ownership	Acres	Percent Public Land
Bureau of Land Management	1,833,258	35.38%
California State Lands	159,944	3.09%
Conservancy and Trusts	23	0.00%
Department of Defense	361,772	6.98%
Local Government	171,487	3.31%
National Park Service	1,489,174	28.74%
Native American Lands	6,154	0.12%
Other Federal Lands	14,898	0.29%
USDA Forest Service	1,144,604	22.09%
Public Lands Total	5,181,313	100.00%
Private Industrial Forest Total	4,386	
Region Total	5,974,557	

Source: West Biofuels, LLC

Table 19: Great Basin Wilderness Area

Land Ownership	Wilderness Areas	Acres
Bureau of Land Management		**451,073**
	National Monuments / Conservation Areas	451,073
USDA Forest Service		**617,760**
	Inyo National Forest	612,180
	Modoc National Forest	1,008
	Toiyabe National Forest	4,571
National Park Service		**1,539,398**
	Death Valley National Park	1,539,398
Wilderness Total		**2,608,230**

Source: West Biofuels, LLC

Table 20: Great Basin Dominant Forest Classes by Land Ownership

Forest Class	USFS		BLM		Industry		Total
	Acres	%	Acres	%	Acres	%	Acres
Juniper - Pinyon Juniper	243,986	67%	119,066	33%	8	0%	363,059
Eastside Pine	69,549	95%	3,301	5%	101	0%	72,950
Subalpine Conifer	27,604	97%	980	3%	0	0%	28,585
Lodgepole Pine	24,868	100%	96	0%	0	0%	24,965
Aspen	13,565	90%	1,529	10%	0	0%	15,095

Source: West Biofuels, LLC

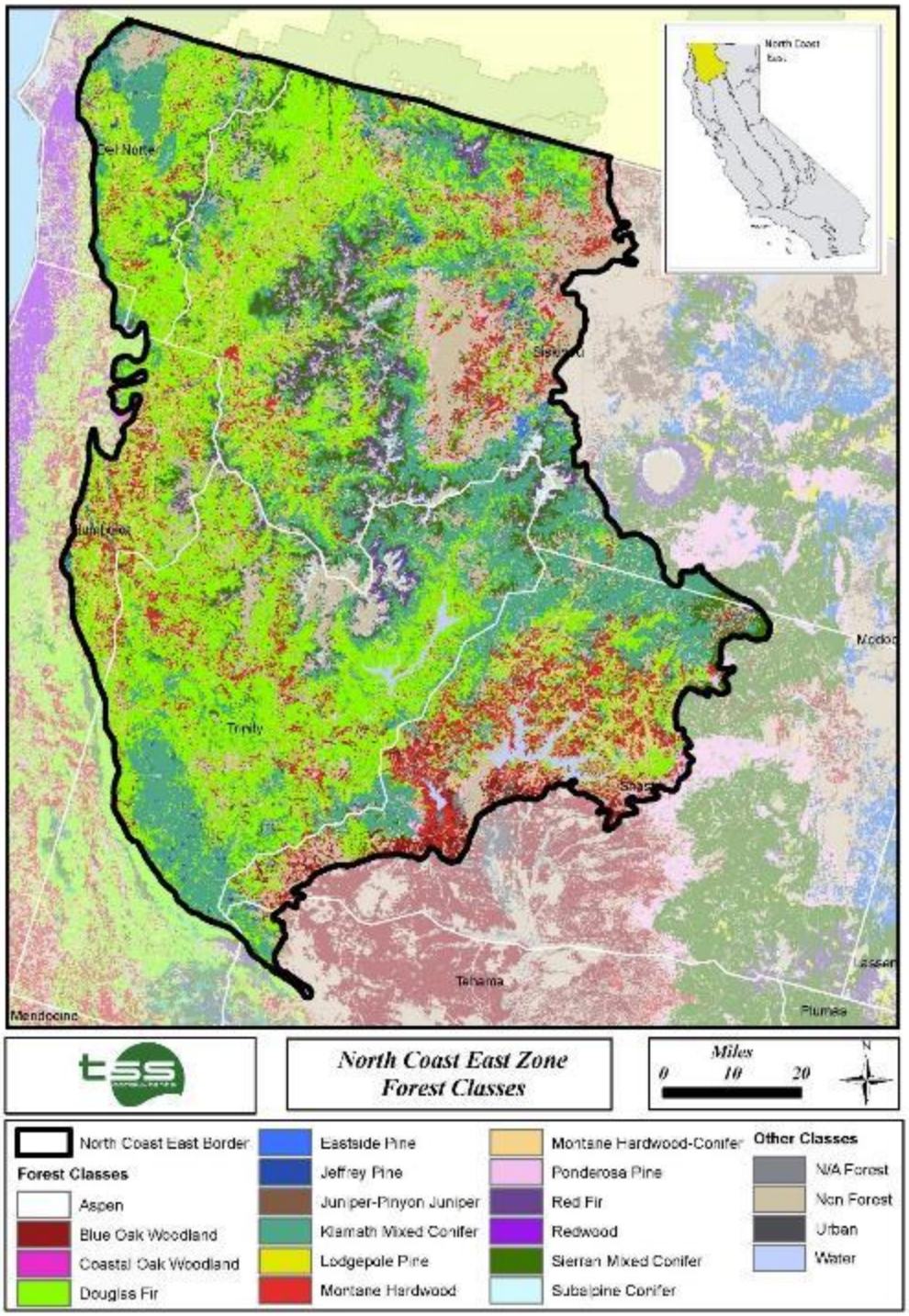
A small slice of the Great Basin ecological zone falls within the California border. It is almost exclusively public land. In the northern half of the zone most land is managed by the BLM, while in the south there is a mix of BLM and wilderness areas (including Death Valley National Park).

Forested lands are dominated by the Juniper-Pinyon Juniper forest type. Private industrial forest lands are practically non-existent.

North Coast East

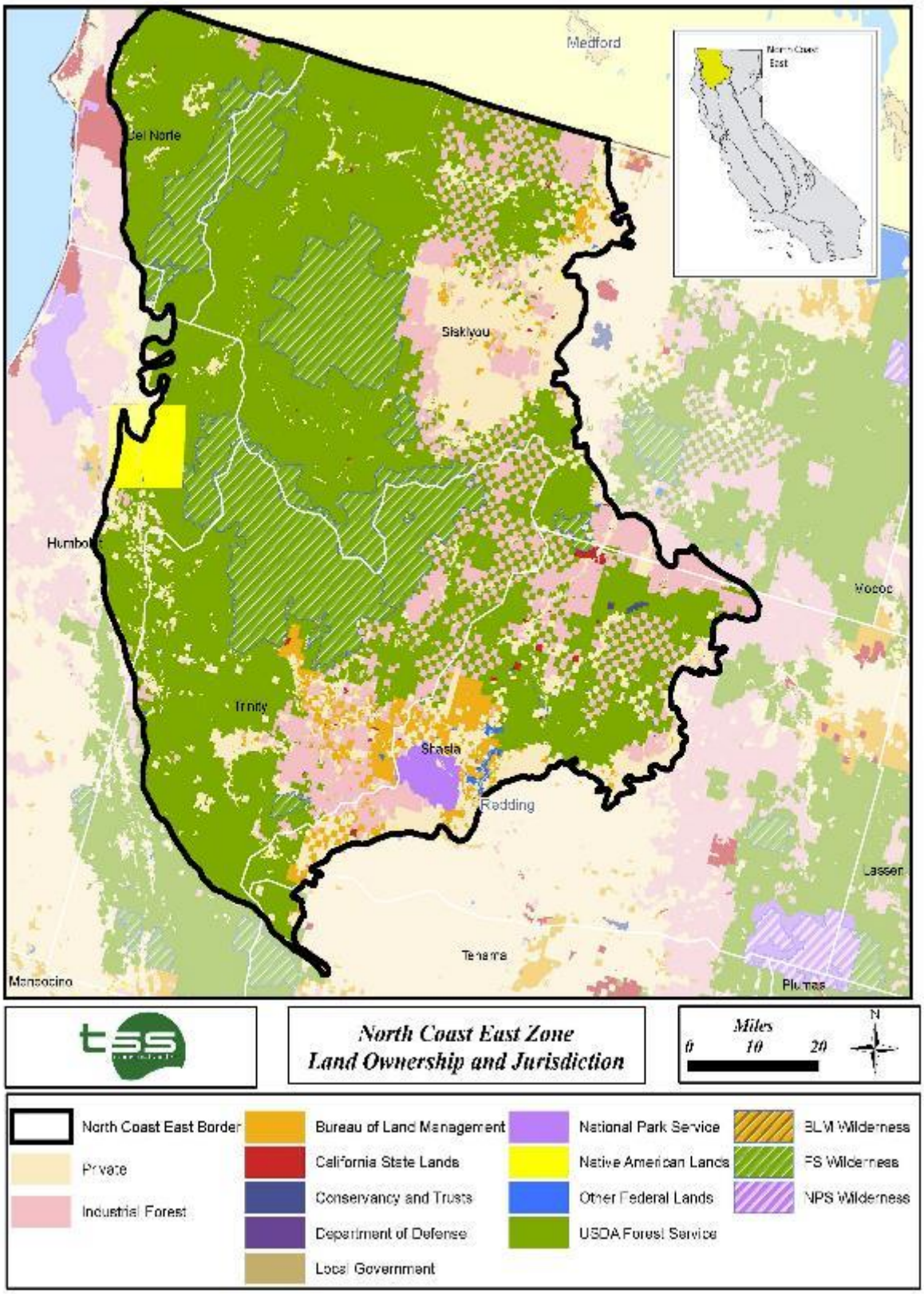
The North Coast East region covers the eastern side of the northern Klamath range and includes Del Norte, Siskiyou, Trinity, and Shasta counties. Figure 13 and Figure 14 identify the forest class and landownership patterns in the region.

Figure 13: North Coast East Forest Classes



Source: West Biofuels, LLC

Figure 14: North Coast East Land Ownership and Jurisdiction



Source: West Biofuels, LLC

Table 21 through Table 24 summarize the data presented in the maps.

Table 21: North Coast East Forest Land Cover

Land Cover Classes	Acres	Percent
Blue Oak Woodland-Foothill Pine	67,828	1.22%
Coastal Oak Woodland	863	0.02%
Douglas Fir	1,696,912	30.45%
Eastside Pine	6,187	0.11%
Jeffrey Pine	35,510	0.64%
Pinyon Juniper	17,723	0.32%
Klamath Mixed Conifer	1,090,288	19.56%
Lodgepole Pine	402	0.01%
Montane Hardwood	465,679	8.36%
Montane Hardwood-Conifer	614,599	11.03%
Ponderosa Pine	114,168	2.05%
Red Fir	148,894	2.67%
Redwood	1,111	0.02%
Sierran Mixed Conifer-White Fir	280,874	5.04%
Subalpine Conifer	48,028	0.86%
N/A Forest	39,063	0.70%
Non Forest	867,100	15.56%
Urban	13,414	0.24%
Water	64,623	1.16%
Total	**5,573,325**	**100.00%**

Source: West Biofuels, LLC

Table 22: North Coast East Land Ownership

Land Ownership	Acres	Percent Public Lands
Bureau of Land Management	163,416	4.04%
California State Lands	10,911	0.27%
Conservancy and Trusts	2,353	0.06%
Local Government	618	0.02%
National Park Service	42,064	1.04%
Native American Lands	70,056	1.73%
Other Federal Lands	10,431	0.26%
USDA Forest Service	3,743,110	92.58%
Public Lands Total	4,042,959	100.00%
Private Industrial Forest Total	786,759	
Region Total	5,573,325	

Source: West Biofuels, LLC

Table 23: North Coast East Wilderness Area

Land Ownership	Wilderness Areas	Acres
USDA Forest Service		**981,299**
	Klamath National Forest	388,912
	Shasta National Forest	125,339
	Siskiyou National Forest	5,562
	Six Rivers National Forest	154,779
	Trinity National Forest	306,707
Wilderness Total		**981,299**

Source: West Biofuels, LLC

Table 24: North Coast East Dominant Forest Classes by Land Ownership

	USFS		BLM		Industry		Total
Forest Class	**Acres**	**%**	**Acres**	**%**	**Acres**	**%**	**Acres**
Douglas Fir	1,283,540	82%	44,694	3%	231,371	15%	1,559,605
Klamath Mixed Conifer	752,133	74%	15,182	1%	249,034	25%	1,016,350
Montane Hardwood-Conifer	408,014	78%	15,500	3%	96,724	19%	520,238
Montane Hardwood	241,769	73%	31,502	10%	57,065	17%	330,335
Sierran Mixed Conifer-White Fir	236,178	87%	222	0%	35,248	13%	271,649

Source: West Biofuels, LLC

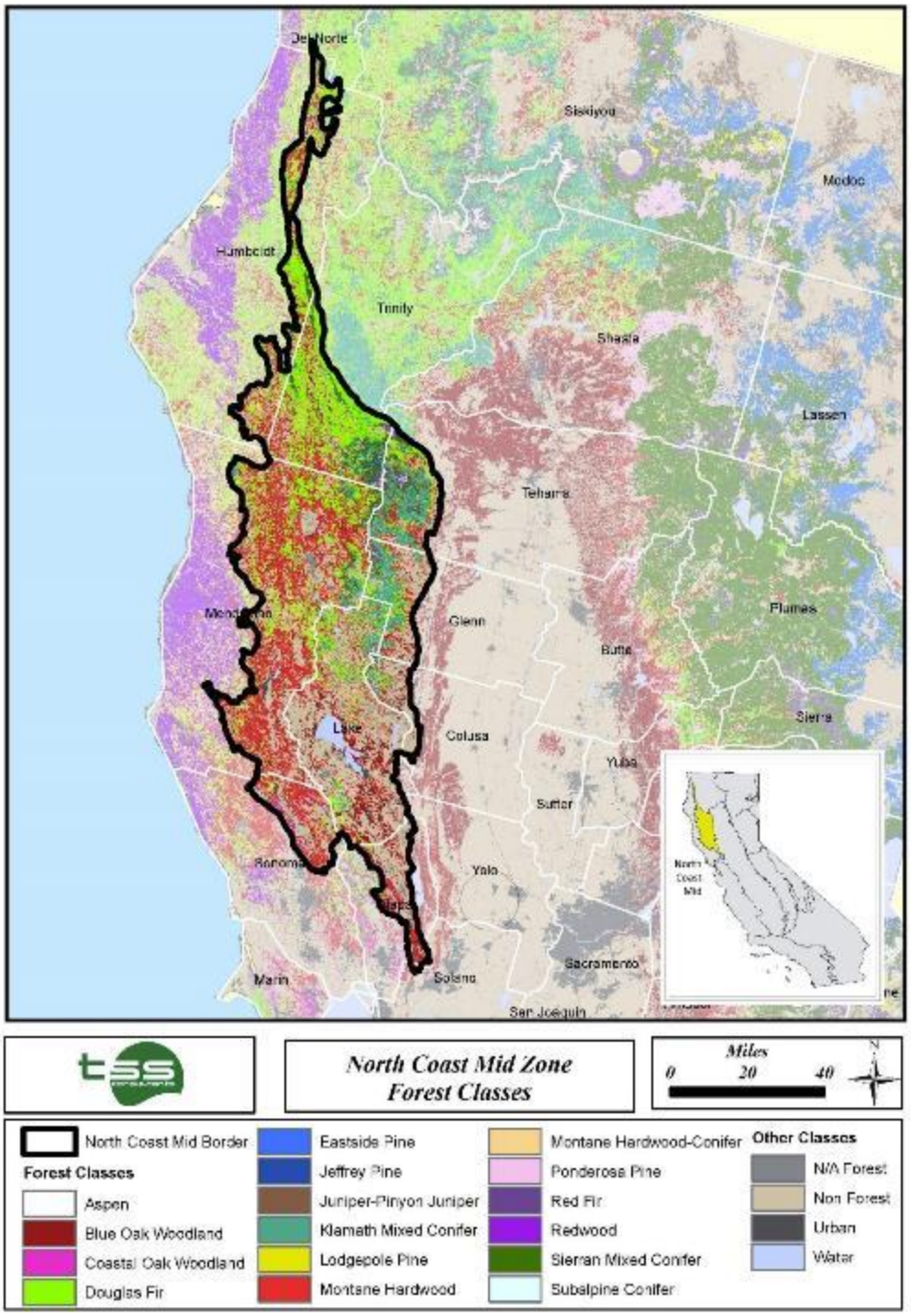
The North Coast East region has large acreages of Douglas Fir, along with Klamath Mixed Conifer and Sierran Mixed Conifer-White Fir forests. Lower elevations are Mountain Hardwood.

The region is mostly public land, making up over 72 percent of the land base, and the USFS is by far the largest land manager. However, the second most common land ownership is Private Industrial with over 780,000 acres. Private industrial lands contain the same forest class mix as described above and are mostly located on the eastern side of the North Coast East region.

North Coast Mid

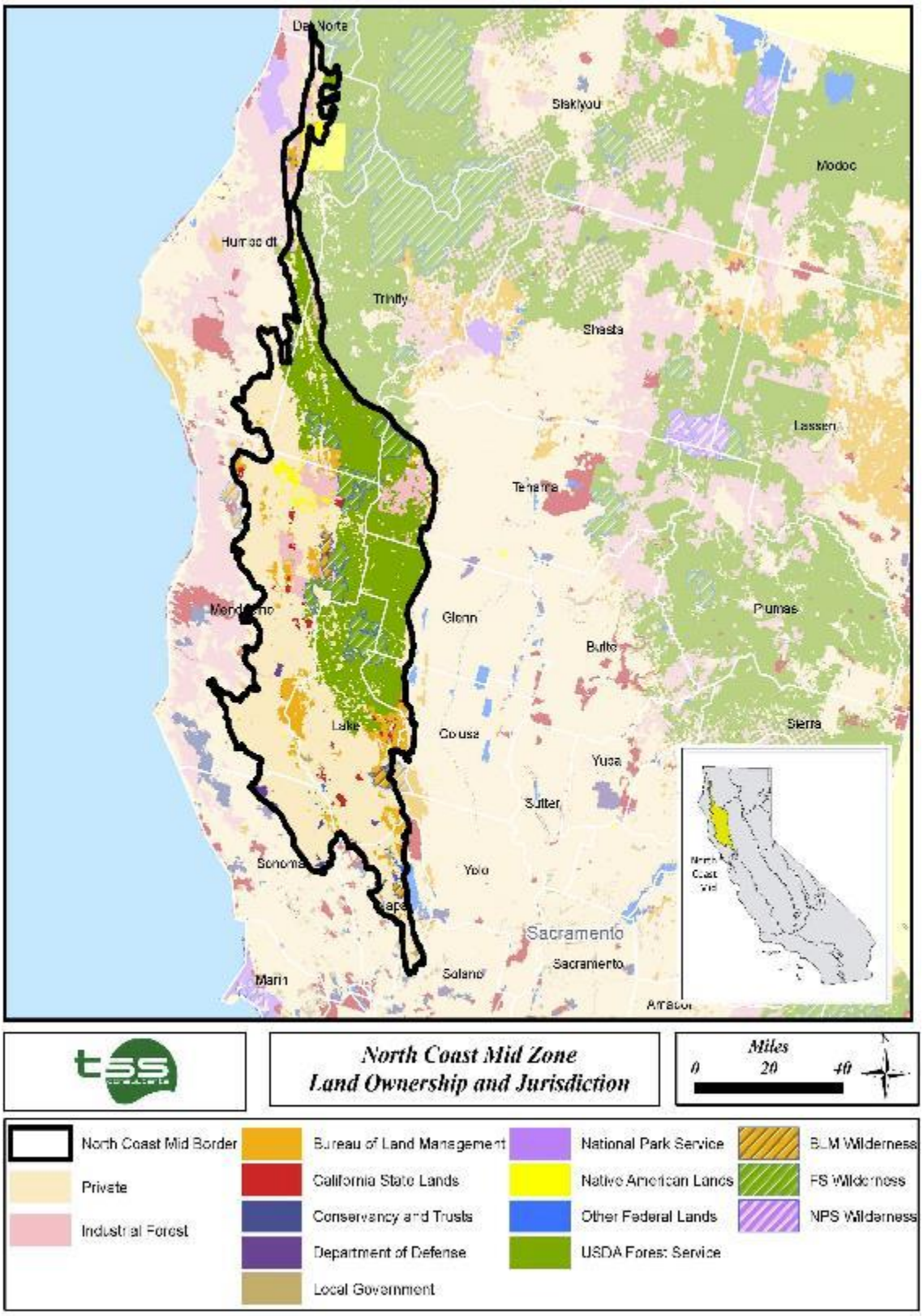
The North Coast Mid region covers the eastern side of the northern Coastal range and includes Humboldt, Trinity, Tehama, Mendocino, Glenn, Lake, Sonoma, Colusa, and Napa counties. Figure 15 and Figure 16 identify the forest class and landownership patterns in the region.

Figure 15: North Coast Mid Forest Classes



Source: West Biofuels, LLC

Figure 16: North Coast Mid Land Ownership and Jurisdiction



Source: West Biofuels, LLC

Table 25 through Table 28 summarize the data presented in the maps.

Table 25: North Coast Mid Forest Land Cover

Land Cover Classes	Acres	Percent
Blue Oak Woodland-Foothill Pine	169,777	4.42%
Coastal Oak Woodland	33,872	0.88%
Douglas Fir	645,498	16.82%
Jeffrey Pine	7,949	0.21%
Klamath Mixed Conifer	243,001	6.33%
Montane Hardwood	872,803	22.75%
Montane Hardwood-Conifer	276,885	7.22%
Ponderosa Pine	48,062	1.25%
Red Fir	32,798	0.85%
Redwood	1,504	0.04%
Sierran Mixed Conifer-White Fir	100,340	2.61%
Subalpine Conifer	1,404	0.04%
N/A Forest	78,192	2.04%
Non Forest	1,235,310	32.19%
Urban	25,914	0.68%
Water	63,722	1.66%
Total	**3,837,120**	**100.00%**

Source: West Biofuels, LLC

Table 26: North Coast Mid Land Ownership

Land Ownership	Acres	Percent of Public Lands
Bureau of Land Management	266,114	15.72%
California State Lands	36,263	2.14%
Conservancy and Trusts	6,074	0.36%
Department of Defense	13,166	0.78%
Local Government	14,978	0.88%
Native American Lands	55,402	3.27%
Other Federal Lands	8,583	0.51%
USDA Forest Service	1,292,310	76.34%
Public Lands Total	1,692,889	100.00%
Private Industrial Forest Total	225,478	
Region Total	3,837,120	

Source: West Biofuels, LLC

Table 27: North Coast Mid Wilderness Area

Land Ownership	Wilderness Areas	Acres
Bureau of Land Management		**39,386**
	National Monument / Conservation Area	39,386
USDA Forest Service		**211,666**
	Mendocino National Forest	150,497
	Six Rivers National Forest	23,364
	Trinity National Forest	37,805
Wilderness Total		**251,052**

Source: West Biofuels, LLC

Table 28: North Coast Mid Dominant Forest Classes by Land Ownership

	USFS		BLM		Industry		Total
Forest Class	**Acres**	**%**	**Acres**	**%**	**Acres**	**%**	**Acres**
Montane Hardwood	173,051	65%	36,963	14%	55,417	21%	265,431
Douglas Fir	335,857	81%	17,060	4%	63,666	15%	416,583
Montane Hardwood-Conifer	79,158	56%	36,963	26%	25,720	18%	141,841
Klamath Mixed Conifer	187,626	82%	4,665	2%	35,279	16%	227,570
Blue Oak Woodland-Foothill Pine	28,329	69%	12,094	30%	516	1%	40,938

Source: West Biofuels, LLC

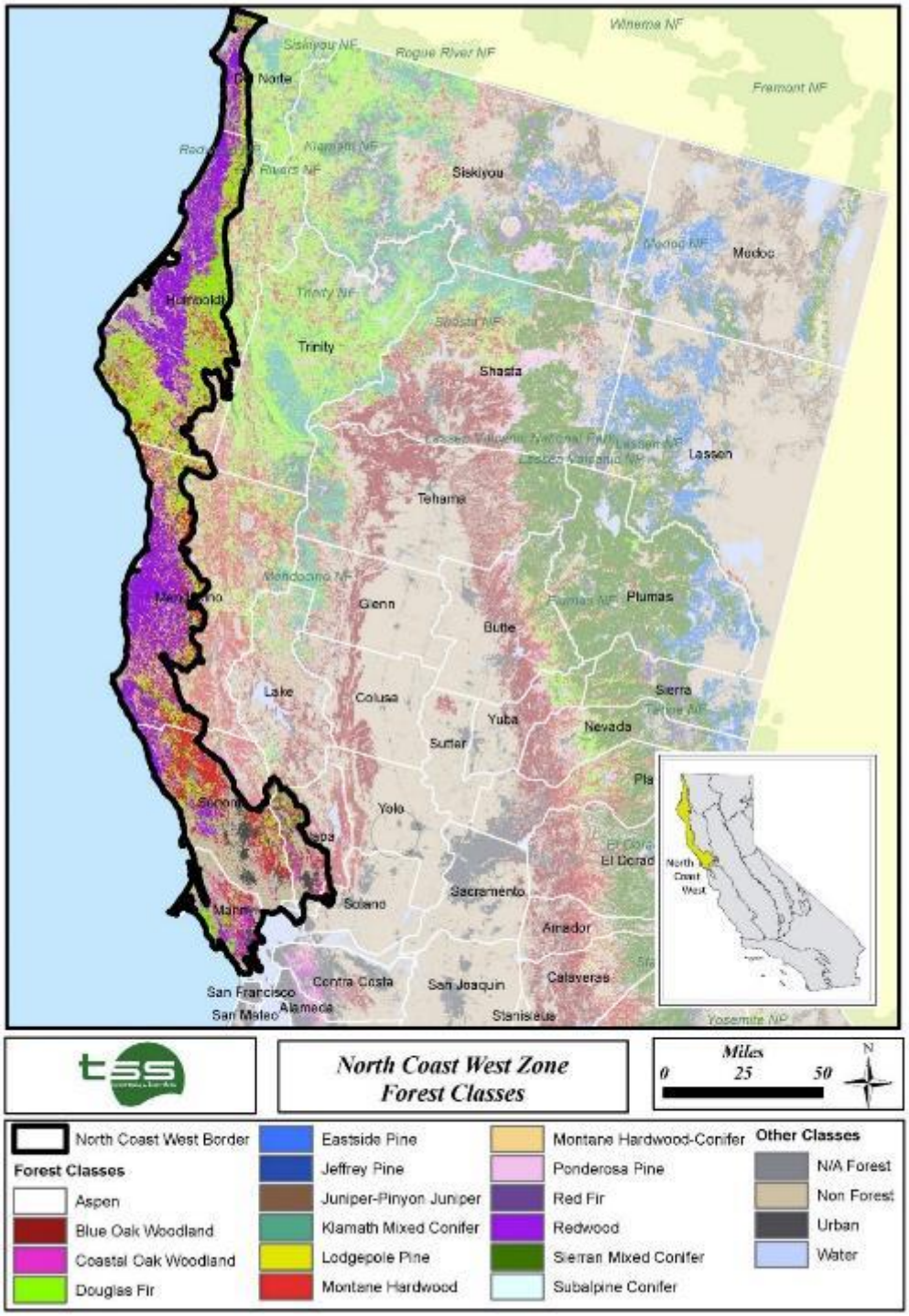
The North Coast mid region is neither as mountainous as the North Coast East, nor quite as wet as the coastal zone. Montane Hardwoods and Blue Oak Woodlands are typical forests with Douglas Fir and Klamath Mixed Conifer along the eastern side of the zone.

Public lands occupy about half of the land base (mostly USFS). Private industrial forests occupy about 225,000 acres. Private forest lands possess about 15 percent of the Douglas Fir and 16 percent of the Klamath Mixed Conifer forest classes in North Coast mid region.

North Coast West

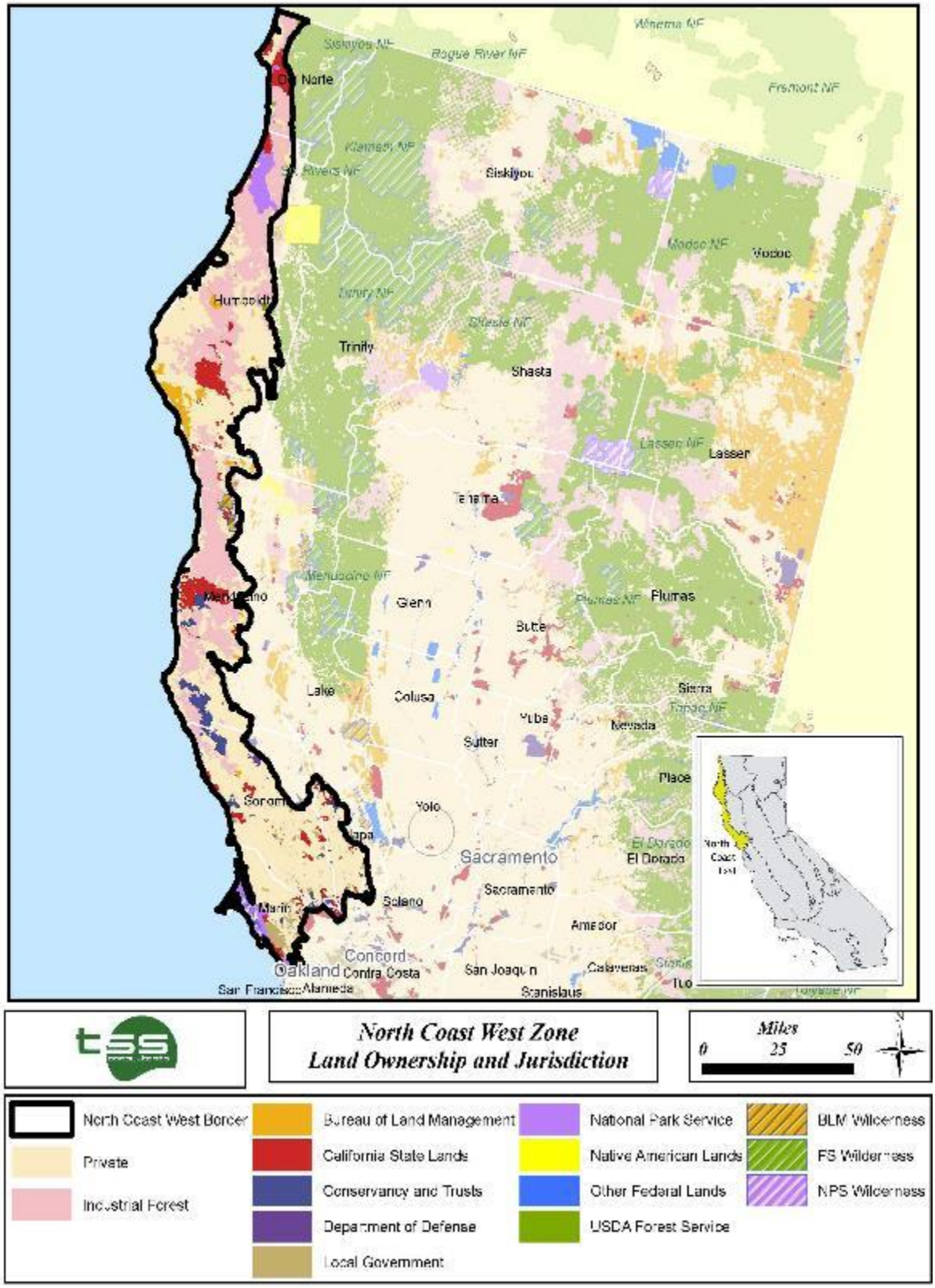
The North Coast West region covers the western and coastal side of the Klamath and Coastal ranges and includes Del Norte, Humboldt, Mendocino, Sonoma, and Marin counties. Figure 17 and Figure 18 identify the forest class and landownership patterns in the region.

Figure 17: North Coast West Forest Classes



Source: West Biofuels, LLC

Figure 18: North Coast West Ownership and Jurisdiction



Source: West Biofuels, LLC

Table 29 through Table 31 summarize the data presented in the maps.

Table 29: North Coast West Forest Classes

Land Cover Classes	Acres	Percent
Blue Oak Woodland-Foothill Pine	6,183	0.15%
Coastal Oak Woodland	103,216	2.44%
Douglas Fir	553,789	13.07%
Jeffrey Pine	1,001	0.02%
Klamath Mixed Conifer	2,126	0.05%
Montane Hardwood	507,880	11.99%
Montane Hardwood-Conifer	721,025	17.02%
Ponderosa Pine	356	0.01%
Redwood	959,014	22.64%
Sierran Mixed Conifer-White Fir	3,274	0.08%
Subalpine Conifer	4,125	0.10%
N/A Forest	117,549	2.77%
Non Forest	1,068,107	25.21%
Urban	137,256	3.24%
Water	51,307	1.21%
Total	**4,236,209**	**100.00%**

Source: West Biofuels, LLC

Table 30: North Coast West Forest Land Ownership

Land Ownership	Acres	Percent Public Land
Bureau of Land Management	124,926	15.33%
California State Lands	312,658	38.37%
Conservancy and Trusts	101,509	12.46%
Department of Defense	8,508	1.04%
Local Government	74,176	9.10%
National Park Service	156,750	19.24%
Native American Lands	6,012	0.74%
Other Federal Lands	8,949	1.10%
USDA Forest Service	21,269	2.61%
Public Lands Total	814,759	100.00%
Private Industrial Forest Total	1,121,706	
Region Total	4,236,209	

Source: West Biofuels, LLC

Table 31: North Coast West Wilderness Areas

Land Ownership	Wilderness Areas	Acres
Bureau of Land Management		**19,574**
	National Monument / Conservation Area	19,574
USDA Forest Service		**4,489**
	Six Rivers National Forest	4,489
National Park Service		**24,122**
	Point Reyes National Seashore	24,122
Wilderness Total		**48,185**

Source: West Biofuels, LLC

Table 32: North Coast West Dominant Forest Classes by Land Ownership

	USFS		BLM		Industry		Total
Forest Class	**Acres**	**%**	**Acres**	**%**	**Acres**	**%**	**Acres**
Redwood	1,228	0%	7,523	2%	473,425	98%	482,176
Montane Hardwood-Conifer	2,819	2%	38,058	30%	84,802	67%	125,679
Douglas Fir	12,881	6%	46,310	21%	162,552	73%	221,744
Montane Hardwood	550	1%	16,105	16%	84,802	84%	101,458
Coastal Oak Woodland	0	0%	427	18%	2,002	82%	2,429

Source: West Biofuels, LLC

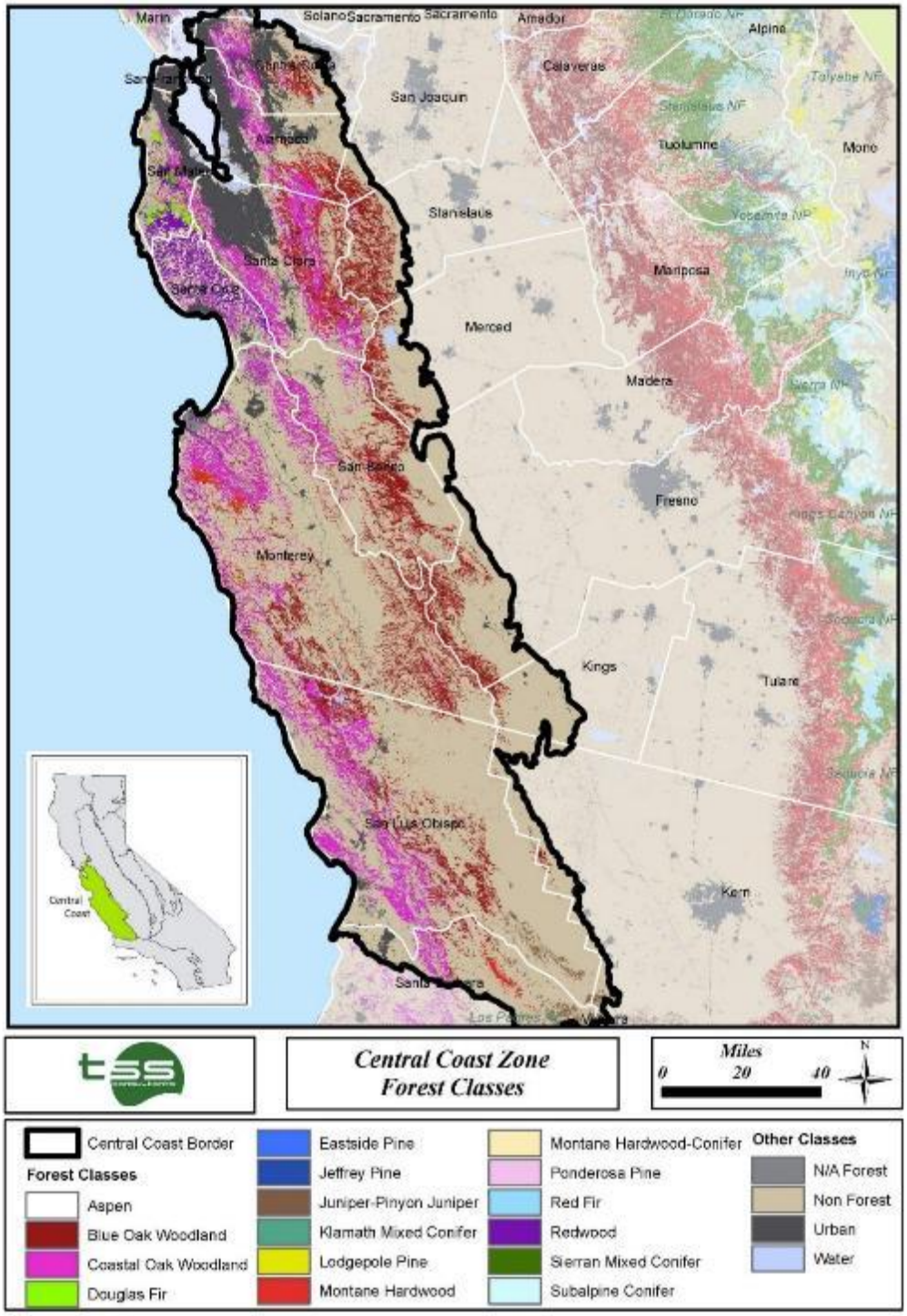
The North Coast West region exhibits significant differences from the other North Coast regions. Redwood forest is unique to this zone and about 23 percent of the land base is in this forest cover class.

Private Industrial land acreage, over 1,121,000 acres, exceeds the public managed lands. Almost 100 percent of the Redwood forest type is in Private Industrial forest. The USFS has the least acreage under its management, and the State of California is the largest public land management agency in the North Coast West region.

Central Coast

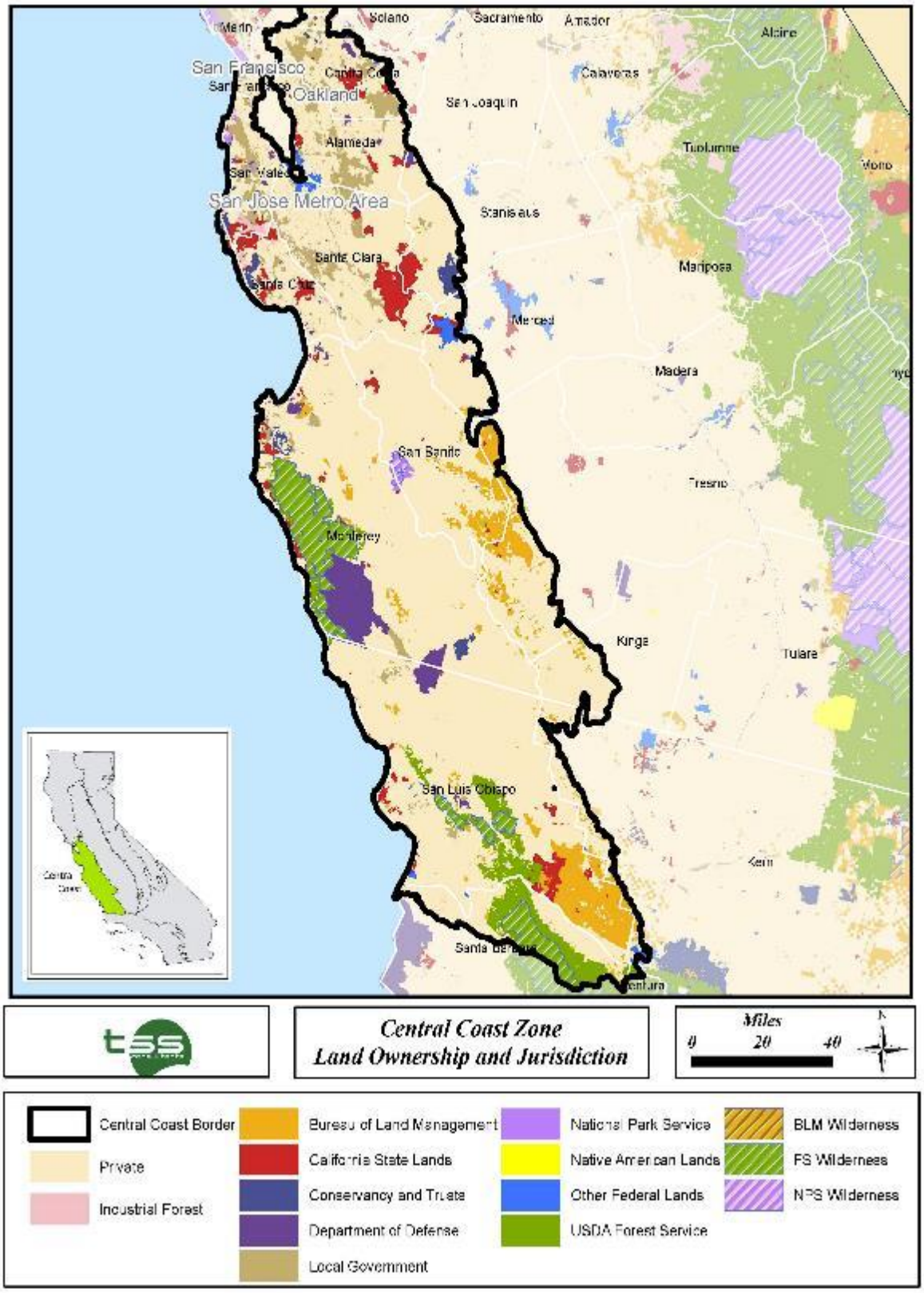
The Central Coast region covers the southern Coastal range and includes Del Norte, Humboldt, Mendocino, Sonoma, and Marin counties. Figure 19 and Figure 20 identify the forest class and landownership patterns in the region.

Figure 19: Central Coast Forest Classes



Source: West Biofuels, LLC

Figure 20: Central Coast Land Ownership and Jurisdiction



Source: West Biofuels, LLC

Table 33 through Table 36 summarize the data presented in the maps.

Table 33: Central Coast Forest Land Cover

Land Cover Classes	Acres	Percent
Blue Oak Woodland-Foothill Pine	923,759	9.65%
Coastal Oak Woodland	825,712	8.63%
Douglas Fir	31,106	0.32%
Juniper / Pinyon Juniper	57,157	0.60%
Montane Hardwood	158,785	1.66%
Montane Hardwood-Conifer	107,879	1.13%
Ponderosa Pine	2,180	0.02%
Redwood	142,415	1.49%
Sierran Mixed Conifer-White Fir	6,994	0.07%
N/A Forest	129,290	1.35%
Non Forest	6,349,655	66.33%
Urban	717,083	7.49%
Water	120,963	1.26%
Total	**9,572,983**	**100.00%**

Source: West Biofuels, LLC

Table 34: Central Coast Land Ownership

Land Ownership	Acres	Percent Public Lands
Bureau of Land Management	555,589	21.96%
California State Lands	348,828	13.79%
Conservancy and Trusts	106,380	4.21%
Department of Defense	238,330	9.42%
Local Government	437,361	17.29%
National Park Service	35,829	1.42%
Native American Lands	130	0.01%
Other Federal Lands	65,538	2.59%
USDA Forest Service	741,566	29.32%
Public Lands Total	2,529,552	100.00%
Private Industrial Forest Total	24,045	
Region Total	9,572,983	

Source: West Biofuels, LLC

Table 35: Central Coast Wilderness Areas

Land Ownership	Wilderness Areas	Acres
USDA Forest Service		**416,411**
	Los Padres National Forest	416,411
National Park Service		**16,056**
	Pinnacles National Monument	16,056
Wilderness Total		**432,467**

Source: West Biofuels, LLC

Table 36: Central Coast Dominant Forest Classes by Land Ownership

Forest Class	USFS		BLM		Industry		Total
	Acres	%	Acres	%	Acres	%	Acres
Blue Oak Woodland-Foothill Pine	28,541	41%	40,994	59%	0	0%	69,535
Coastal Oak Woodland	63,923	88%	7,907	11%	865	1%	72,695
Montane Hardwood	39,819	89%	4,961	11%	17	0%	44,797
Redwood	6,091	33%	42	0%	12,597	67%	18,730
Montane Hardwood-Conifer	8,920	51%	72	0%	8,503	49%	17,495

Source: West Biofuels, LLC

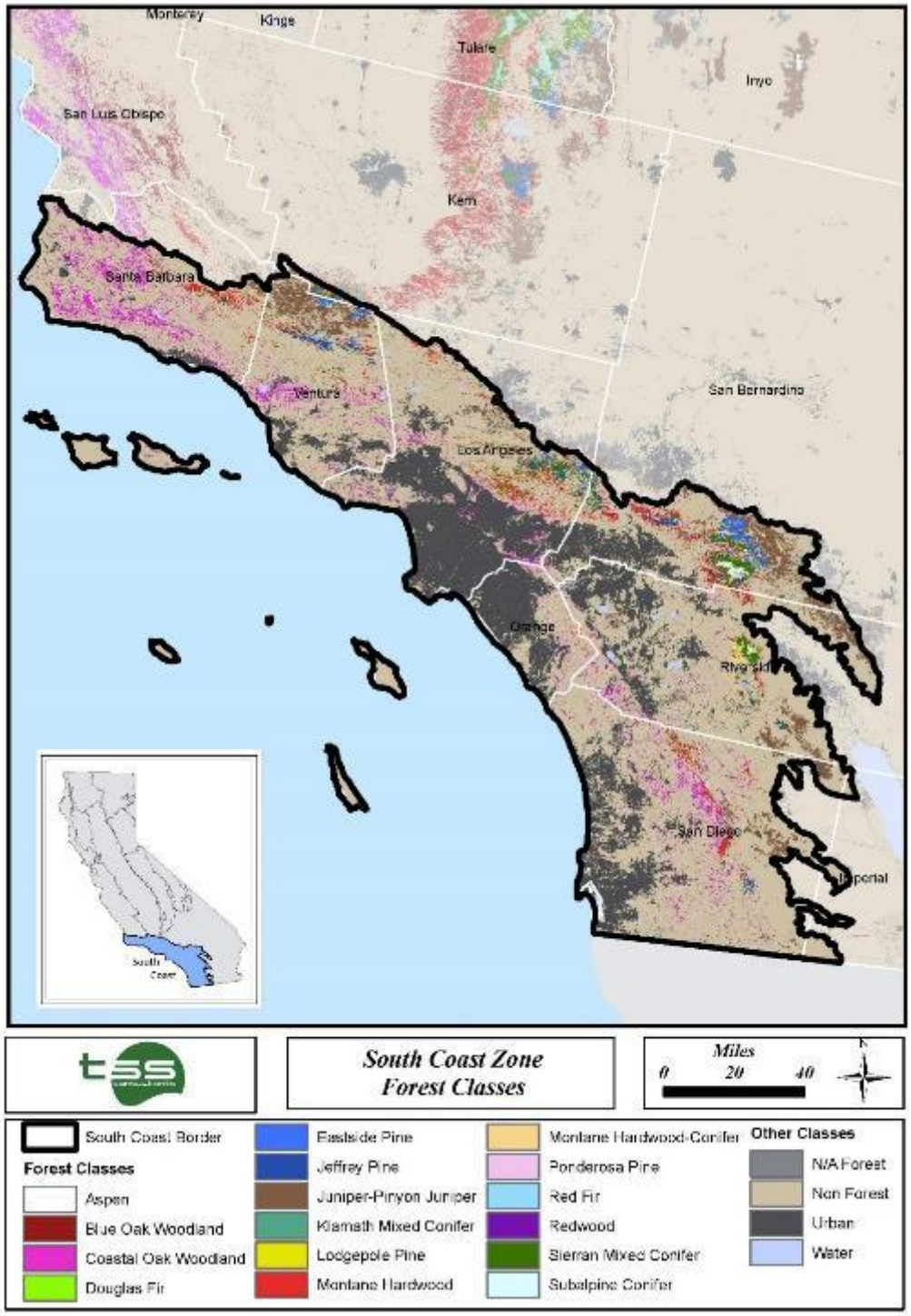
The Central Coast forested land is mostly Coastal Oak Woodland and Blue Oak Woodland-Foothill Pine. There is a small island of Redwood forest along the northern coast of the region. Over 66 percent of the region is Non-Forest.

Although the Central Coast is the second largest region, with almost 9,600,00 acres, public lands constitute only about a quarter of the land base. Public land management is evenly spread out between the USFS, BLM, State of California, Department of Defense, and local government. Private Industrial lands are limited to less than 1 percent of total land ownership in this region. However, Private Industrial forests contain about 12,500 acres, or 67 percent, of the Redwood class.

South Coast

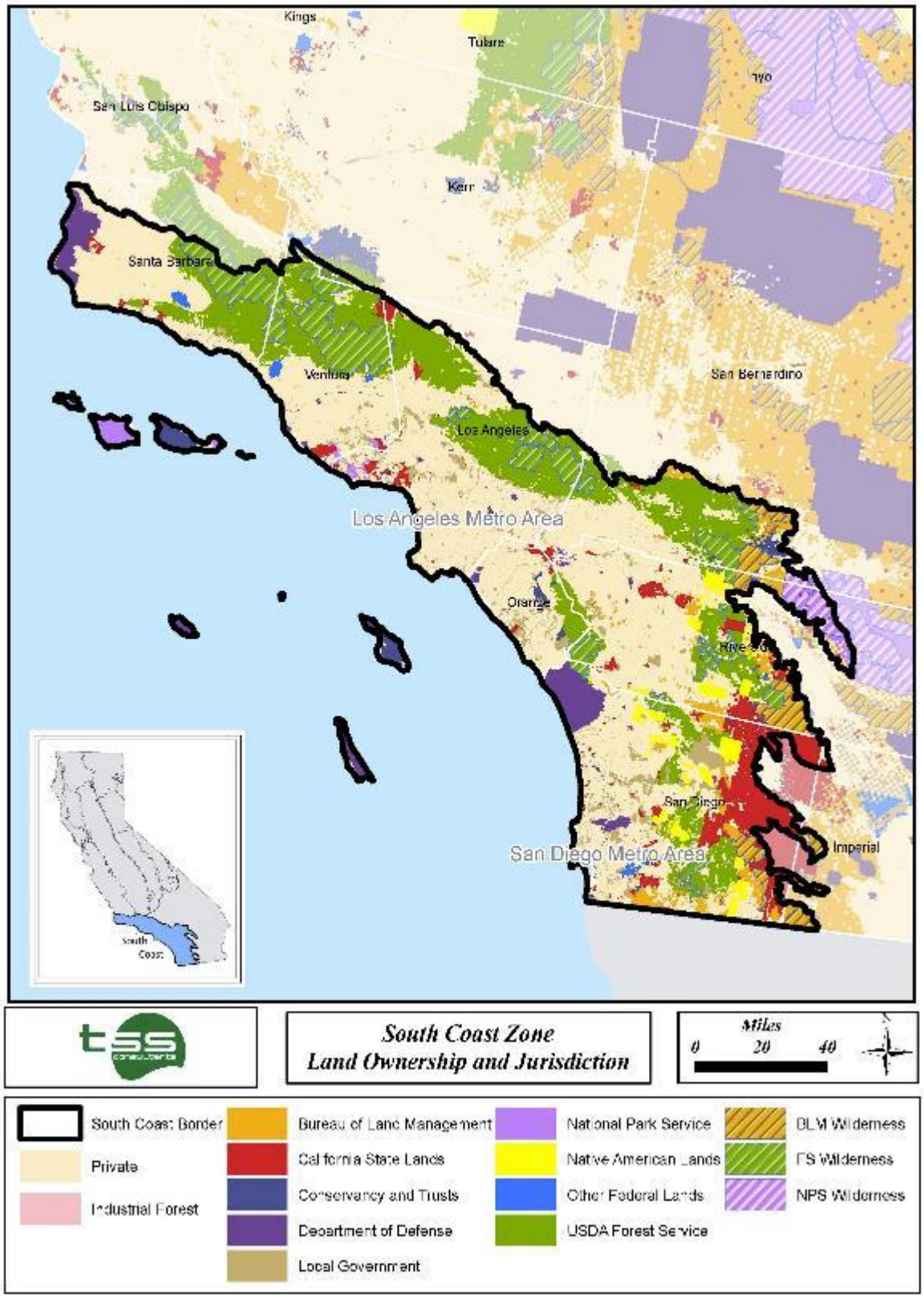
The South Coast region covers the Transverse and Peninsular ranges and includes Santa Barbara, Venture, Los Angeles, Orange, San Bernardino, Riverside, and San Diego counties. Figure 21 and Figure 22 identify the forest class and landownership patterns in the region.

Figure 21: South Coast Forest Classes



Source: West Biofuels, LLC

Figure 22: South Coast Land Ownership and Jurisdiction



Source: West Biofuels, LLC

Table 37 through Table 40 summarize the data presented in the maps.

Table 37: South Coast Forest Land Cover

Land Cover Classes	Acres	Percent
Blue Oak Woodland-Foothill Pine	3,179	0.03%
Coastal Oak Woodland	362,251	3.49%
Eastside Pine	43,939	0.42%
Jeffrey Pine	75,972	0.73%
Pinyon Juniper	394,577	3.80%
Montane Hardwood	196,510	1.89%
Montane Hardwood-Conifer	106,004	1.02%
Ponderosa Pine	1,975	0.02%
Sierran Mixed Conifer-White Fir	135,677	1.31%
Subalpine Conifer	11,457	0.11%
N/A Forest	159,942	1.54%
Non Forest	6,747,095	64.93%
Urban	2,086,228	20.08%
Water	66,695	0.64%
Total	**10,391,759**	**100.00%**

Source: West Biofuels, LLC

Table 38: South Coast Land Ownership

Land Ownership	Acres	Percent of Public Lands
Bureau of Land Management	568,959	10.51%
California State Lands	687,437	12.70%
Conservancy and Trusts	168,612	3.11%
Department of Defense	340,200	6.28%
Local Government	423,996	7.83%
National Park Service	224,530	4.15%
Native American Lands	227,404	4.20%
Other Federal Lands	48,827	0.90%
USDA Forest Service	2,723,789	50.31%
Public Lands Total	5,413,754	100.00%
Private Industrial Forest Total	None	
Region Total	10,391,759	

Source: West Biofuels, LLC

Table 39: South Coast Wilderness Areas

Land Ownership	Wilderness Areas	Acres
Bureau of Land Management		**316,980**
	National Monument / Conservation Area	275,108
	San Mateo Canyon Wilderness	41,872
USDA Forest Service		**747,147**
	Angeles National Forest	121,805
	Cleveland National Forest	37,445
	Los Padres National Forest	446,179
	San Bernardino National Forest	141,718
National Park Service		**102,743**
	Joshua Tree National Park	102,743
Wilderness Total		**1,166,870**

Source: West Biofuels, LLC

Table 40: South Coast Dominant Forest Classes by Land Ownership

Forest Class	USFS		BLM		Industry		Total
	Acres	%	Acres	%	Acres	%	Acres
Juniper - Pinyon Juniper	182,596	83%	37,478	17%	0	0%	220,074
Coastal Oak Woodland	55,052	96%	2,084	4%	0	0%	57,136
Montane Hardwood	151,051	100%	645	0%	0	0%	151,696
Sierran Mixed Conifer-White Fir	117,790	100%	54	0%	0	0%	117,844
Montane Hardwood-Conifer	77,509	98%	1,301	2%	0	0%	78,809

Source: West Biofuels, LLC

Like the Central Coast, the South Coast is a large region of over 10,390,000 acres. Despite its large urban land use, almost half of the region is made up of public lands. Private Industrial lands appear to be nonexistent according to the CAL FIRE database.

Regional Assessment of Forest Management Practices

The vegetation cover and landownership analyses show that each region has a unique mix of forest land cover classes, ownership and forest stand characteristics. Understanding FMP in each forest region is critical to determining the potential supply of forest biomass material that could be available as a byproduct of forest management activities. Forest biomass that is cost-effectively removed for use as feedstock will typically be a byproduct of an integrated operation that is primarily focused on commercial sawlog removal, forest restoration, and/or fuels treatment. With recent high-profile catastrophic wildfires[10] impacting several of the forest regions analyzed, and increasing concern regarding climate change impacts on forest ecosystems, an increased emphasis on fuels treatment activities is expected in the coming years.

[10] For example, the Butte Fire, Valley Fire, Rough Fire, and Willow Fire of 2015.

In California forest biomass material is removed in accordance with either the California Environmental Quality Act (CEQA) on lands with private/local/state jurisdiction or in accordance with the National Environmental Policy Act (NEPA) on federally managed lands. Both CEQA and NEPA guidelines provide clear direction and oversight to assure that FMP are implemented after public outreach, scoping and detailed planning. In addition, both CEQA and NEPA protocols help to assure that forest operations are implemented using best management practices focused on long-term sustainable forest health.

The FMPs are presented by region with an emphasis on key components of forest management that impact economic access to forest biomass, and the potential for biomass utilization as feedstock. Table 41 and Table 42 describe the following FMPs and biomass characteristics for each of the regions previously mapped.

- Dominant Forest Biomass Classes – Listing of the top five forest cover classes that fall within the region.
- Management Return Interval – Depending on site productivity (a function of soil fertility, topography, land management objectives, and precipitation) forest managers will schedule a timeframe for sequential forest operations. In California, management return intervals typically range from 20 to 30 years in duration. Catastrophic events such as windstorms or wildfire will cause the return interval to be adjusted based on the need to restore forest ecosystems.
- Average Yield Per Acre – This metric provides a general estimate of the volume (preferred unit of measure is bone dry tons)[11] of forest biomass that is potentially available per acre. The higher the site productivity the higher the average yield per acre. Some forest regions have high tree retention standards (for example, Central Coast) that require a minimum number of trees be retained on site following operations. This results in a lower average yield per acre.
- Biomass Characteristics - Key physical characteristics of forest biomass when utilized as feedstock for production of bioenergy include moisture content and high heat value. Both of these metrics speak to the amount of latent energy that is potentially available. The lower the moisture content, the less energy will be required to drive off water and the higher the available energy. The higher the heating value (Higher Heating Value, HHV, measured in British thermal units/dry pound of wood) the more energy available and fewer bone dry tons required per unit of electricity or thermal energy produced.

Table 42 describes the following FMPs, biomass utilization practices and observations on the biomass industry for each region:

- Current Forest Biomass Utilization Practices –Description of current techniques and equipment deployed within the region. Even-age management practices typically generate more forest biomass material per acre than uneven-age practices due to the

[11] One bone dry ton equals 2,000 pounds of moisture-free wood fiber.

fact that almost all vegetation is removed from the site (typically accomplished as a regeneration harvest in preparation for tree planting).

- Biomass Industry Observations - California has a very active biomass power generation sector, with over twenty operating commercial-scale facilities and new community-scale \facilities in early stage development (newer community-scaled biomass power plants are less than 3 MW and California SB 1122 compliant). Some forest regions are home to numerous facilities – both existing and in early stage development.

Table 41: Biomass Characteristics by Region

Forest Region	Dominant Forest Biomass Classes	Management Return Interval	Average Yield Per Acre12	Biomass Characteristics
North Interior	Sierran Mixed Conifer – White Fir Ponderosa Pine Red Fir	25 to 30 years	10 to 16 BDT.	35 to 50% moisture content. HHV of 8,000 to 8,400 Btu/dry pound.
North Sierran	Sierran Mixed Conifer – White Fir Montane Hardwood Ponderosa Pine Montane Hardwood-Conifer	20 to 30 years	12 to 18 BDT	35 to 50% moisture content. HHV of 8,000 to 8,400 Btu/dry pound.
South Sierran	Sierran Mixed Conifer – White Fir Montane Hardwood Red Fir	20 to 30 years	12 to 18 BDT	35 to 50% moisture content. HHV of 8,000 to 8,400 Btu/dry pound.
Great Basin	Pinyon Juniper Eastside Pine	40 to 50 years	4 to 8 BDT	35 to 50% moisture content. HHV of 8,000 to 8,800 Btu/dry pound.
North Coast East	Douglas Fir Klamath Mixed Conifer Montane Hardwood-Conifer Montane Hardwood Sierran Mixed Conifer – White Fir	25 to 30 years	10 to 16 BDT	35 to 50% moisture content. HHV of 8,000 to 8,400 Btu/dry pound.
North Coast Mid	Montane Hardwood Douglas Fir Montane Hardwood-Conifer Blue Oak Woodland-F Pine Sierran Mixed Conifer – White Fir	25 to 30 years	8 to 16 BDT	35 to 50% moisture content. HHV of 8,000 to 8,400 Btu/dry pound.
North Coast West	Redwood Montane - Hardwood Conifer Douglas Fir Montane Hardwood	25 to 30 years	12 to 18 BDT	35 to 50% moisture content. HHV of 8,000 to 8,400 Btu/dry pound.
Central Coast	Blue Oak Woodland-Fir-Pine Coastal Oak Woodland Montane Hardwood Redwood	30 to 40 years	10 to 20 BDT	35 to 50% Moisture content. HHV of 7,800 to 8,400 Btu/dry pound.
South Coast	Juniper-Pinyon Coastal Oak Woodland Montane Hardwood Sierran Mixed Conifer – White Fir Montane Hardwood-Conifer	30 to 40 years	5 to 10 BDT	35 to 50% Moisture content. HHV of 7,800 to 8,400 Btu/dry pound.

Source: West Biofuels, LLC

[12] Variable due to wide range of stand densities and forest retention practices.

Table 42: Forest Management Practices, Biomass Utilization and Biomass Industry by Region

Forest Region	Predominant FMPs Producing Biomass	Predominant Biomass Utilization	Biomass Industry Observations
North Interior	- Forest Thinning/ Fuel Reduction - Timber Harvest (Even- and Uneven-Aged Management)	- Pile & Burn - Biomass Power	This zone currently has the highest concentration of operating commercial scale biopower facilities in California. Forest biomass supply chain is highly developed. Several commercial scale biomass plants have closed in the last three years (Burney Mountain Power, Mt Lassen Power) and more are likely to close by 2017 (Wheelabrator Shasta Energy, Burney Forest Power). Several community-scale projects are in early stages of development (Burney/Hat Creek, Bieber).
North Sierran	- Forest Thinning/ Fuel Reduction - Timber Harvest (Even- and Uneven-Aged Management)	- Pile & Burn - Biomass Power	This zone has a long history of commercial forest management on both federal (USFS) and private lands (mostly Sierra Pacific Industries). All of the existing sawmills have biomass cogeneration facilities. Forest biomass supply chain is highly developed. At least one commercial scale biomass plant is likely to close by 2017 (Rio Bravo Rocklin). Several community-scale projects are in early stage development (Camptonville, Grass Valley and Crescent Mills).
South Sierran	- Forest Thinning/ Fuel Reduction	- Pile & Burn - Chip & Scatter - Limited Biomass Power - Animal Bedding	Much of the South Sierra zone is off limits to commercial forest management. This zone includes major national parks (Yosemite NP, Kings Canyon-Sequoia NP) and large wilderness areas. Most of the forest landscape is federally managed. At least one commercial-scale biomass plant is likely to close by 2017 (Chinese Station). Several community-scale projects are in early stage development (North Fork and Mariposa). High levels of tree mortality brought on by drought and insects is severe and will likely take several years to address.
Great Basin	- Limited Forest Thinning/Fuel Reduction	- Pile & Burn - Chip & Scatter - Limited Biomass Power - Firewood	Almost all of the Great Basin is not forested (82 percent non-forest). There is a biomass thermal project underway at the Mono County maintenance facility in Bridgeport. Primary biomass feedstock sources include clean construction wood and chipped brush/small trees removed as hazardous fuel near communities. Some forest biomass utilization in eastside pine and juniper dominated landscapes - all in the northern portion of the Great Basin within transport distance of an existing biomass power plant (Honey Lake Power). In the southern portion, most forest biomass is utilized as firewood with local and regional markets.
North Coast East	- Forest Thinning/Fuel Reduction - Timber Harvest (Even- and Uneven-Aged Management)	- Pile & Burn - Biomass Power	This zone currently has one operating commercial-scale biopower facility, co-located with a large veneer mill (Roseburg Forest Products - Weed, CA). The forest biomass supply chain is well developed. The northern portion of this zone is served by Pacific Power and Light, which is not required to participate in the SB 1122 process. Wide-ranging forest ownership (private, federal, tribal) with diverse management objectives characterizes this zone.

Forest Region	Predominant FMPs Producing Biomass	Predominant Biomass Utilization	Biomass Industry Observations
North Coast Mid	- Forest Thinning/Fuel Reduction - Limited Timber Harvest (Even- and Uneven-Aged Management)	- Pile & Burn - Chip & Scatter	Forest ownership is primarily federal (Six Rivers National Forest and Mendocino National Forest) with some commercial forest ownership (Green Diamond, Crane Mills). Minimal forest biomass recovery due to challenging terrain, poor road systems for chip transport. High level of interest in community-scale projects but only one community is in early stage development (Covelo). Commercial agriculture (rangeland, wine grapes) is a major economic sector in this zone, whereas forest management is not.
North Coast West	- Forest Thinning/Fuel Reduction - Limited Timber Harvest (Even- and Uneven-Aged Management)	- Pile & Burn - Chip & Scatter	Historically three biomass power plants were in commercial service in this region so forest biomass supply chain is well developed. The northern portion of this zone is served by Pacific Power and Light, which is not required to participate in the SB 1122 process. High level of interest in community-scale projects but only one community is engaged (Fort Bragg). Commercial agriculture (rangeland, wine grapes) is an active economic sector in this zone.
Central Coast	- Forest Thinning/Fuel Reduction	- Pile & Burn - Chip & Scatter - Firewood	Very little forest biomass utilization due to limited commercial markets and challenging topography. No biomass power plants are currently operating in this zone. One idle biomass plant exists at Soledad (Soledad Energy) that utilized primarily urban wood waste. High levels of drought and insect mortality in San Luis Obispo County. Historically, there have been significant volumes of urban wood waste transported to commercial-scale biomass plants in the Central Valley.
South Coast	- Forest Thinning/Fuel Reduction	- Pile & Burn - Chip & Scatter - Firewood	There is some forest biomass within transport distance of scattered commercial markets; however, challenging topography and significant urban development limit access. No biomass power plants are currently operating in this zone. Significant volumes of urban wood waste are transported to commercial-scale biomass plants in the San Joaquin Valley and a biomass power plant facility at Mecca (Desert View Power).

Source: West Biofuels, LLC

Biomass Outlook

Based on the above analyses, Table 43 summarizes the regional forest biomass outlook for California and opines on the existing biomass industry outlook for each of the identified forest regions.

Table 43: California Regional Forest Biomass Outlook

Region	Dominant Biomass Forest Classes	Percent Public Forest	Percent Private Industrial Forest	Existing Forest Biomass Industry Characterization
North Interior	Sierran Mixed Conifer-White Fir Ponderosa Pine Red Fir	54%	46%	Robust
North Sierran	Sierran Mixed Conifer-White Fir Montane Hardwood Red Fir Ponderosa Pine	80%	20%	Robust
South Sierran	Sierran Mixed Conifer-White Fir Montane Hardwood Red Fir	94%	6%	Limited
Great Basin	Pinyon Juniper Eastside Pine	100%	0%	Very Limited
North Coast East	Douglas Fir Klamath Mixed Conifer Montane Hardwood-Conifer Montane Hardwood Sierran Mixed Conifer-White Fir	82%	18%	Limited
North Coast Mid	Montane Hardwood Douglas Fir Montane Hardwood-Conifer Klamath Mixed Conifer	83%	17%	Limited
North Coast West	Redwood Montane Hardwood-Conifer Douglas Fir Montane Hardwood	13%	87%	Limited
Central Coast	Limited Biomass Utilization	>99%	<1%	Very Limited
South Coast	Limited Biomass Utilization	100%	0%	Very Limited

Source: West Biofuels, LLC

Private forest lands, both non-industrial and industrial, have historically been more productive than public lands in the collection, processing and transport of forest biomass material for value-added use. Four of the nine regions have significant amounts of private industrial forest acreage: The North Interior Region (1.35 million acres), North Coast West (815,000 acres), North Coast East (787,000 acres) and North Sierran (700,00 acres). Among these four regions, the North Interior and North Sierran have the most developed biomass supply chains.

Recently, public lands have become potential significant sources of biomass due to increased concerns over wildfire. Forest operations for restoration and fuel reduction are more common. High levels of tree mortality due to drought-induced insect infestations have led to substantial amounts of timber removal of standing dead or dying trees. Fall 2015 mapping of tree mortality by CAL FIRE show the North Sierran and South Sierran regions to be the most severely affected. Removal of forest material as a result of recent drought related tree mortality may take several years. Hopefully drought conditions are mitigated due to recent El Nino related weather and this 'pulse' of forest biomass is only an episodic occurrence.

Wilderness areas reduce the potential for forest biomass production from public lands since their FMPs typically do not permit any active forest operations. The South Sierran region has 3.6 million acres of wilderness and would not be considered highly suitable for biomass production except for the current unusual circumstances of drought, tree mortality and wildfire.

Juniper and Pinyon-Juniper (PJ) forest cover classes are almost exclusively under public land management by the BLM. The Great Basin and eastern side of the North Interior region have substantial acreages of Pinyon-Juniper and Western Juniper respectively. The efficiency of PJ feedstocks for gasification is not well known. Recent federal funding allocated to PJ removal in support of Sage Grouse habitat restoration has provided short-term support for removal of PJ on BLM and some privately managed lands. It is not clear how long this funding may be available.

The Central Coast and South Coast have woodland and hardwood forests such as Blue Oak Woodland-Foothill Pine, Coastal Oak Woodland, Montane Hardwood and Montane Hardwood-Conifer. The Central Coast has over 1.75 million acres of oak woodlands. The close proximity to major urban areas could favor biomass utilization, especially if forest biomass were to be combined with urban wood waste.

Feedstock Processing

Forest derived biomass has been a significant fuel source for California's biomass power generation sector for decades. Since the early 1980s, developers built numerous biomass power plants in northern California's forested regions. Initially, the early biomass power plants' derived their primary fuel supplies from the residues generated by forest products manufacturing operations that were generally within close proximity to the power plants. These residues would typically be processed at the mill site through a stationary hammer mill or grinder known as a hog. These hogs were large, high horsepower machines with numerous rotating arms or hammers that would break up the residues into smaller pieces suitable for utilization as biomass fuel. As the use of biomass expanded and additional biomass power plants were constructed in the state, it was necessary to access biomass fuel directly from the forest. These in-forest fuel processing operations required the use of mobile grinding and chipping equipment and an entire industry developed in California for the sole purpose of producing in-forest biomass fuel.

The mobile in-forest biomass processing equipment industry initially got its start in the agricultural sector, beginning in the 1940s with the development of the tub grinder for

processing hay and alfalfa into animal feed. Many of these same early grinder manufacturers realized that if they increased the size and horsepower of the grinding equipment, they could process larger woody material. Today there are numerous manufacturers throughout the United States producing mobile wood grinding machines. However, the basic wood grinding design principles have remained much the same: high horsepower and lots of energy to force woody material through a sizing screen to reduce the size of material. The prominent names in California over the past 30 years have been Morbark, Peterson Pacific, Bandit, Rotochopper, Vermeer, and Diamond-Z.

Along with the advent of mobile wood grinding equipment, several manufacturers undertook development of large, whole tree chippers. In particular, Morbark is credited with designing one of the first portable whole tree chippers in the early 1970s. Morbark held significant whole tree chipper market share in California throughout the 1980s, selling one of the first whole tree chippers under a CEC grant in Lassen County in 1983.[13] In the early 1990s, Peterson Pacific entered the market and began to carve out market share from Morbark in both the whole tree chipper market and the horizontal grinder market.

After almost 30 years of operation, a number of these early California biomass power plants have been closed and with the passage of SB1122, a new generation of smaller biomass fired power plants are under development. As part of this development effort, the current status of forest biomass fuel processing equipment infrastructure was reviewed within California's primary forested regions. An important focus of this review was to assess the ability of this existing processing equipment to satisfy the fuel specifications for this new generation of community-scale biomass fired power plants.

Chipper/Grinder Technologies

Chippers and grinders are the two most common types of in-forest wood processing. Based on the fact that these new power plants will likely require a tighter fuel sizing specification than the previous generation of biomass power plants, it is critical to understand the capabilities and limitations of the existing biomass fuel production infrastructure.

Comminution or size reduction of woody biomass is the critical first step in the successful operation of a biomass fired power plant. Combustion or gasification will not be possible if the woody biomass cannot be properly fed into the system. Proper sizing of biomass fuel starts with an understanding of the specific woody biomass to be processed. In the case of forest derived fuel, different parts of the tree actually result in different chip or grinding composition. The choice of using a grinder or a chipper is highly dependent upon which part of the tree is being processed. In the case of bole wood, tops or logs, the desirable comminution method would be a chipper; for logging slash, a grinder would be more appropriate. For this reason, it is not unusual for many forest biomass fuel producers to have both types of machines.

[13] Monchamp Logging, Lookout, California.

Chippers

Wood chippers incorporate two primary mechanisms for wood comminution: discs and drums. As the names imply, these machines rely on a series of knives fixed to a rotating disc or drum, which cut across the grain of the log during chipping. By adjusting various settings, such as knife edge sharpness and angle, knife/anvil clearance, number of knives, in-feed rate and disc or drum speed, it is possible to produce larger or smaller chip sizes. Due to their reliance upon maintaining a sharp knife edge, chippers are not recommended for use with dirty or heavily contaminated feedstocks, which can quickly dull or damage chipper knives.

Large stationary disc chippers have been the primary wood comminution system used for decades in the pulp industry to produce clean pulp-grade chips. In the early 1970s, Morbark took this concept to the woods in the form of the mobile disc chipper, known as the Chiparvestor. Since that time, several other manufacturers have produced similar mobile disc chippers. These machines work well with clean, roundwood of similar size diameter and length and limited lateral branches.

Drum chippers, as the name implies, utilize a horizontally mounted drum with various knife mounting configurations. Smaller sized drum chippers have been the domain of the residential and commercial tree service industry for decades. Starting in the 1980s, Morbark began designing large horsepower drum type chippers. These machines worked well with varying diameter feedstocks containing limbs and tops and typically were manufactured with a wide in-feed table. This design allowed for easy feeding of material with varying lengths and diameters. These machines quickly found a home in California's agricultural orchard removal industry. However, as with the disc type chipper, drum chippers also rely on a sharp knife edge to produce a well-sized product.

Drum chippers and disc chippers typically produce a well-sized finished product and if given a choice, most biomass power plants prefer a chipped product. Chipped material tends to be more uniform in size, and there is something of a self-regulating aspect regarding dirt and contamination since most chipper operators tend to stay clear of dirty, contaminated feedstocks. In the forest environment, disc chippers were ideally suited for the processing of whole trees and logs while drum chippers were able to handle brush, tops, limbs, and clean logging slash.

Based on the results of this survey, it is obvious that drum type chippers now dominate the forest fuel processing infrastructure within most of California. However, it should also be noted that many of these machines are over 20 years old and some with Tier 1 engines will no longer be able to operate in California. In addition, several equipment manufacturers have begun to build a more versatile type of grinder that allows for an interchangeable rotor or modification of the rotor cutting bits and allows a grinder to essentially operate as a drum chipper. In recent years, these machines appear to be taking market share away from the traditional drum type chipper.

Grinders

Unlike chippers that depend on a cutting or shearing action using sharp knives, grinders utilize high speed and repetitive impacting of wood into smaller and smaller pieces through a combination of tensile, sheer and compressive forces. These machines typically use fixed or swinging hammers attached to a rotor or mill with specially designed bits or tips attached to the hammers. Sizing of the finished product is accomplished by a combination of the bit or tip design used and the size and shape of the screens. Additionally, there are upturn or up grind rotors and downturn or down grind rotors. In the case of upturn rotors, the wood is impacted several times in the rotation of the rotor before it actually contacts the anvil, where major compressing action takes place. Conversely with the downturn rotor, wood hits the anvil almost immediately. Morbark and Peterson both use the upturn rotor design while Bandit uses the downturn design. Some manufacturers claim that the upturn rotor produces fewer fines.

The grinder screen size and shape are important for determining the final sizing of the finished product. Most operators contacted during this survey indicated they typically used 3-inch and 4-inch hexagonal screens for producing biomass fuel to the specifications of the existing biomass power plants.

Key issues regarding the choice of comminution equipment are the type of feedstock that is to be processed and the end markets for the product produced. Since the inception of the biomass power industry in California in the early 1980s, the fuel size specification has been 3 inch minus with 99 percent under 6 inches and 15 percent less than ¼ inch. This is essentially the fuel specification that has been the norm for over 30 years. New power plant developers should keep this in mind when approaching existing biomass fuel processors with different product specifications.

Portable Chipper/Grinder Technologies Currently Deployed in California

In an effort to quantify the chipping and grinding equipment infrastructure in California's forest regions, a high-level survey of California forest biomass fuel processors within the CALVEG Zones was conducted. Table 44 provides a summary of the processing equipment and the CALVEG Zones where the equipment typically operates.

It should be noted that this report's focus was on the larger, industrial-sized whole-tree chippers (>400 horsepower) and did not include data for smaller hand fed chippers used by the residential or commercial tree service industry. Based on this survey of California forest fuel processors, there were equal numbers of chippers (19) and grinders (19). Table 45 provides a summary of the chipping equipment survey results.

Table 46 provides a summary of survey results for in-forest fuel grinding equipment.

Table 44: Summary Results of Forest Biomass Processing Equipment Survey

Operator #	CALVEG Zones	Equipment Mix
1	North Coast East	Morbark 30 (disc chipper)
	North Coast Mid	Peterson 5710 (horizontal track grinder)
	North Coast West	Peterson 7400 (horizontal grinder)
2	North Interior	Morbark 50/48 (drum chipper)
3	North Sierran	(3) Peterson 4710 (horizontal track grinder)
4	Great Basin	Peterson 4310 (track chipper)
	North Sierran	Morbark 30 (disc chipper)
		Morbark 20 (drum chipper)
5	South Sierran	Peterson 4310 (track chipper)
	North Sierran	Morbark 4600 (horizontal track grinder)
		Morbark 6600 (horizontal grinder)
		Peterson 4710 (horizontal track grinder)
6	North Interior	Morbark 30 (disc chipper)
	Great Basin	(2) Morbark 50/48 (drum chipper)
		Morbark 30/36 (drum chipper)
		Morbark 4600 (horizontal grinder)
		(2) Rotochopper B66 (horizontal grinder)
7	North Interior	Morbark 3800 (horizontal track grinder)
8	North Interior	Peterson 4300 (drum chipper)
9	North Interior	Morbark 4600 (horizontal track grinder)
10	South Sierran	(2) Morbark 60/36 (drum chipper)
11	South Sierran	Morbark 60/36 (track drum chipper)
		Morbark 22 (disc chipper)
12	North Sierran	Morbark 60/36 (drum chipper)
13	North Sierran	Bandit 2680XP (horizontal grinder)
14	South Sierran	Bandit 4680XP (track mounted grinder)
15	South Sierran	Bandit 1850 (disc chipper)
		Vermeer HG6000 (horizontal grinder)
16	South Sierran	Vermeer HG6000 (horizontal grinder)
17	South Sierran	Diamond-Z (horizontal grinder)
18	South Coast	Morbark 2036 (track mounted drum chipper)
		Bandit 2290 (drum chipper)
19	South Sierran	Morbark 2036 (track mounted drum chipper)

Source: West Biofuels, LLC

Morbark models represent almost 80 percent of the whole tree chippers surveyed. It should be noted that the Morbark Model 60/36 are older machines with Tier 1 engines. These machines will need to be upgraded to Tier III or Tier IV in order to continue to operate in California (and meet California Air Resources Board air emissions standards). It is uncertain if any of these operators will make this upgrade. However, for purposes of this review, it is assumed that these machines are still part of the existing forest biomass processing infrastructure. Further analysis of this chipper data shows that almost 75 percent are drum type chippers with the remaining 25 percent that are disc type. Towed rubber tired machines are most prevalent at about 80 percent with track mounted units making up only 20 percent. More recently purchased

machines appear to be moving toward track undercarriages for added mobility and other regulatory considerations.[14]

Table 45: Summary Results of Forest Biomass Chipping Equipment Survey

Make/Model	Number of Units	Percentage
Morbark		
- 60/36 drum chipper	4	
- 50/48 drum chipper	3	
- 30/36 drum chipper	1	
- 20/36 drum chipper	2	
- Model 30 disc chipper	3	
- Model 22 disc chipper	1	
- Model 20 drum chipper	1	
Subtotal	**15**	**79%**
Peterson		
- 4310 drum chipper	2	
- 4300 drum chipper	1	
Subtotal	**3**	**16%**
Bandit		
- 1859 disc chipper	1	
Subtotal	**1**	**5%**
TOTAL	**19**	**100%**

Source: West Biofuels, LLC

Table 46: Summary Results of Forest Biomass Grinding Equipment Survey

Make/Model	Number of Units	Percentage %
Morbark		
- 4600 horizontal grinder	4	
- 6600 horizontal grinder	1	
- 3800 horizontal grinder	1	
Subtotal	**6**	**32%**
Peterson		
- 4610 horizontal grinder	4	
- 5710 horizontal grinder	1	
- 7400 horizontal grinder	1	
Subtotal	**6**	**32%**
Bandit		
- 4680XP horizontal grinder	1	
- 2680XP horizontal grinder	1	
Subtotal	**2**	**10%**
Vermeer		
- HG6000 horizontal	2	
Subtotal	**2**	**10%**
Rotochopper		
- B66 horizontal grinder	2	
Subtotal	**2**	**10%**
TOTAL	**19**	**100%**

Source: West Biofuels, LLC

[14] Part of the popularity of track mounted machines may be that Tier IV engine upgrades are not required on self-propelled machines until 2018.

Morbark and Peterson manufactured machines make up almost two-thirds of the grinders in the survey. However, Bandit, Vermeer, and Rotochopper represent newer machines purchased within the past year or so. All of the grinders have horizontal in-feed systems. Of these grinders, track mounted units and rubber tired towed units are almost equally represented with track machines making up 47 percent of the grinders.

The researchers surmise that the nineteen operators represented by this survey work in eight of the California Vegetation Zones (CALVEG Zones) with the greatest number of operators located in the South Sierran and North Interior Zones. This is not surprising, as these Zones have been home to several biomass-fired power plants that historically used forest derived fuel.

As a result of this survey, the researchers concluded that four machine types were representative of the forest fuel processing infrastructure within these CALVEG Zones. These machines include the Morbark drum type chippers in the 800 to 1,050 horsepower (HP) range, the Morbark horizontal grinders in the 800 to 1,050 HP range, the Peterson horizontal grinders in the 765 to 1,050 HP range, and the Bandit Beast XP series grinders in the 500 to 1,050 HP range.

Top Four Technologies Deployed in California

Morbark Drum Chippers

Morbark currently makes 3 drum chipper models, 30/36, 40/36 and the 50/48. The 50/48 was the most commonly encountered drum chipper during the survey. Although there were more 60/36 chippers around, many of these are over 20 years old and their engines will not meet current California air emission standards.

The machine is available with an optional forestry grate system, which is designed to slide into the discharge chute just after the chipper drum. This grate slices oversized chips and reduces the number of overs in the finished product. The project team did not identify any contractors that use the forestry grate system during this survey.

Observations

- Ability to Process Various Feedstocks: The 50/48 will accommodate a 27” diameter log and with the wide in-feed table, it can handle tops, limbs and brush.
- Optimized Screen and Knife/Hammer Configurations: The standard 10 knife chipper drum can be replaced with a 16 or 20 knife drum for producing ¼-inch to 3/8-inch size microchips for use by wood pellet plants. The project team is not aware of any contractors that operate a microchip machine in California.
- Equipment Size and Transportability: The 50/48B is 40’9” in length and has a gross weight of 68,000 lbs.

Morbark Horizontal Grinders

Morbark currently makes 6 horizontal grinder models; the most common unit encountered during the survey was the model 4600. The 4600 comes with a 1,050 HP diesel engine and uses pinned free swinging hammers. The most common grate or screen size encountered during the

survey was the 3-inch and 4-inch hexagonal. Morbark also sells a louvered or baffled screen, which blocks oversized material from exiting the grinding area until they are broken up. This helps to limit the amount of oversized wood in the finished product. Morbark sells its own line of inserts or tips, but there are numerous other manufacturers as well. These inserts or tips come in dozens of different designs. The most common appears to be the carbide tip, although a sharper knife edge tip is sometimes recommended for forestry residues. Obviously, the knife edge tips are susceptible to damage from rock, dirt and other contaminants.

Observations

- Ability to Process Various Feedstocks: The in-feed is 60-inches x 46-inches wide and is well suited for handling tops, limbs, brush and logging slash.
- Optimized Screen and Knife/Hammer Configurations: All Morbark horizontal grinders are available with the optional Quick Switch Grinder-to-Chipper conversion kit. This system allows the user to convert the grinder to a chipper in less than half a day. The project team did not encounter any contractors using this system in California.
- Equipment Size and Transportability: The towable rubber tired unit is 42-feet long with a gross weight of 75,660 lbs and will require an overweight permit from Cal Trans.

Peterson Horizontal Grinders

Peterson currently offers 11 mobile horizontal grinder models, and the most common unit encountered during the survey was the 4710D. This track mounted grinder has a 755 HP diesel engine. The machine comes standard with a drum rotor and 22 drum rotor bits. Peterson sells its own line of bits or inserts but there are numerous other manufacturers as well. Various bit designs can be used to create different sized finished product. Peterson also makes both a baffled grate and an anvil breaker grate. Both mechanisms are designed to help retain and break up oversized wood in the grinding chamber. Like the Morbark design, the Peterson uses an upturning or up cutting rotor. Some manufactures claim this design helps reduce fines.

Observations

- Ability to Process Various Feedstocks: The in-feed is 60-inches wide by 38-inches high and is well suited for handling tops, limbs, brush and logging slash.
- Optimized Screen and Knife/Hammer Configurations: Peterson uses four separate screen or grate segments, which allows the operator to mix and match screen opening sizes for the preferred end product. Generally smaller screen openings are located in the first and second segments for sizing, followed by progressively larger opening grates further back as material moves out of the grinding chamber.
- Equipment Size and Transportability: This track mounted unit is 44-feet 11-inches long with a gross weight of 79,000 lbs and will require an overweight permit from Cal Trans.

Bandit Horizontal Grinders

Bandit manufactures four models of horizontal grinders. The survey found two Bandit machines (the 2680XP and the 4680XP) deployed in California. Bandit grinders come standard with a cuttermill with teeth, versus the typical hammers found in most grinders. The cuttermill

contains 60 teeth and can accommodate several types of Bandit tooth designs. Bandit uses a downturning or down cutting mill versus the upturning or up cutting rotors used in Morbark and Peterson grinders. Some in the industry believe the upturning rotor or mill design produces fewer fines, but no specific data to quantify this claim was found.

Bandit also makes a dedicated chipping drum available with 8 knife pockets or 20 knife pockets. This interchangeable drum allows the grinder to operate essentially like a drum chipper. Like Morbark and Peterson, it is also possible to install baffled or louvered grates which help to break up oversized material and provide a more consistent sized product.

Observations

- Ability to Process Various Feedstocks: The 2680XP has an in-feed of 60-inches wide by 35-inches high and is well suited for handling tops, limbs, brush and logging slash.
- Optimized Screen and Knife/Hammer Configurations: As with all grinder manufacturers, Bandit makes numerous tooth designs that mount into the cutter-bodies. The various teeth designs combined with various sized grates or screens enable operators to carefully adjust the sizing of the finished product. In addition to these standard teeth designs, Bandit also makes a chipper knife that can be bolted into the cutter-bodies and provide more of a cutting or slicing action for producing a chip-like finished product.
- Equipment Size and Transportability: The towable unit is 38-feet 4-inches long and has a gross weight of 49,000 lbs.

Investment Analysis

Owning and operating cost analysis for heavy equipment can be a challenge, as there are numerous variables that can impact these values. Within the forest products industry and particularly timber harvest operations, the challenges are even greater. The often isolated and varying terrain and the limited or restricted operating season makes it difficult to estimate actual machine hourly operating costs. In addition, estimating the scheduled versus productive machine hours in this operating environment can be difficult. As such, these cost breakdowns and cost per unit results should be considered estimates only and actual costs will vary.

The choice of a particular piece of comminution equipment for producing forest-derived biomass fuel is based on several variables. Perhaps first and foremost is the actual fuel specification of the purchaser. In the case of the operators surveyed during this review, it was apparent that their comminution equipment selection was based on the long-standing fuel specification of the existing biomass power plants in California. As previously discussed, the 3-inch minus with 99 percent below 6-inches specification has been around for more than 30 years and seems to have resulted in the most common screen or grate openings of 3 to 4 inches and the most common hammer bits or tips being the carbide welded tip without a sharp or cutting edge. There are ways to help reduce the occurrence of oversized spears in these existing grinders. The use of baffled or louvered grates or anvil breaker grates can help; however, the project team is not aware of operators currently using such systems. Perhaps as the development of these smaller SB1122 power projects progress, it would be appropriate to investigate these options. Similarly, for the drum chippers, these machines are generally

considered to produce a premium quality fuel, but if knives are not maintained, the problem of excessive overs or spears can result. In such a case, the slide-in forest grates or screens may be appropriate to remedy this issue. The project team is not, however, aware of any chipper operators currently using this forest grate option.

In addition to the end market product specification, another key consideration regarding the selection of comminution equipment is the specific feedstock to be processed. Generally speaking, chippers are much more efficient at processing clean woody material such as logs and trees of similar dimension. Feed rates for whole-tree chippers can be around 120 feet per minute, whereas grinders can be 25 to 30 feet per minute. It also takes more horsepower to grind wood versus chipping, and the initial price of a chipper is much less. Grinders are generally more expensive because they have to be built heavier to withstand the forces necessary to crush the wood rather than cut it. However, grinders are extremely flexible. With the combination of hammer inserts or tips or in some cases cutter teeth and the varying screen or grate sizes and configurations, it is possible to come up with an almost unlimited array of possible combinations to achieve a particular finished product.

Recent studies related to feedstock type and grinder bit and screen configurations have revealed some insightful information regarding finished product sizing, bulk density and grinder fuel consumption.[15] These studies evaluated grinder performance on three different forest derived feedstocks: branches-and-tops size class (average diameter 4 inches, average length 3 feet); pulpwood logs (diameter range 4 inches to 12 inches, lengths 4 feet to 6 feet); and butt-log-chunks size classes (diameter >12 inches, length 20 inches). By varying screen sizes (small 2-inch to 3-inch, medium 3-inch to 4-inch, large 4-inch to 5-inch) and bits (carbide hammer and knife-edge) along with the feedstock, this research found that in general it is better to process material in the woods using mobile grinding equipment at as high of machine utilization rate as is feasible. In other words, using larger grinder screens producing some oversized product, and then screening the oversized out using re-sizing equipment at a centralized facility. A key conclusion of these studies is that it appears to be most economical for feedstock purchasers to buy larger sized product, reducing in-forest production costs significantly and lowering the costs associated with producing fines. Researchers concluded that oversized product in the range of 10 to 15 percent can be re-sized at very low costs in fixed, electrically-powered hammer hogs.[16]

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[15] Zamora-Cristales, R., Sessions, J., Smith, D., Marrs, G. Effect of grinder configuration on forest biomass bulk density, particle size distribution and fuel consumption. Biomass and Bioenergy 81 (2015) 44-54.

[16] Marrs, G., Mulderig, B., Davio, D., Burt, M. Feedstock Logistics – Sourcing Final Report. Northwest Advanced Renewables Alliance 2013.

Morbark Drum Chipper Model 40/36

Figure 23: Morbark 40/36 Drum Chipper

Source: West Biofuels, LLC

Capital Costs and Cost of Ownership

Table 47 provides a detailed breakdown of the ownership costs for a Morbark Model 40/36 drum chipper.

Table 47: Ownership Costs for Morbark 40/36 Drum Chipper[17]

Expense Item	Cost Estimate	Time Duration	Unit Cost/SMH ($/Hour)
Purchase Price	$689,540	5 years @ 1,500 hours /year 7,500 hours	
Residual Value	$172,385		
Depreciated Value	$517,155	7,500 hours 5 years @ 1,500/year	$68.95
Interest Expense	$110,304 (6.00% per year declining balance)	7,500 hours	$14.71
Insurance	$17,239 (2.5% of replacement value per year)	1,500 hours	$11.49
Total Ownership Costs			**$95.15**

Source: West Biofuels, LLC

Based on this analysis, the total ownership and operation cost of the Morbark 40/36 drum chipper are estimate to be $231 per scheduled machine hour.[18] However, for in-forest chippers and grinders, a 50 percent utilization rate is not uncommon.[19] Assuming a 50 percent

[17] Cost estimates have been updated from information provided by Morbark dated 6/1/2012.

[18] Scheduled Machine Hour = the number of hours a machine is available for production.

[19] Thompson, J. and Spinkle, W., Production, Cost and Chip Characteristics of In-Woods Microchipping. 2013 Council on Forest Engineering Annual Meeting.

utilization rate results in an owning and operating cost of $462 for productive machine hour. Production rates of over 70 green tons (GT) per productive machine hour have been reported for this machine. Assuming 70 GT per productive machine hour, this equates to approximately $6.60 per GT of material processed.

Operation and Maintenance Costs

Table 48 provides a detailed breakdown of the operation, maintenance and total costs to operate a Morbark Model 40/36 drum chipper.

Table 48: Operation and Maintenance and Total Costs for Morbark 40/36 Drum Chipper[20]

Expense Item	Cost Estimate	Duration (Hours)	Unit Cost/SMH ($/Hour)
Knives	$920, (8) knives @ $115	100	$9.20
Knife Sharpening	$110, (8) knives @ $13.75	8	$13.75
Knife Clamps	$2,480, (8) clamps @ $310	2,000	$1.24
Knife Holders	$3,960, (8) knife holders @ $496 each	2,000	$1.98
Counter Knives	$640, (8) counter knives @ $80 each	500	$1.28
Counter Knife Sharpening	$110, (8) knives @ $13.75	60	$1.83
Anvils	$800, (1) Anvil @ $800	700	$1.14
Labor	$46.00, (1) hour @ $46/hr	8	$5.75
Grease	$5.50, (1) tube @ $5.50	8	$0.69
Engine Maintenance			
(2) hydraulic filters @ $78.55	$157.10	250	$0.62
(1) air filter @ $115	$115	250	$0.46
(1) air filter @ $78	$78	250	$0.31
(2) oil filters @ $22	$44	250	$0.17
(1) fuel filter @ $32	$32	250	$0.13
Misc. Parts			$2.30
Total Maintenance Costs			$40.85
Fuel	$55, 765-HP engine @ 22 gals/hr. and $2.50/gal	1	$55.00
Operator	$40.00	1	$40.00
Total Operating and Maintenance Costs			**$135.85**
Total Ownership Costs			**$95.15**
TOTAL COSTS			**$231.00**

Source: West Biofuels, LLC

[20] Ibid.

Labor Requirements/Costs

The chipper operator typically feeds the grinder with a hydraulic excavator or front-end loader. Many of the newer chippers are equipped with remote control to allow a single operator to handle the grinding operation. Obviously labor costs and overhead will vary for each operation. This example assumes a labor rate of $40 per hour.

Production

Numerous factors will impact machine production rates including the size and type of material being processed. Based on discussions with operators as well as vendor literature, 70 GT per hour is used as a reasonable production rate per productive machine hour.

Total Costs

Based on this analysis, a total cost per schedule machine hour is $231 per hour. Assuming a machine utilization rate of 50 percent results in a total cost per productive machine hour of $462 per hour.

Morbark Horizontal Grinder Model 4600

Figure 24: Morbark 4600 Grinder

Source: West Biofuels, LLC

Capital Costs and Cost of Ownership

Table 49 provides a detailed breakdown of ownership costs for a Morbark 4600 horizontal grinder. Based on this analysis, the total ownership and operation cost of the Morbark 4600 track mounted horizontal grinder is $307.19 per scheduled machine hour. However, for in-

forest chippers and grinders, a 50 percent utilization rate is not uncommon.[21] Assuming a 50 percent utilization rate results in an owning and operating cost of $614.38 for productive machine hour. Production rates of 72 GT per productive machine hour using a 3-inch grate have been reported for this machine. Assuming 72 GT per productive machine hour, this equates to approximately $8.53 per GT of material processed.

Table 49: Ownership Costs for Morbark 4600 Horizontal Grinder

Expense Item	Cost Estimate	Time Duration	Unit Cost/SMH ($/Hour)
Purchase Price	$927,154		
Residual Value	$231,789		
Depreciated Value	$695,365	7,500 hours 5 years @ 1,500 hours /year	$92.72
Interest Expense	$148,315 (6.00% per year declining balance)	7,500 hours	$19.78
Insurance	$23,179 (2.5% of replacement value per year)	1,500 hours	$15.45
Total Ownership Costs			**$127.95**

Source: West Biofuels, LLC

Operation and Maintenance Costs

Table 50 provides a detailed breakdown of operation, maintenance and total costs to operate a Morbark 4600 horizontal grinder.

Table 50: Operation and Maintenance and Total Costs for Morbark 4600 Horizontal Grinder

Expense Item	Cost Estimate	Time Duration (Hours)	Unit Cost/SMH ($/Hour)
Inserts, Bolts & Nuts			
(18) Inserts @ $22.91 each	$412	80	$5.15
(36) Insert bolts @ $2.40 each	$86.40	80	$1.08
(36) Insert nuts @ $1.00 each	$36	80	$0.45
Grates	$2,540 (3) grates @ $846.65 each	900	$2.82
Hammers	$5,486.40 (18) hammers @ $304.80 each	2,000	$2.74
Rakers	$3,888 (18) rakers @ $216 each	3,000	$1.30

[21] Thompson, J. and Spinkle, W., Production, Cost and Chip Characteristics of In-Woods Microchipping. 2013 Council on Forest Engineering Annual Meeting.

Expense Item	Cost Estimate	Time Duration (Hours)	Unit Cost/SMH ($/Hour)
Raker Resurfacing	$196 (18) rakers resurfaced @ $10.90 each	500	$0.39
Rods	$1671.45 (8) hammer rods @ $208.93 each	2,000	$0.84
Anvils	$612 (1) Anvil @ $612 ea	1,000	$0.61
Undercarriage	Terrain Conditions Determine Life Est. $8,175 for parts	8,750	$0.93
Labor	$46.00 (1) hour @ $46/hr	8	$5.75
Grease	$5.50 (1) tube @ $5.50/tube	8	$0.69
Engine Maintenance			
(2) hydraulic filters @ $78.55 ea.	$157.10	250	$0.62
(1) air filter @ $115	$115	250	$0.46
(1) air filter @ $78	$78	250	$0.31
(2) oil filters @ $22	$44	250	$0.17
(1) fuel filter @ $32	$32	250	$0.13
Misc. Parts			$2.30
Total Maintenance Costs			$26.74
Operations			
Fuel	$112.50 1,050-HP engine @ 45 gals/hr. and $2.50/gal	1	$112.50
Operator	$40.00	1	$40.00
Total Operating and Maintenance Costs			**$179.24**
Total Ownership Costs			**$127.95**
TOTAL COSTS			**$307.19**

Source: West Biofuels, LLC

Labor Requirements/Costs

The grinder operator typically feeds the grinder with a hydraulic excavator or front-end loader. Many of the newer grinders are equipped with remote control to allow a single operator to handle the grinding operation. Obviously labor costs and overhead will vary for each operation. For this example, a labor rate of $40 per hour is assumed.

Production

Numerous factors will impact machine production rates including the size and type of material being processed. Based on discussions with operators as well as vendor literature, 72 GT per hour is used as a reasonable production rate per productive machine hour.

Total Costs

Based on this analysis, the total cost per schedule machine hour is $307.19 per hour. Assuming a machine utilization rate of 50 percent results in a total cost per productive machine hour of $614.38 per hour.

Peterson Horizontal Grinder Model 4710

Figure 25: Peterson 4710 Grinder

Source: West Biofuels, LLC

Capital Costs and Cost of Ownership

Table 51 provides a detailed breakdown of ownership costs for a Peterson Model 4710 horizontal grinder. Based on this analysis, the total ownership and operation cost of the Peterson 4710 grinder is $240.36 per scheduled machine hour. However, for in-forest chippers and grinders, a 50 percent utilization rate is not uncommon.[22] Assuming a 50 percent utilization rate results in an owning and operating cost of $480.72 per productive machine hour.[23] Production rates of 65 GT per productive machine hour processing solid wood have

[22] Thompson, J. and Spinkle, W., Production, Cost and Chip Characteristics of In-Woods Microchipping. 2013 Council on Forest Engineering Annual Meeting.

[23] Productive machine hours = that portion of scheduled machine hours during which a machine performs its designated functions, excluding time to transport the machine and operational or mechanical delays.

been reported for this machine. Assuming 65 GT per productive machine hour, this equates to approximately $7.40 per GT of material processed.

Table 51: Ownership Costs for Peterson 4710 Horizontal Grinder

Expense Item	Cost Estimate	Time Duration	Unit Cost/SMH ($/Hour)
Purchase Price	$681,250		
Residual Value	$170,313		
Depreciated Value	$510,937	7,500 hours 5 years @ 1,500 hours/year	$68.12
Interest Expense	$108,978 (6.00% per year declining balance)	7,500 hours	$14.53
Insurance	$17,031 (2.5% of replacement value per year)	1,500 hours	$11.35
Total Ownership Costs			**$94.00**

Source: West Biofuels, LLC

Operation and Maintenance Costs

Table 52 provides a detailed breakdown of operation, maintenance and total costs for a Peterson Model 4710 horizontal grinder.

Table 52: Operation and Maintenance and Total Costs for Peterson 4710 Horizontal Grinder

Expense Item	Cost Estimate	Time Duration (Hours)	Unit Cost/SMH ($/Hour)
Bits - Standard	$490.38 (22) Standard Bits @ $22.29 each	90	$5.45
Grates	$6,291.50 (4) grates @ $1,572.87 each	954	$6.59
Hammers – Pinned Rotor	$13,976 (22) hammers @ $635.28 each	5,375	$2.60
Rotor Wear Liner Set - Standard	$2,909.45 (1) set @ $2,909.45 each	2,125	$1.37
Compression Roll Wear Liner	$699 (1) liner @ $699 each	2,500	$0.27
Rotor Bearings	$3,807.26 (2) rotor bearings @ $1903.63 each	5,055	$0.75
Discharge Conveyor Belt - Standard	$5,629.85 (1) belt @ $5,629.85	6,704	$0.83
Main Drive Belt Set	$2,284.64	2,849	$0.80

Expense Item	Cost Estimate	Time Duration (Hours)	Unit Cost/SMH ($/Hour)
	(1) belt set @ $2,284.64 each		
In-feed Chain	$4,017 (4) chains @ $1,004 each	4,863	$0.82
Life time maintenance labor	$7.36 $46/hr @ 16%	-	$7.36
Grease		-	$1.57
Engine Maintenance			$8.90
Misc. Parts			$3.30
Total Maintenance Costs			$40.61
Fuel	$65.75 765-HP engine @ 26.3 gals/hr. and $2.50/gal	1	$65.75
Operator	$40.00	1	$40.00
Total Operating and Maintenance Costs			**$146.36**
Total Ownership Costs			**$94.00**
TOTAL COSTS			**$240.36**

Source: West Biofuels, LLC

Labor Requirements/Costs

The grinder operator typically feeds the grinder with a hydraulic excavator or front-end loader. Many of the newer grinders are equipped with remote control to allow a single operator to handle the grinding operation. Obviously labor costs and overhead will vary for each operation. For this example, a labor rate of $40 per hour is assumed.

Production

Numerous factors will impact machine production rates including the size and type of material being processed. Based on discussions with operators as well as vendor literature, 65 GT per hour is used as a reasonable production rate per productive machine hour.

Total Costs

Based on this analysis, the total cost per schedule machine hour is $240.36 per hour. Assuming a machine utilization rate of 50 percent results in a total cost per productive machine hour of $480.72 per hour.

Bandit Horizontal Grinder Model 3680XP

Figure 26: Bandit 3680XP Grinder

Source: West Biofuels, LLC

Capital Costs and Cost of Ownership

Table 53 provides a detailed breakdown of ownership costs for a Bandit Model 3680XP horizontal grinder. Based on this analysis, the total ownership and operation cost of the Bandit 3680 horizontal grinder is $197.06 per scheduled machine hour. However, for in-forest chippers and grinders, a 50 percent utilization rate is not uncommon.[24] Assuming a 50 percent utilization rate results in an owning and operating cost of $394.12 for productive machine hour.[25] Production rates of 45 to 60 GT per productive machine hour processing roundwood have been reported for this machine. 53 GT per productive machine hour is assumed, equating to approximately $7.44 per GT of material processed.

[24] Thompson, J. and Spinkle, W., Production, Cost and Chip Characteristics of In-Woods Microchipping. 2013 Council on Forest Engineering Annual Meeting.

[25] Productive machine hours = that portion of scheduled machine hours during which a machine performs its designated functions, excluding time to transport the machine and operational or mechanical delays.

Table 53: Ownership Costs for Bandit 3680XP Horizontal Grinder

Expense Item	Cost Estimate	Time Duration	Unit Cost/SMH ($/Hour)
Purchase Price	$550,000		
Residual Value	$137,500		
Depreciated Value	$412,500	7,500 hours 5 years @ 1,500 hours/year	$55.00
Interest Expense	$87,982 (6.0% per year declining balance)	7,500 hours	$11.73
Insurance	$13,750 (2.5% of replacement value per year)	1,500 hours	$9.17
Total Ownership Costs			**$75.90**

Source: West Biofuels, LLC

Operation and Maintenance Costs

Table 54 below provides a detailed breakdown of operation, maintenance and total costs for a Bandit Model 3680XP horizontal grinder.

Table 54: Operation and Maintenance and Total Costs for Bandit Model 3680XP Horizontal Grinder

Expense Item	Cost Estimate	Time Duration (Hours)	Unit Cost/SMH ($/Hour)
Cutterbodies (60) @ $80.00 each	$4,800.00	1,250	$3.84
Cutterbody Hardware (120) @ $30.00 each	$3,600.00	2,000	$1.80
Teeth (60) @ $20.00 each	$1,200.00	125	$9.60
Teeth Hardware (60) @ $1.00 each	$60.00	250	$0.24
Raker/Raker Bolt (60) @ $17.75 each	$1,065.00	150	$7.10
Screens (1) @ $1,500 each	$1,500.00	1,500	$1.00
Gates (1) @ $1,300 each	$1,300.00	1,500	$0.87
Engine Maintenance			
Hydraulic Filter	$315.00	400	$0.79
Primary Air Filter (2) @ $60.00 each	$120.00	250	$0.48
Secondary Air Filter (2) @ $35.00 each	$70.00	250	$0.28
Oil Filter (2) @ 19.00 each	$38.00	500	$0.08
Fuel Filter	$38.00	500	$0.08
Total Maintenance Costs			$26.16

Expense Item	Cost Estimate	Time Duration (Hours)	Unit Cost/SMH ($/Hour)
Fuel	$55 765-HP engine @ 22 gals/hr. and $2.50/gal		$55.00
Operator	$40.00		$40.00
Total Operating and Maintenance Costs			**$121.16**
Total Ownership Costs			**$75.90**
TOTAL COSTS			**$197.06**

Source: West Biofuels, LLC

Labor Requirements/Costs

The grinder operator typically feeds the grinder with a hydraulic excavator or front-end loader. Many of the newer grinders are equipped with remote control to allow a single operator to handle the grinding operation. Obviously labor costs and overhead will vary for each operation. For this example, a labor rate of $40 per hour is used.

Production

Numerous factors will impact machine production rates including the size and type of material being processed. Based on discussions with operators as well as manufacturer's literature, 53 GT per hour is used as a reasonable production rate per productive machine hour.

Total Costs

Based on this analysis, the total cost per schedule machine hour is $197.06 per hour. Assuming a machine utilization rate of 50 percent results in a total cost per productive machine hour of $394.12 per hour.

Investment Analysis Summary

Table 55 provides a summary of the hourly rates and cost per GT for these four machines.

Table 55: Summary of Hourly Rates and Cost Per Ton for Top Four Technologies

Make	Morbark	Morbark	Peterson	Bandit
Model	40/36 Chipper	4600 Grinder	4710 Grinder	3680 Grinder
Hourly Rate SMH	$231.00	$307.19	$240.36	$197.06
Hourly Rate PMH	$462.00	$614.38	$480.72	$394.12
Estimate Production (GT/PMH)	70 GT	72 GT	65 GT	53 GT
Cost/GT	$6.60/GT	$8.53/GT	$7.40/GT	$7.44/GT

Source: West Biofuels, LLC

While cost per GT is an important consideration in any machine operation, it is equally important to understand the particular strengths and weaknesses of the machine. As discussed

earlier, the type of feedstock that will be processed is critical in this selection process. For example, while the Morbark chipper appears to have the lowest cost per GT, it also has the least flexibility to handle a wide variety of feedstocks.

Transportation Systems

A major drawback with woody biomass is the low energy density of the material. This property becomes critical when considering transportation options for hauling this fuel from the forest to the power plant. One of the redeeming aspects of the SB1122 small scale biomass projects is their decentralized distribution throughout the forested regions of California and their smaller fuel demand. Previously, the smallest stand-alone wood fired power plants in the state were the 10 MW units developed by Ultrapower in the mid 1980s. However, even these units required almost 100,000 BDT of fuel annually and were required to reach out considerable distance to procure sufficient fuel. Although the 3 MW and smaller SB1122 projects will not require nearly as much fuel as commercial-scale biomass power plants, they will nonetheless need to utilize currently available trucking transportation infrastructure.

There are essentially three main transport methods commonly used by the existing biomass power industry in California. These include the traditional open top possum-belly chip trailers commonly used for hauling sawmill residuals and pulp-grade chips, open-top walking floor or live floor trailers used for hauling bulk commodities (such as wood and agricultural products), and converted closed-top dry cargo vans. Each of these systems for transporting biomass fuel have pros and cons. However, perhaps most problematic for all three systems is the limited accessibility of much of the low-standard roads where much of the forest-derived fuels are generated.

Due to the often steep and rugged terrain of the Sierra Nevada forests, early logging roads were not built with biomass chipping or grinding in mind. Conventional logging trucks with their hinge point in the center of the trailer have a much tighter turning radius than a rigid 45-foot open top chip trailer. As such, many of the existing mountain roads within the forests of California are inaccessible to the possum-belly chip vans and walking floor trailers commonly used on flatter, straighter roadways. For this reason, it has been fairly common for chipping and grinding contractors to purchase shorter length used closed-top dry cargo vans and modify them to haul biomass fuel out of the woods.

Walking Floor Systems

The floor of these trailers is constructed of interlocking slats that slide forward and backward under the load and as the name implies, essentially they walk the load out the back of the trailer. The advantage of these trailers is that they do not need a truck dump or tipper in order to unload cargo. They can also be loaded from the back with a chipper or over the top using a grinder or front-end loader. The drawback is these trailers are expensive and they tend to be 45-feet or longer in length and not suitable for many logging roads. They usually come in 110 to 125 cubic yard capacities and typically with most moderate moisture fuels, it is possible to haul up 25 GT of material. Figure 27 is an image of a walking floor trailer with tractor.

Figure 27: Walking Floor Trailer

Source: West Biofuels, LLC

Conventional Chip Trailers

Chip trailers are either standard box trailer or a possum belly design. These trailers come in a variety of lengths, but 42 and 45-foot are common. These trailers are open top, which allows for conveying material directly from a grinder. In addition, it is common to have a hatch in the rear door of the trailer, which allows for blowing chips in from a chipper. The possum belly design, as the name implies, has extra hauling capacity built into the trailer and allows the operator to haul more volume with the same length of trailer. For in-forest chipping and grinding operations, the possum belly can be problematic due to low ground clearance. At around 14 inches clearance, this can be a problem on many low-standard logging roads. Figure 28 is an image of a possum belly trailer.

Figure 28: Possum Belly Trailer

Source: West Biofuels, LLC

Converted Dry Vans

In an effort to reduce cost and provide for shorter trailer lengths, many chipping operators purchased used dry cargo vans and converted them to haul chips. By cutting a hatch in the rear door of the van, operators were able to blow chips into the van. These vans had closed tops and generally are only suitable for use with chippers. However, there are chip flingers that attach to the out-feed of grinder conveyors and allow a grinder to essentially blow grindings into the rear of a trailer. Figure 29 is an image of a dry van trailer.

Figure 29: Dry Van Trailer

Source: West Biofuels, LLC

Best Management Practices for Processing Systems

Feedstock Preparation

Minimize Dirt and Non-Combustibles

The type of comminution equipment available will dictate the best management practices for processing forest-derived feedstocks. However, maintaining a clean feedstock with minimal dirt is important regardless of the equipment used. In the case of limbs and tops from conventional logging or thinning operations, this material is usually fairly easy to keep clean, especially with the common use of delimbers in the landing. This material is usually stacked at the landing and has minimal contact with the ground. Larger log chunks and cull material is sometimes pushed up and piled using a dozer. This can result in dirt and rock contamination of the logging debris. In these cases, the use of a hydraulic excavator to break down these piles is preferred. The excavator can be used to separate out dirt and debris.

Maximize Drying

Green freshly harvested wood often has a moisture content of 50 percent or more. During California's hot summer months, it is possible to lower moistures to 40 to 45 percent in a matter of days. Lower moistures can be obtained but it is not always possible to allow material to sit for weeks. From the standpoint of chipping, green wood requires less energy to chip than drier wood.

Maintain Processing Equipment

All chipping and grinding equipment manufacturers provide detailed information on the maintenance and upkeep of their machines. In the case of chippers, it is critical to maintain the knives and the anvil clearance for optimum chip sizing and production.

Findings

There is adequate fuel processing infrastructure existing throughout most of the northern Sierra Nevada forests of California. The southern portion of the state is somewhat limited, but that appears to be changing. Over the past two years, significant tree mortality has occurred within the forests of the southern Sierras. As a result, several wood collection yards have been established in the region and wood grinding equipment is currently operating in these yards. This tree mortality situation should continue to add grinding and/or chipping capacity in the southern Sierra Nevada over the next few years. Further south in the San Bernardino and San Jacinto mountains of southern California, there is very limited in-forest fuel processing infrastructure.

Most of the wood fuel processors surveyed during the course of this assessment expressed an interest in additional biomass fuel markets. However, some adjustments to current comminution equipment operating parameters may be in order to meet the new SB1122 small-scale biomass plant sizing specifications. Fortunately, most of the equipment manufacturers have systems that can be retrofitted into existing machines to help reduce oversized material. The forestry screen or grate system on drum type chippers, the louvered or baffled screen or grate on grinders, and the interchangeable chipper rotors all have the potential of helping to accommodate the fuel specifications for these small-scale biomass systems.

Feedstock Properties

Sample Collection

Soper Company supplied nine feedstock types that were evaluated by West Biofuels and the project team. Soper delivered the first four by the truckload while the last five in 42-gallon contractor bags. Figure 30 shows an image of a walking floor truck delivery of one of Soper Company's feedstock samples.

Figure 30: Walking Floor Truck Delivery

Source: West Biofuels, LLC

Feedstock Source

The Soper Company is a family-owned sustainable forestry enterprise founded in 1904 and currently manages over 97,000 acres in Northern California with extensive holdings in the North Sierran region. Soper Company delivered several truckloads of forest biomass for the project in 2015 and 2016. Soper Company provided West Biofuels with processed woody biomass from recent harvesting and thinning activities at four sites representing four different California forest cover classes. The four forest land cover classes and their sites are listed below (Table 56), along with their GPS coordinates, approximate elevation and general topography. Figure 31 displays a map of their locations.

SW supplied the following information about management of the four forest sites.

- Montane Hardwood & Montane Hardwood-Conifer - This site produced feedstock materials from two management units. One unit was an even-aged regeneration harvest, and the other was a thinning operation in a 35-year-old plantation that had a large component of Tan Oak (a hardwood). Yield per acre was not given by Soper Company.
- Sierran Mixed Conifer - This site produced feedstock materials from an even-aged regeneration harvest. Yield per acre was not given by Soper Company.

- Red Fir - This site produced feedstock materials from a selective harvest in an uneven-aged stand. Sawlog harvest Yield is estimated by SW to be approximately 5,000 board feet per acre. Yield per acre was not given by Soper Company.
- Ponderosa Pine - This site produced feedstock materials from two management units. One unit was an even-aged regeneration harvest and the other was a thinning operation in a 35-year-old plantation. Sawlog harvest was 25,000 board feet per acre, and the thinning operation was approximately 3,000 board feet per acre.

Table 56: Soper-Wheeler Feedstock Forest Classes and Site Location

Forest Land Cover Class	Soper-Wheeler Site GPS Coordinates	Elevation	Topography
Montane Hardwood & Montane Hardwood-Conifer	39° 29' 47.89" N 121° 15'47.05" W	3,500 ft.	Rolling foothills
Sierran Mixed Conifer-White Fir	39° 32' 49.21" N 121° 07' 40.28" W	3,600 ft.	Rolling foothills
Red Fir	39° 43' 17.94" N 120° 57' 14.93" W	5,500 ft.	Westerly facing slopes generally
Ponderosa Pine	39° 29' 40.30" N 121° 16' 31.84" W	2,500 ft.	Rolling foothills

Source: West Biofuels, LLC

Soper Company produced these feedstocks using a Beast Model 2680 horizontal grinder (Bandit Industries, Inc.). The grinder is fed timber harvest residuals and sub-merchantable stems the woody biomass using a Komatsu PC 2700 track excavator equipped with 60-inch logging grapples.

Analysis across all nine regions showed five dominant forest land cover classes that together occupy 41 percent of forested lands statewide. These five classes, their acres statewide, and their percent of the total forested acres in California are shown in Table 57. (The researchers mapped Montane Hardwood and Montane Hardwood-Conifer separately but combined them for this discussion.)

Table 57: Five Largest Forest Cover Classes in California

Forest Land Cover Class	Class Acres in California	Statewide Distribution	Percent of California Forests
Montane Hardwood & Montane Hardwood-Conifer	5,624,887	9 zones	13.66%
Sierran Mixed Conifer-White Fir	5,201,586	9 zones	12.63%
Douglas Fir	3,104,473	7 zones	7.54%
Klamath Mixed Conifer	1,768,253	3 zones	4.29%
Eastside Pine	1,312,350	6 zones	3.19%
Percent of California forest in the five largest cover classes			41.32%
***Total forest acres in the 9 regions is 41,172,704**			

Source: West Biofuels, LLC

Figure 31: Soper-Wheeler Feedstock Supply Sites

Source: West Biofuels, LLC

SW holdings and the team selected forest biomass materials for gasifier testing to reflect California's dominant forest cover classes. The four selected feedstock forest classes are shown in Table 58.

Table 58: Soper-Wheeler Feedstock Supply Forest Cover Classes

Forest Land Cover Class	Class Acres in California	Statewide Distribution	Percent of California Forests
Montane Hardwood & Montane Hardwood-Conifer	5,624,887	9 zones	13.66%
Sierran Mixed Conifer-White Fir	5,201,586	9 zones	12.63%
Red Fir	1,169,461	6 zones	2.84%
Ponderosa Pine	1,130,735	9 zones	2.75%
Percent of California forest represented by Soper-Wheeler feedstock*			31.88%
***Total forest acres in the 9 regions is 41,172,704**			

Source: West Biofuels, LLC

The feedstock supply forest cover classes:

- Combined occur in over 32 percent of the forested acreage in California.
- Include the top two dominant forest classes in California: Sierran Mixed Conifer –White Fir and Montane Hardwood / Montane Hardwood-Conifer.
- Include Ponderosa Pine and Red Fir which have widespread distribution occurring in six and nine zones (respectively). Their percent occurrence is very similar to that of Eastside Pine.

Sample Preparation

Feedstock provided by Soper Company was processed at West Biofuels with screen systems to sort the physical sizes. West Biofuels arranged a demonstration day with Peterson to test a deck screen (Figure 32) and a trommel screen (Figure 33).

Figure 32: Deck Screen Sorting Forest-Sourced Feedstock – Peterson Trial

Source: West Biofuels, LLC

Figure 33: Trommel Screen Sorting Forest-Sourced Feedstock – Peterson Trial

Source: West Biofuels, LLC

The deck screen configuration has two screen, producing three products: overs, mids (accepts), and unders (fines). The deck screen uses two flat screens to sort material with the over fraction removed at the first screen, the mid fraction removed at the second screen, and the fines fraction passing through the second screen. The principal advantage of a deck screen is the ability to generate three distinct fractions.

The trommel configuration uses a rotating drum with a screen to create two products: overs and unders. The trommel screen is a more cost-effective system; however, only produces two products. To produce three products, two trommel screens would need to operate in series. The rotating drum configuration also helps with spearing effect, where a long thin stick is able to make it through a small screen size (for example a 3”x1/4”x1/4” stick can make it through a 1/2" grate).

Based on the Peterson demonstration and subsequent feedstock testing, the deck screen was determined to be the most appropriate equipment configuration for forest-sourced feedstock. The deck screen allowed for overs removal which is important for feedstock flow and fines removal which have a high fraction of ash (see further analysis below). Based on these findings, West Biofuels invested in a deck screen to allow for further process refinements. This system was procured used at an equipment auction (Figure 34 and Figure 35). West Biofuels converted the deck screen to an electric drive to eliminate diesel consumption.

Figure 34: West Biofuels Deck Screen

Source: West Biofuels, LLC

Figure 35: West Biofuels Deck Screen Operations

Source: West Biofuels, LLC

West Biofuels team ran the four feedstock types that were provided by the truckload through the deck screen to separate into overs, mids, and fines.

Sample Evaluation

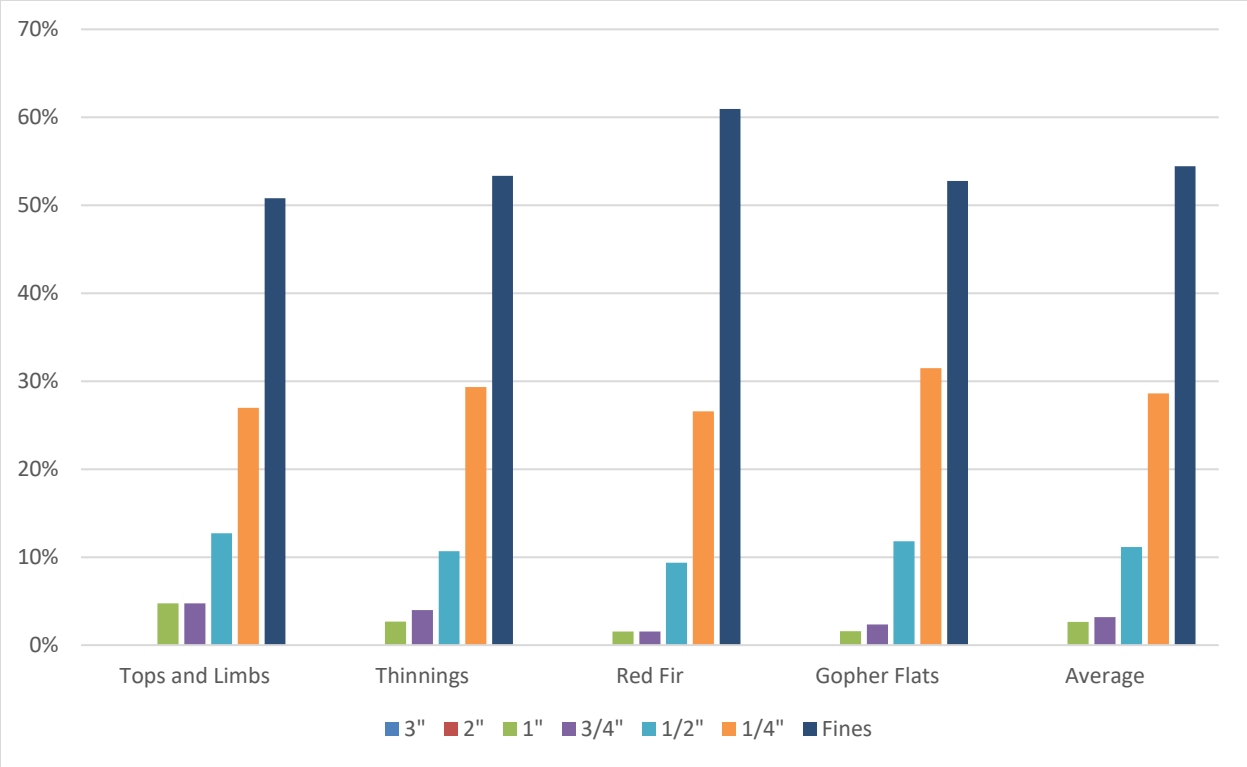
West Biofuels outlined specific objectives for feedstock evaluation. Targets, after processing, include:

- Particle Size: <1 percent 3-inch and over, <5 percent fines (Less than ¼ inch);
- Total Inert Content <5 percent;
- Ash Characteristics: Melting point greater than 900˚C;
- Moisture Content: Less than 25 percent; and
- Higher Heating Value (HHV): Greater than 7,500 Btu/dry pound.

Sizing

A technician classified the mid-fraction of the feedstock that was sorted with a deck screen. The size classification took place on a six-screen deck (yielding seven sizes). The screen size used for the primary sorting included 3”, 2”, 1”, 3/4", 1/2", and 1/4".

Figure 36: Preliminary Classification

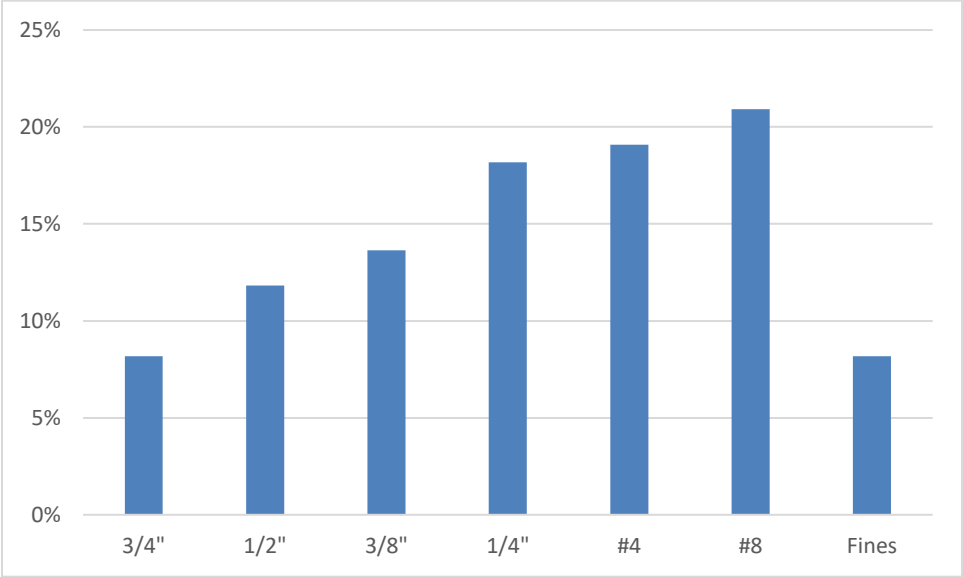


Source: West Biofuels, LLC

The preliminary results show significant material classified below 1/4" (fines). However, the classification protocol includes aggressive vibration, which creates spearing.

To better evaluate the classification of the material, additional classification was performed with a new set of screens: 3/4", 1/2", 3/8”, 1/4", #4 mesh (0.185”), and #8 mesh (0.093”). This secondary classification better distributed the material. Figure 37 and Figure 38 show the distribution of the raw feedstock sample.

Figure 37: Secondary Classification, Unproceesed



Source: West Biofuels, LLC

Figure 38: Photograph of the Secondary Classification Distribution

Source: West Biofuels, LLC

Using a deck screen, West Biofuels was able to create a feedstock that met the feedstock first objective: Particle Size: <1 percent 3-inch and over, <5 percent fines (Less than ¼ inch).

Density

While density was not a defined measureable objective of the research project, it is an important metric for feed rate. Bulk density of the feedstock was measured after sorting to determine physical characteristics of the different components. Table 59 shows the measured bulk density of the incoming product. The bulk density on a wet basis is important to understand the cost of transportation and the dry bulk density is important to understand the implications of feeding a gasification system.

Table 59: Feedstock Density

Description	Fraction	Bulk Density (dry basis lb/ft^3)	Photograph
Ponderosa Pine	Mid	10.16	
Ponderosa Pine	Fines	10.88	
Montane Hardwood-Conifer	Mid	11.47	

Description	Fraction	Bulk Density (dry basis lb/ft^3)	Photograph
Montane Hardwood-Conifer	Fines	13.00	
Red Fir	Mid	9.25	
Red Fir	Fines	12.46	

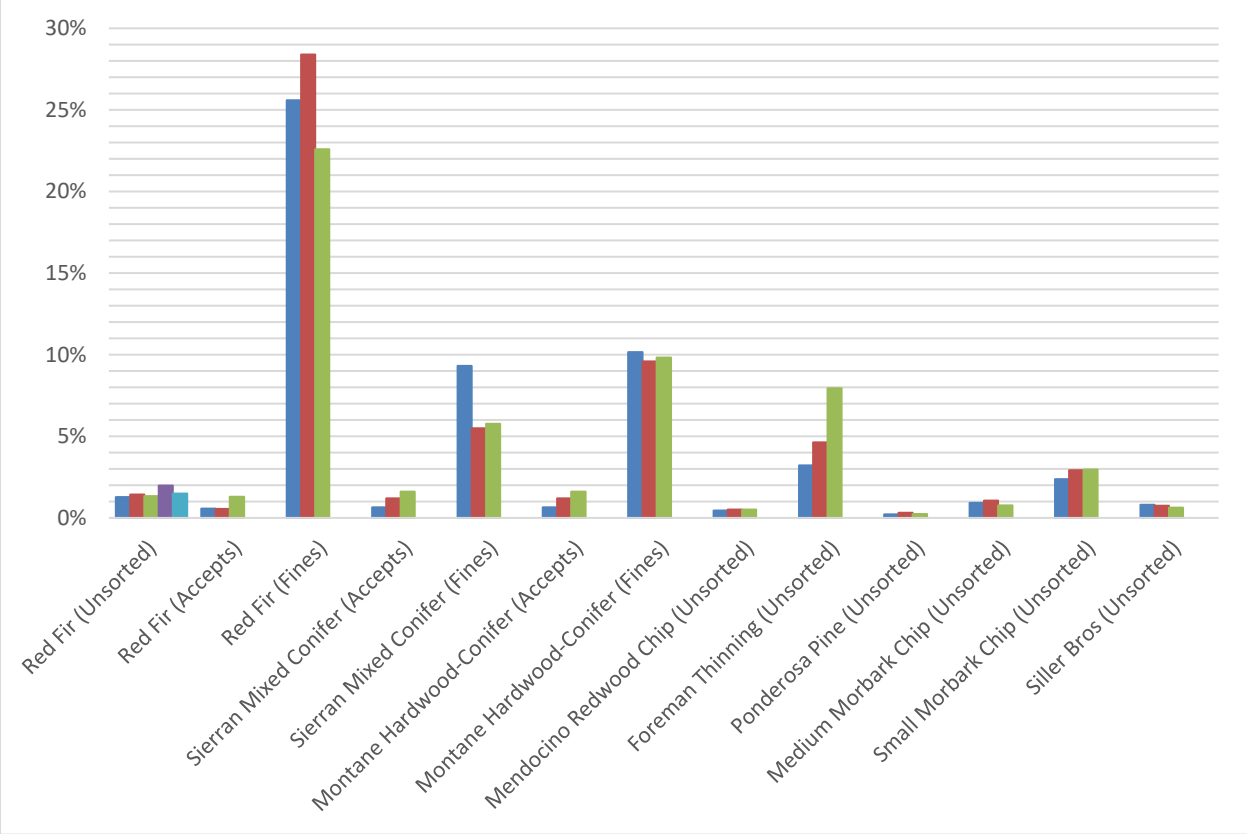
Source: West Biofuels, LLC

The fines fractions were consistently denser than the mid fraction, averaging 17 percent higher. The mid fraction, averaging 10.29 dry lb/ft^3 was consistent with the values existing in the literature.

Inert Content/Ash

Ash content of the feedstock was measured using ASTM 1755-01. Results are shown in Figure 39.

Figure 39: Feedstock Ash Content



Source: West Biofuels, LLC

The average, maximum, and minimum ash percentages for unsorted feedstock, mid-fraction accepts, and fines are shown in Table 60.

Table 60: Ash Composition by Processing Fraction

	Average	Maximum	Minimum
Unsorted	1.72%	5.26%	0.26%
Mid-Fraction Accepts	1.04%	1.15%	0.80%
Fines	14.08%	25.53%	6.86%

Source: West Biofuels, LLC

The fines fraction contains significantly higher percentages of ash. After screening, the mid-fraction accepts were significantly below the 5 percent quantitative objective.

Moisture Content

Moisture content was measured used ASTM D4442-07. Moisture content was measured as-received and after air drying prior to use in the gasifier.

Table 61: Feedstock Moisture Content, As Received

	As Received
Red Fir (Lumpkin)	19.53%
Mixed Conifer (Gopher Flats)	26.38%
Tops & Limbs	8.55%
Thinnings	19.80%
Mendocino Redwood	14.99%
Foreman Thinning	13.12%
Siller Bros	15.48%
Medium Morbark	13.57%
Small Morbark	28.12%

Source: West Biofuels, LLC

Feedstock provided by Soper Company was dried over the summer prior to processing. This in-field management may have contributed to relatively low as-received moisture content compared to the literature.

Prior to use in the gasifier, West Biofuels windrowed all feedstock samples over the summer. Feedstock was air-dried to approximately 10 percent and then moved indoors for storage.

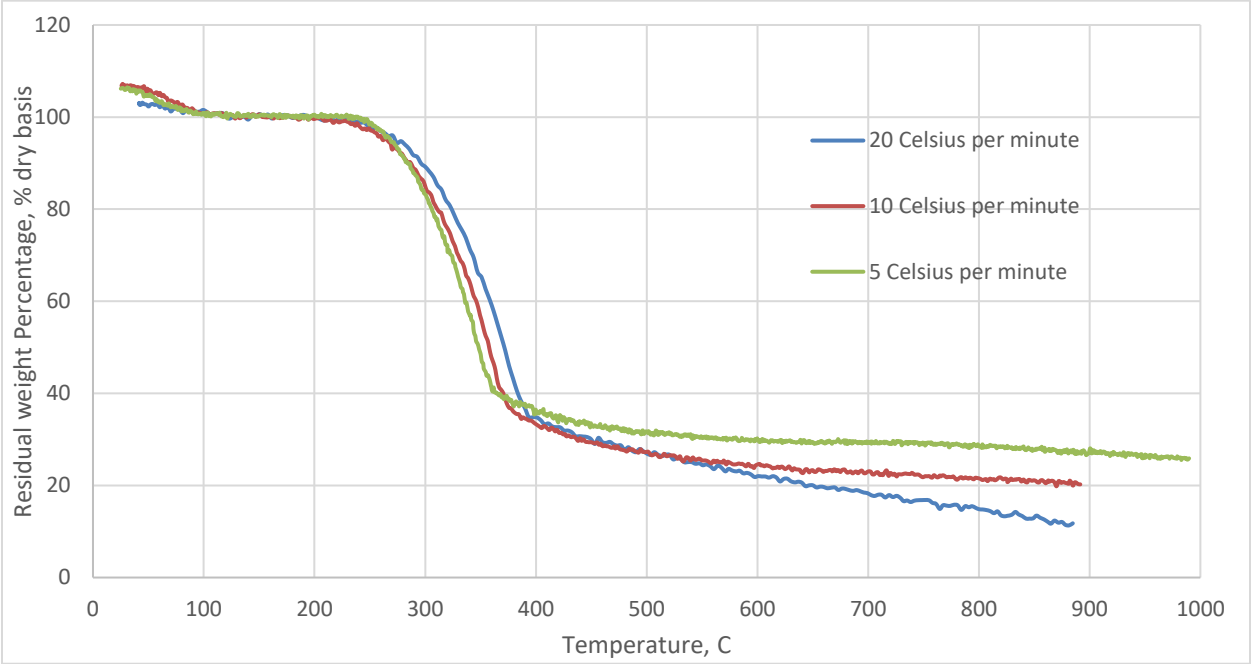
West Biofuels was successfully able to meet the moisture content objective of less than 25 percent without mechanical drying. However, at commercial scale, feedstock drying will be required to ensure appropriate moisture content.

Volatiles

While not an explicit objective, West Biofuels evaluated the volatile curve for feedstock using thermogravimetric analysis (TGA). TGA was conducted at three different temperature rates, 5, 10, and 20 C increments per minute.

TGA analysis identified that the majority of the volatile fraction of feedstock was released between 250C and 400C. The TGA evaluation is important to understanding the gas production characteristics of the biomass at a specific temperature profile.

Figure 40: Volatile Fraction as a Function of Temperature



Source: West Biofuels, LLC

Conclusion

Forest feedstock can be procured and processed to meet the specifications outlined in the objectives. To accommodate the high variability in ground material, pre-processing must include screening of both the fines and over fractions to reduce particle size and inorganics.

CHAPTER 3:
Gasifier Performance

Gasifier Test Plan

The Gasifier Test Plan provides a detailed account of the methodology that will be utilized to evaluate the CircleDraft gasifier system for its potential to convert forest-sourced feedstock material in producer gas to the stated objective:

- Test the gasifier to determine operating conditions (for example temperature, flow rates, grate speed) for optimized efficiency and producer gas quality. Targets for efficiency and producer gas quality include:
    - Thermal Efficiency: ≥70 percent
    - Throughput Rate: ≥ 900 dry pounds per hour
    - Producer Gas Energy Content: ≥ 150 Btu per ft^3
    - Tar Content: < 20 mg per Nm^3
    - Tar Dew Point: < 15˚C
    - Particulates: < 5 mg per Nm^3 and less than 1 micron
    - Hydrogen Sulfide: < 50 ppm
    - Biochar Production: ≥ 72 dry pounds per hour
    - Biochar Quality: Meets or exceeds International Biochar Initiative (IBI) Biochar Standards[26]

Gasifier Test Objectives and Technical Approach

Description of the Process

- Current Technology: There are two community-scale (0.5 MW to 3 MW) biomass gasification systems in commercial operation in California, both using Ankur Scientific downdraft gasifier.
- Technological Advancement: West Biofuels has been working with international partners to bring gasification technology from Europe to California. In particular, the company has been working on the patented CircleDraft® gasification with technology partner INSER, S.P.A from Italy. There are two working plants based on the INSER CircleDraft® design shown in Table 62 and Source: West Biofuels, LLC
- Figure 41 that have been operating on clean wood chips in Italy.

[26] Standardized Product Definition and Product Testing Guidelines for Biochar That Is Used in Soil (aka IBI Biochar Standards) Version 2.0, International Biochar Initiative, Westerville, OH, USA, October-2014.

Table 62: INSER CircleDraft® Installations in Torino Region of Italy

Installations	Input/Output	Description
Cherasco Plant Installed 2009	0.25 ton/hr, wood chips 250 kW (MANN genset)	Beta plant for the technology. INSER tested several feedstocks and has modified the plant over time to optimize operation and efficiency.
Caluso Plant Installed 2013	0.4 ton/hr, wood chips 400 kW (CHI genset)	First plant with upgraded design. Commercial power is fed into grid. According to INSER, lack of new utility contracts and current high cost of clean wood chip ($90/ton) has suppressed additional capacity expansion in Italy.

Source: West Biofuels, LLC

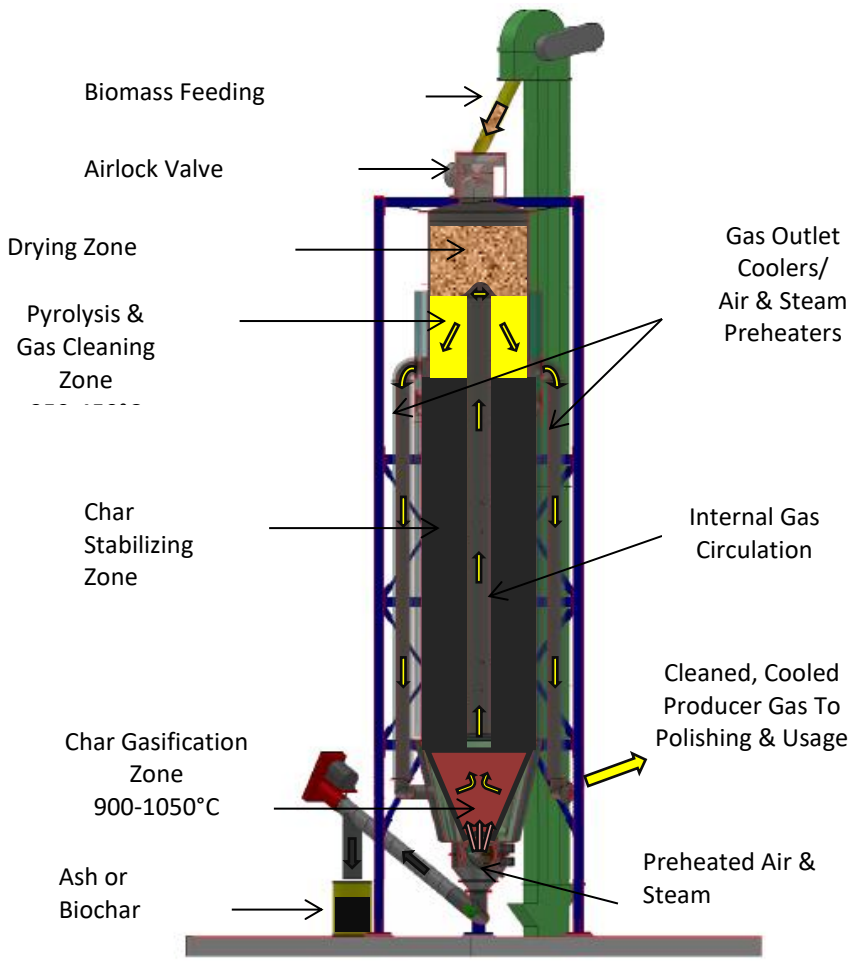
Figure 41: Cherasco Plant (L) and Caluso Plant (R) in operation using CircleDraft® Technology

Source: West Biofuels, LLC

The CircleDraft® technology builds on traditional fixed-bed draft-type gasifiers and addresses some of the key operational issues that have been encountered with these systems that limit their broad application in modern commercial settings. In particular, the CircleDraft® system has a unique way of internally filtering the tars and particulates in the product gas that is not available in traditional up-draft and down-draft systems. The CircleDraft® system works by separating the gas generation process into two zones, and pyrolysis and filtering zone that takes place in the upper part of the reactor and the char gasification that takes place over a grate system in the lower part of the reactor. As shown in Figure 42, the biomass enters the reactor through an airlock valve at the top of the system and works its way down the reactor by gravity on a fixed bed. The biomass goes through a drying zone and then enters the pyrolysis

and filtering zone held at a temperature of 350-450˚C. All of the gases produced by the system filter through this zone before exiting the reactor. The biomass converts to char in this zone which then enters a stabilization zone as it works its way down the reactor to the grate. Preheated air and steam is pumped through the grate and the char oxidizes and gasifies in this lower hot zone approaching 900-1050˚C from the exothermic oxidation. The gases produced in this zone preferentially circulate back up to the filtering zone via a circulation tube at the center of the reactor because of the lower pressure drop. The filtered gas exits the reactor and cools via four gas tubes that exchange the heat of the synthetic gas with the air and steam to enter the reactor, conserving the heat of the process. The filtered, cooled gas goes to a quench step to lower the dewpoint for final usage in a combustion device, like an engine or boiler. The gasifier also has a grate system that allows for the rejection of stones and agglomerates that might accumulate in the bed of other systems.

Figure 42: The CircleDraft® Gasification System in Cross-Section Showing Gas Flows and Zones



Source: West Biofuels, LLC

Both updraft and downdraft gasifier systems can produce gas with substantial amounts of particulate (char dust) and tars in the producer gas, requiring these to be coupled with complex

multi-step (up to 11 stages) cleanup systems.[27,28] The CircleDraft® system was designed to address this issue and has a very low tar and particulate load making for a simple cleanup stage to lower the dew point of the gas after the gas-to-air heat exchanger. This quench stage uses a structured media bed that can be integrated into the modular gasifier unit or as a small separate unit substantially reducing the footprint required for the plant without the large multi-stage gas cleanup process required for other downdraft and updraft systems. In addition, no wastewater or solid waste is generated as may be the case with other systems as the CircleDraft® quench condensate is all returned directly to the gasification zone of the process.

Prior to the grant award, West Biofuels had constructed a full-scale pilot unit of the CircleDraft® at their Woodland, CA research and development (R&D) facility in order to address the technical issues for the variety of biomass feedstock available in California and North America. Figure 43 is a collage of the construction of this facility.

Figure 43: North America's First Pilot CircleDraft® Unit at Woodland Biomass Research Center

Source: West Biofuels, LLC

Rationale for the Tests

To determine the performance of the CircleDraft gasifier system on forest sourced feedstock, West Biofuels will conduct a number of test runs and measure the inputs and outputs of the gasifier to determine the performance on these feedstocks. These tests will be done on two

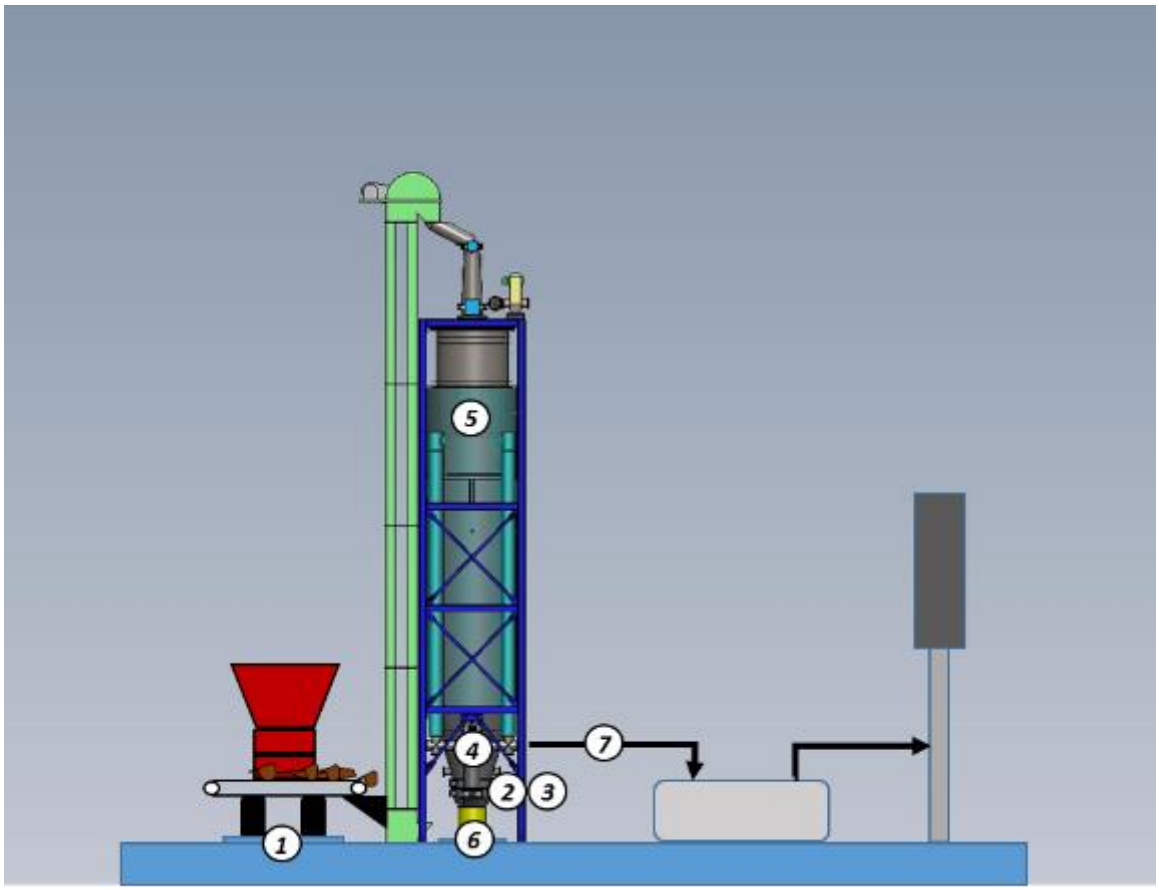
[27] Greg Stangl, Phoenix Energy, Personal Communication on Downdraft Gasifier System, August 2014.

[28] J.H. Jaganda, GP Energy, Personal Communication on Updraft Gasifier System, July 2014.

representative forest feedstocks that have been collected as part of Task 2. In addition, the testing is phased to first test the raw gas specifications to determine procedures for starting up the plant and determining how much additional gas conditioning is needed to meet the specifications for an engine generator. In the second phase, the gas conditioning system will be implemented to test the raw gas but also the conditioned gas to show it meets the specifications required for an engine generator.

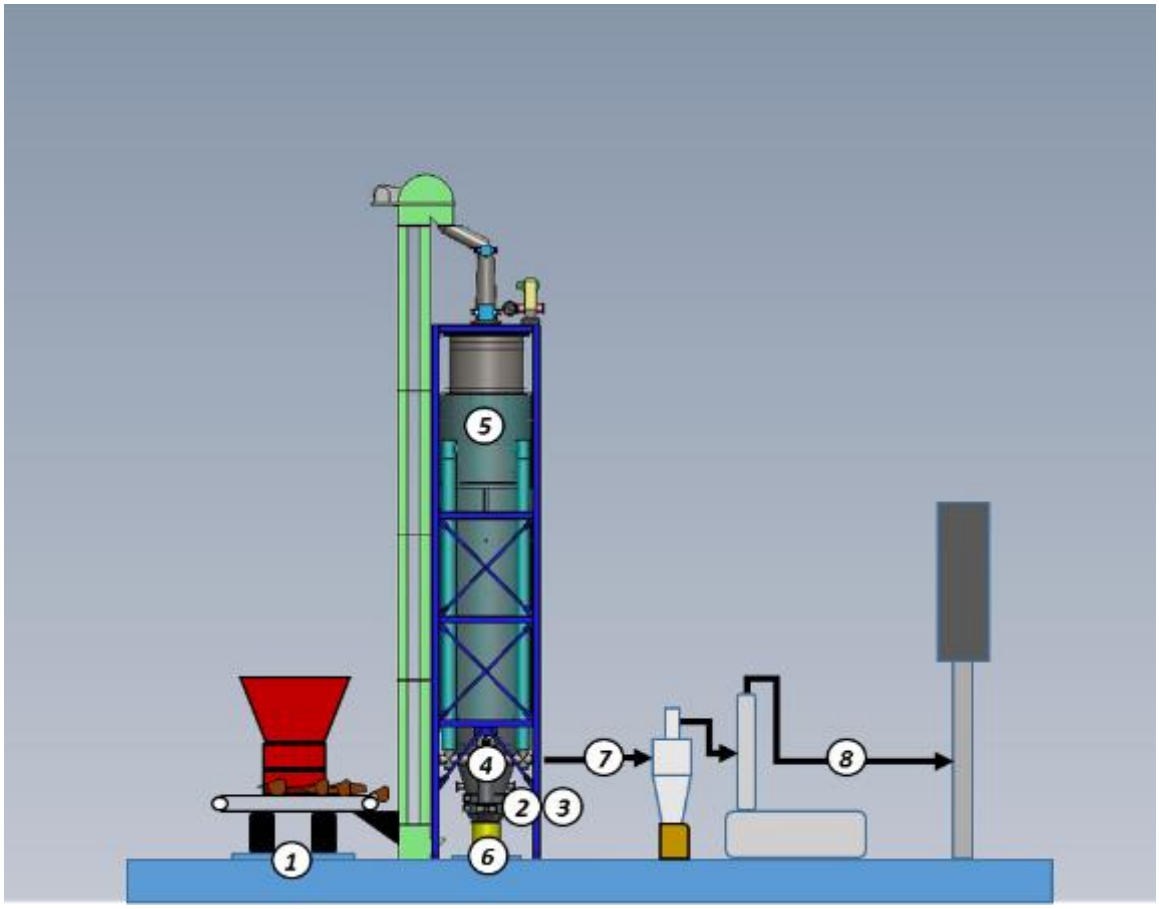
The sampling locations the first phase of raw gas testing is shown in Figure 44. In this case the raw producer gas is tested before it goes to a knockout tank to remove particles and condensate and before the gas is sent to a gas flare. Two gas testing locations, raw gas and conditioned gas, are used for the second phase with the fully implemented gas conditioning system is shown in Figure 45.

Figure 44: Sampling Locations for the First Phase Raw Gas Testing



Source: West Biofuels, LLC

Figure 45: Sampling Locations for the Second Phase Raw and Conditioned Gas Testing



Source: West Biofuels, LLC

Test Matrix

The text matrix specifies the operating conditions of the gasifier and the measurement variables and techniques for characterizing the producer gas from the CircleDraft® gasifier. In addition to the gas cleaning within the reactor, there are a few external gas conditioning steps to take out particulate and condensate included in the second phase, where measurements are taken of both the raw gas and the cleaned gas. Measuring the input/output mass and energy balance and the gas composition are the main objective of the testing, but monitoring other variables such as settings, rates, pressures, and temperatures are also necessary to give a complete understanding of the operating conditions. Below Table 63 outlines the sampling to be conducted at the locations shown in the schematic in Figure 44 and Figure 45.

Table 63: Types of Variables to be Sampled during Testing by Location

Loc #	Description	Units	Sensor Type	Expected Range	Precision
1	Biomass Feedrate	(kg/hr)	Load Cell, Continuous	300 - 500	10
1	Biomass Heating Value	(MJ/kg)	Lab Sample, Lower and Higher	17 - 20	0.1
1	Biomass Composition	(wt%)	Lab Sample, Proximate and Ultimate Analysis	Various	Various
2	Air Flow Rate	(Nm^3/hr)	Pitot Tube, Continuous	0 – 1000	10
2	Air Temp.	(°C)	Thermocouple, Continuous	0-50	0.5
2	Air Pressure	(mbar)	Pressure Transducer, Continuous	0-500	0.5
3	Steam Flow Rate	(kg/hr)	Pitot Tube, Continuous	0-200	1
3	Steam Temp.	(°C)	Thermocouple, Continuous	100-120	0.5
3	Steam Pressure	(mbar)	Pressure Transducer, Continuous	0-500	0.5
4	Gasification Zone Temp.	(°C)	Thermocouple, Continuous	800-1100	5
4	Gasification Zone Pressure	(mbar)	Pressure Transducer, Continuous	0-100	0.5
5	Filtration Zone Temp.	(°C)	Thermocouple, Continuous	0-400	5
5	Filtration Zone Pressure	(mbar)	Pressure Transducer, Continuous	0-100	0.5
6	Biochar Rate	(kg/hr)	Load Cell, Continuous	0-100	1
6	Biochar Composition	(wt%, var)	Lab Samples, Proximate and Ultimate Analysis, IBI Analysis	Various	Various
7	Raw Gas Flowrate	(kg/hr)	Ratio to Air Flow, Continuous	0-1000	10
7	Raw Gas Temp.	(°C)	Thermocouple, Continuous	0-200	0.5
7	Raw Gas Pressure	(mbar)	Pressure Transducer, Continuous	0-50	1
7	Raw Gas Composition	(vol %)	Lab Samples, Gas Chromatography	0-50	Various
7	Raw Gas Tar Content	(mg/Nm3)	SPE & CEN/TS 15439 Samples	500-5000	10
7	Raw Gas Particulate	(mg/Nm3)	Particulate Sampler	500-5000	10
8	Cond. Gas Flowrate	(kg/hr)	Pitot Tube and Ratio to Air Flow, Continuous	0-1000	10

Loc #	Description	Units	Sensor Type	Expected Range	Precision
8	Cond. Gas Temp.	(°C)	Thermocouple, Continuous	0-100	0.5
8	Cond. Gas Pressure	(mbar)	Pressure Transducer, Continuous	0-50	1
8	Cond. Gas Composition	(vol %)	Lab Samples, Gas Chromatograph	0-50	Various
8	Cond. Gas Tar Content	(mg/Nm3)	SPE & CEN/TS 15439 Samples	0-50	0.1
8	Cond. Gas Particulate	(mg/Nm3)	Particulate Sampler	0-20	0.1

Source: West Biofuels, LLC

Table 64 shows the test matrix with four operating conditions that are selected for the gasification plant for both the first and second phase testing. The objective is to only vary biomass type and steam input, but it is unlikely that all operating conditions like gasification zone temperature will be equal for the different steam settings and feedstocks. A higher steam input should decrease the gasification zone temperature and increase the H_2/CO ratio in the output gas but could reduce the gasifier efficiency. The steam could have a significant impact on the gas composition, contaminant loading, and biochar properties so this will be tested as part of the program along with the feedstock differences. Test 1 and 2 use the "hardwood" feedstock from forest thinning project at two different steam settings, moderate and high. Test 3 & 4 use the "softwood" feedstock which is largely composed of from tops and limbs from stand management. Note also that the biomass feed rate is not controlled but rather follows the demand of the gasifier for more feedstock as it is consumed by the process and biochar removal from the bottom of the reactor. The tests will use a constant airflow, steam input, and biochar removal rate and measure the biomass feed rate for both conditions and materials.

Table 64: Test Matrix for Gasifier Testing

Parameter	Units	Test 1	Test 2	Test 3	Test 4
Biomass Type		Hardwood	Hardwood	Softwood	Softwood
Biomass Feed Rate*	(kg/hr)	400	400	400	400
Air Flowrate	(Nm3/hr)	850	850	850	850
Steam Input	(kg/hr)	140	70	140	70
Biochar Removal Rate	(kg/hr)	60	60	60	60
Gasification Zone Temp.*	(°C)	850	1000	850	1000
Filtration Zone Temp.	(°C)	350	350	350	350

***Estimates only. Actual federate and temperature to be measured.**

Flow rates are approximated from modeling and prior tests but may be adjusted to maintain stable operating conditions.

Source: West Biofuels, LLC

Instruments and Methods

Dry-gas Composition of the Producer Gas

- The permanent gases will be measured with a gas chromatograph (Agilent 2000 Micro GC). The gas will be sampled through an impinger in an ice-bath, filled with either biodiesel or toluene. This removes most of the water and other condensable. Alternatively, sample bags or syringes can be used to collect a gas sample, and water/tars will condense in the bag or syringe.
- The following permanent gases will be measured: H_2, N_2, O_2, CH_4, CO, CO_2, C_2H_4, C_2H_6, C_3H_6, C_3H_8, and H_2S.
- The instrument will be calibrated with three calibration-gas mixtures at the beginning of a test campaign, and double-checked with one calibration-gas mixture at the end of the campaign.

Tar Content in the Producer Gas

Two methods will be used to measure tars in the producer gas, the SPE method (Solid phase extraction) and European tar protocol (CEN/TS 15439)

SPE Method

Solid phase extraction (SPE) is a method of measuring tar compounds in the gas phase, originally developed by Brage et al. (1997)[29]. Gas sampling is performed by pulling 100mL of sample through a SPE column (Alltech Extract Clean™ Amino 500mg, 4mL) using a syringe pump. Tars are then extracted off the column using a simple procedure involving eluotropic polar (isopropyl alcohol) and non-polar (dichloromethane) solvent desorption separately. Extracted samples can then analyzed using GC-FID.

- Calibration: GC chromatogram peaks are identified using Supelco EPA VOC Mix 2 and other external tar standards. EPA VOC Mix 2 contains 2000 µg/mL of the following compounds: benzene, bromobenzene, butylbenzene, ethylbenzene, p-isopropyltoluene, naphthalene, styrene, toluene, 1,2,3-trichlorobenzene, 1,2,4-trichlorobenzene, 1,2,4-trimethylbenzene, 1,3,5-trimethylbenzene, and m-xylene. Tar compound quantification of a compound within the external standard was calculated by multiplying the area of the analyte by the factor (cs / As).

$$c_x = \frac{(A_x c_s)}{(A_s)}$$

[29] Brage, C., Qizhuang Yu, Guanxing Chen, Krister Sjöström, Use of amino phase adsorbent for biomass tar sampling and separation, Fuel, Volume 76, Issue 2, January 1997, Pages 137-142.

where, cx, cs are the concentrations of analyte and standard, respectively (µg/mL) and Ax, As are the peak areas for analyte and standard, respectively. The concentration of compounds not in the standard will be estimated by averaging the (cs / As) factor of the compounds in the standards.

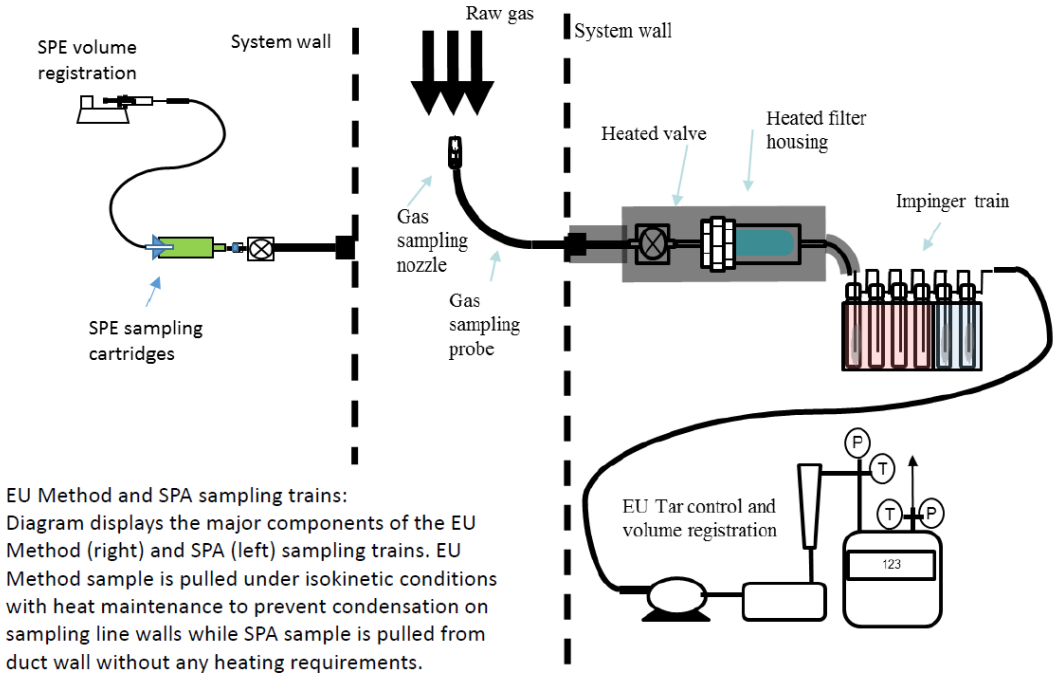
Tar Protocol

The tar protocol follows CEN/TS 15439 and EPA Method 5, by isokinetically drawing a sample stream and flowing it through a set of six impingers filled with solvent (isopropanol). The first four impingers are in a water-bath held at 40C, the last two impingers ar in a water bath chilled to -20 C. The dry gas flow is measured with a dry test meter over a certain time period. After that, the impinger liquids are combined and analyzed in a gas chromatograph as well as gravimetrically by evaporating the solvent.

The sampling nozzles and sampling flow rates are selected so that the velocity of the gas stream inside and outside of the nozzle are identical (isokinetic). The gas velocity will be calculated from the producer gas flow rate at sampling locations 7 and 8. The average gas velocity is calculated by dividing the gas flow rate by the cross section of the pipe. The tar-laden solvent will be analyzed in a gas chromatograph (Agilent 7820A with FID detector)

- Calibration: The gas chromatograph will be calibrated with EPA VOC Mix 2 (48777 Supelco) at the beginning of the test campaign. The calibration factors for unknown tar species will be derived from other known tar species.

Figure 46: Schematic of tar-sampling methods



Source: West Biofuels, LLC

Particulate Content in Producer Gas

The method follows EPA Method 5, by isokinetically sampling a gas stream and collecting particulates on a filter. The same setup as for tar sampling will be used, together with a heated filter (see Figure 2). After the collection of solids (and tars) on the filter, the filter will be washed in a Soxhlet extractor. The filter will be then be dried and weighed and compared to its original weight.

Water Content in Producer Gas

A gas-sample stream will be flow through an impinger filled with toluene immersed in an ice bath. The total sample-flow volume will be measured with a dry-test meter. At the end of the sampling, the liquid will be separated in a separation funnel. The amount of water will be measured in a graduated cylinder.

Sulfur Species in Producer Gas

Gas samples will be collected in Tedlar bags (2 L volume) and analyzed in a gas-chromatograph (GC) with sulfur-chemiluminescence detector (SCD). Teflon lines will be used to connect to the sampling bags during sampling.

Biomass Feed Rate

The feed rate of the biomass will be measured by load cells on the scale underneath the biomass supply bin. The weight and weight changes are recorded over the duration of the test to determine the average feed rate of the reactor.

Biomass Heating Value and Composition

Please refer to the Feedstock Test Plan for this project for more details on these analysis.

Air Flow Rate

The air flow rate into the combustor is measured using pitot tubes and a compressor flow curve.

Steam Flow Rate

The total steam flow rate will be measured by pitot tube flowmeter.

Producer Gas Flow Rate

The producer gas flow rate is measured with a pitot tube after sampling location 8. The sensor is calibrated with nitrogen. In addition, knowing the airflow to the gasifier and nitrogen content of the producer gas provides another means to confirm gas flow rate by nitrogen mass balance.

Temperature and Pressures

Temperatures are measured with Type-K thermocouples and pressures are measured with pressure transducers. The probes are located at various locations throughout the plant. The values are recorded with a National Instruments cRIO (NI-9074).

Data Analysis and Quality Assurance

Description of Data Analysis Procedures

The researchers averaged the data collected in the tests over the relevant testing period for both the continuous or periodically sampled data. The team reviewed the data to determine if there are any missing data, anomalies, or other possible errors in the instrumentation. The team computed efficiencies and mass and energy flowrates using standard accepted methodologies for engineering practice.

Quality Assurance Procedures and Contingency Measures

The technicians calibrated the instruments as described above and the team reviewed the data for quality assurance. Lab samples involve three replicates as described above. All samples collected are representative of the process and analysis is always run in triplicate. If the coefficient of variation for triplicate samples are larger than 10 percent, the test was repeated. Additional sample material will be preserved for re-testing as a contingency measure.

Predicted Performance

Test results are expected to meet the objectives identified for this task:

- Thermal Efficiency: $\geq$70 percent
- Throughput Rate: $\geq$ 900 dry pounds per hour
- Producer Gas Energy Content: $\geq$ 150 Btu per ft^3
- Tar Content: < 20 mg per Nm^3
- Tar Dew Point: < 15°C
- Particulates: < 5 mg per Nm^3 and less than 1 micron
- Hydrogen Sulfide: < 50 ppm
- Biochar Production: $\geq$ 72 dry pounds per hour
- Biochar Quality: Meets or exceeds International Biochar Initiative (IBI) Biochar Standards

Gasifier Performance Report

The Gasifier Performance Report provides detailed analysis of the data collected during the implementation of the Gasifier Test Plan. The Gasifier Performance Report evaluates the potential for the CircleDraft gasifier system to convert forest-sourced feedstock material into producer gas suitable for gas engine power generation.

Gasifier Test Schedule

To implement the Gasifier Test Plan, the CircleDraft gasification system (Figure 1) was run periodically between November, 2015 and September, 2017. This system was run for a total of 523 hours of operation including startup and shutdown. Between these test runs, the plant crew implemented many plant and control system modifications and improvements to address operating issues that were identified during the test runs. The team took many pictures to illustrate the main improvements and these pictures are shown in Appendix A. In between

November of 2015 and June of 2016, the team installed the gas conditioning system, which included a cyclone and a scrubber, which allowed for contaminant removal from the gas (Figure 47). The air district required a thermal oxidizer which the team installed in March of 2017. Table 65 shows the test types and timeframes for operating data collected during these test runs. The team conducted the last test using torrefied forest thinnings to try to address some operating issues that persisted with the raw forest wood. The team wanted to see if gas quality objectives could be better met with this approach.

Table 65: Test Schedule for Completed Gasifier Plant Tests

Number	Test Descriptor	Testing Type*	Start Date	End Date
1	October 2015 Run	Raw Gas, MW	10/7/2015	10/7/2015
2	November 2015 Run	Raw Gas, MW	11/11/2015	11/12/2015
3	June 2016 Run	Conditioned Gas, HW	6/2/2016	6/9/2016
4	October 2016 Run	Conditioned Gas, HW	10/11/2016	10/12/2016
5	December 2016 Run	Conditioned Gas, HW	12/6/2016	12/12/2016
6	February 2017 Run	Conditioned Gas, HW	2/13/2017	2/14/2014
7	July 2017 Run	Conditioned Gas, HW	6/19/2017	6/21/2017
8	September 2017 Run	Conditioned Gas, TW	9/13/2017	9/15/2017

***MW = Mixed Wood Feedstock, HW = Hardwood Forest Thinnings, TW= Torrefied Wood Forest Thinnings**

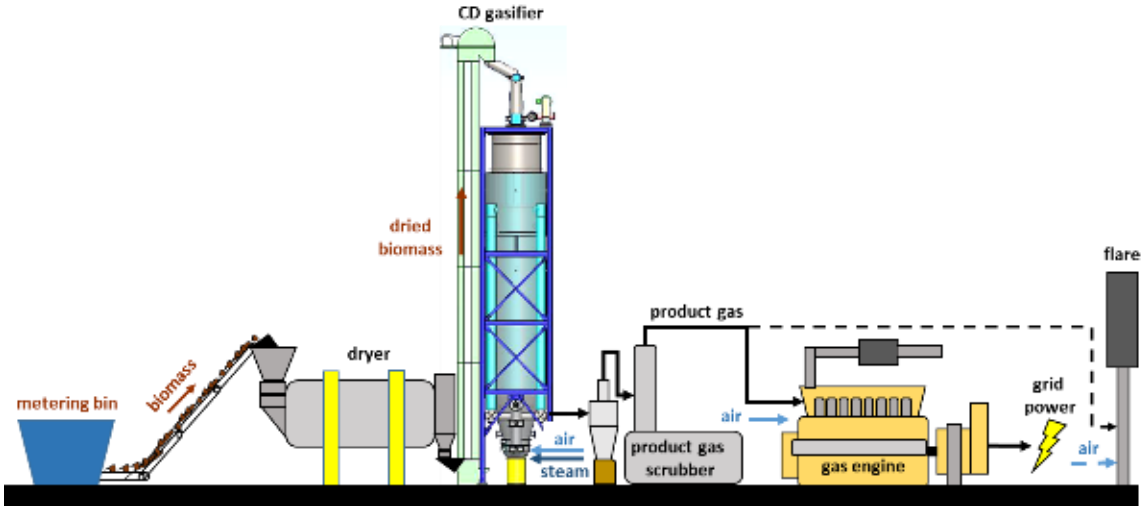
Source: West Biofuels, LLC

Gasifier Performance

Description of the Tests

The goal of this project was to analyze a system for community scale power production from forest residuals using a gasifier system at the core for thermal conversion. The original commercial scale system (System 1) envisioned to meet the performance objectives is shown in Figure 47 and includes a feedstock metering bin, feedstock conveyance, dryer (to take material from 45+ percent moisture to 10-20 percent moisture), CircleDraft gasifier, product gas cleanup system, gas engine generator, and emergency flare. Because of problems with gas quality and bridging/channeling experienced with the raw feedstock inside the CircleDraft gasifier, a second conceptual system (System 2) was analyzed that would include the addition of a rotary drum torrefaction reactor for pre-treatment of the biomass prior to being fed into the gasifier system as shown in Figure 3. The torrefaction served two purposes: 1) to pre-treat the biomass removing a portion of the volatiles prior to gasification to reduce the high level of condensables present in the product gas during raw wood gasification, 2) to pre-treat the biomass to reduce particle size, shape, and inter-particle friction to reduce the amount of bridging and channeling in the reactor during raw wood gasification.

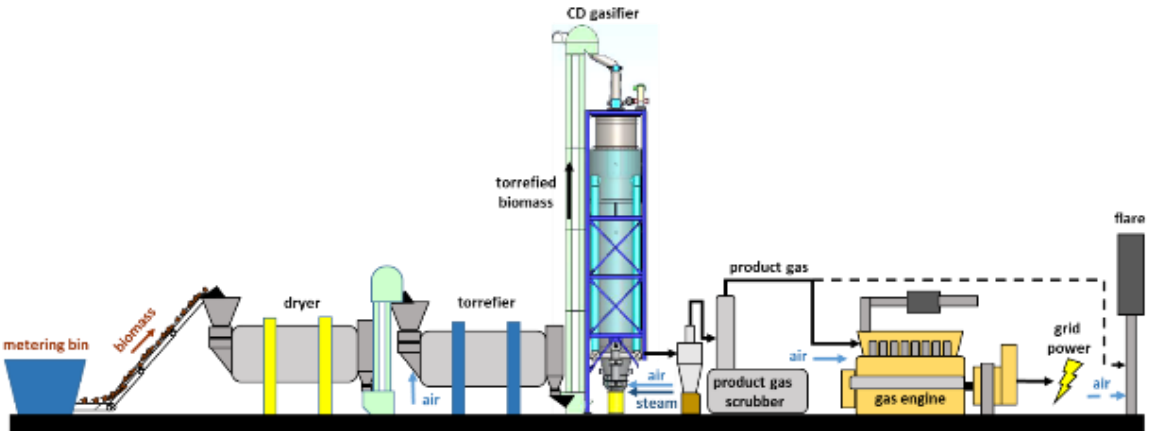
Figure 47: System 1: Biomass Power Production System (including feedstock metering; dryer; CircleDraft gasifier; gas cleanup; gas engine generator)



Source: West Biofuels, LLC

To determine the performance of the CircleDraft gasifier system on forest sourced feedstock, West Biofuels conducted a number of test runs and measured the inputs and outputs of the gasifier to determine the performance on this feedstock. These tests were done on raw gas and conditioned gas from representative forest feedstocks that were collected as part of Task 2. In addition, the testing was phased to first test the raw gas specifications from mixed woody feedstock to determine procedures for starting up the plant and determining how much additional gas conditioning is needed to meet the specifications for an engine generator. In the second phase, the gas conditioning system was implemented to test the raw gas but also the conditioned gas from forest feedstock to test if it can meet the specifications required for an engine generator in Task 4. An additional test on torrefied forest biomass was conducted to analyze the improved performance with the pre-treated wood as envisioned in System 2 as described above (Figure 48).

Figure 48: System 2: Biomass Power Production System (including feedstock metering; dryer; torrefier; CircleDraft gasifier; gas cleanup; gas engine generator)



Source: West Biofuels, LLC

The sampling locations used for the first phase of raw gas testing are shown in Figure 44. In this case the raw producer gas was tested before it goes to a knockout tank to remove particles and condensate and before the gas is sent to a gas flare. During these tests the gasifier was filled with a mixture of woody feedstocks so the performance data was primarily focused on gas composition and not overall performance. In the second phase, two gas testing locations, raw gas and conditioned gas, are used for the second phase with the fully implemented gas conditioning system as shown in Figure 45. In this phase the performance data was also collected to determine the energy and mass balance of the system and the gas composition.

Testing Methods and Conditions

Table 66 shows the test matrix with four gasification plant operating conditions that were demonstrated in the first phase of testing of forest biomass. Due to limitations within the gas handling and flare system, the plant was not able to meet 100 percent capacity during the first phase of testing. The objective was to vary input and output conditions sufficiently to evaluate the gas composition and the system performance factors and the relationship between the variables listed above. In each case, the system was allowed to settle into steady state at a certain setpoint for airflow, steam flow, and biochar removal for a sufficient number of hours to get stable performance. Overall, several of the performance objectives could be evaluated with this testing to see if they were within the capability of the system.

In the second phase of testing at full capacity, the objective was to only vary biomass type and steam input, but it is unlikely that all operating conditions like gasification zone temperature will be equal for the different steam settings and feedstocks. A higher steam input should decrease the gasification zone temperature and increase the H_2/CO ratio in the output gas but could reduce the gasifier efficiency. The steam could impact on the gas composition, contaminant loading, and biochar properties so this will be tested as part of the program along with the feedstock differences. Note also that the biomass feed rate is not controlled but rather follows the demand of the gasifier for more feedstock as it is consumed by the process and biochar removal from the bottom of the reactor. The tests use a constant airflow, steam input, and biochar removal rate and measure the biomass feed rate for both conditions and materials.

Table 66: Gasifier Test Matrix With Targets For Forest Biomass

Parameter	Units	Test #3	Test #4	Test #5	Test #6	Test #7	Test #8
Biomass Type		Forest, HW	Forest, HW	Forest, HW	Forest, HW	Forest, HW	Forest, TW
Biomass Feed Rate*	(kg/hr)	105	105	132	132	200	132
Air Flowrate	(kg/hr)	132	132	171	171	260	171
Steam Input	(kg/hr)	20	65	50	50	50	50
Biochar Removal Rate	(kg/hr)	20	30	25	25	32	25
Gasification Zone T	(°C)	820-1030	650-1000	>1000	>1000	>1000	>1000
Pyrolysis Zone T	(°C)	150-350	100-350	100-350	100-350	150-350	100

***Estimated from mass balance.**

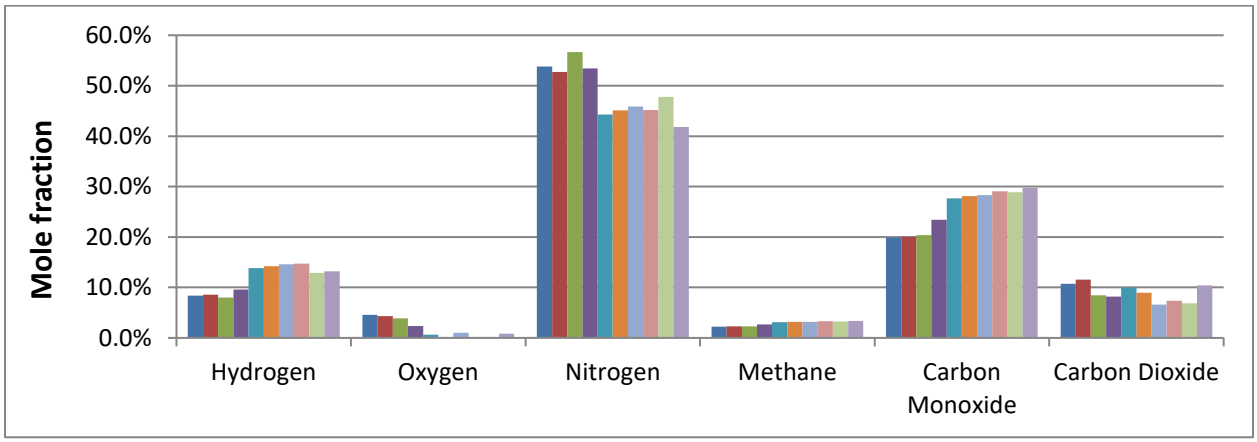
Source: West Biofuels, LLC

Raw Gas Testing Runs

In the raw gas testing phase the plant was operated using mixed woody feedstock (mesquite wood, almond wood, and walnut shell) to get some experience with the system and some preliminary gas data in order to determine some of the performance parameters for the gas conditioning system.

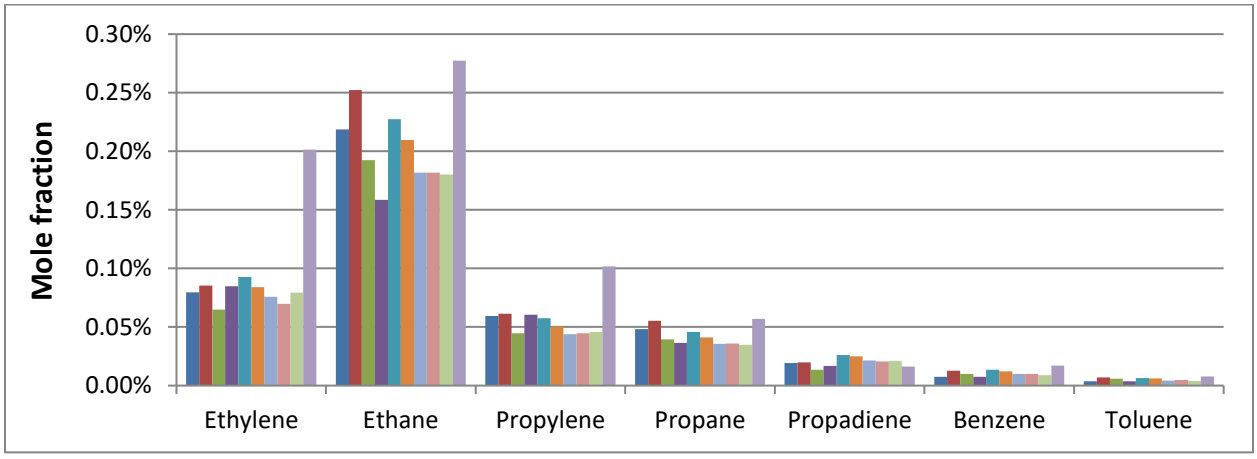
The gas performance for these runs is shown in Figure 49 through Figure 56. In general, the plant demonstrated a gas of sufficient energetic content to perform well in an engine application but that gas conditioning was required to remove condensate from the final gas to meet engine requirements. An interesting result, as shown in Figure 54 and Figure 56, was that the gasification zone gas (Loc 4) was much lower in higher hydrocarbons than the final gas (Loc 7) produced by the system. This indicated that the upper pyrolysis zone actually increased the amount of gas contaminants, opposite of what had been promoted by the technology vendor. Since the char gasification accounts for nearly 80 percent of the total gas, it made the team begin question the filtration effect of the pyrolysis zone and the flow orientation of the gasifier.

Figure 49: Major Gas Composition From Test #1, Location 7



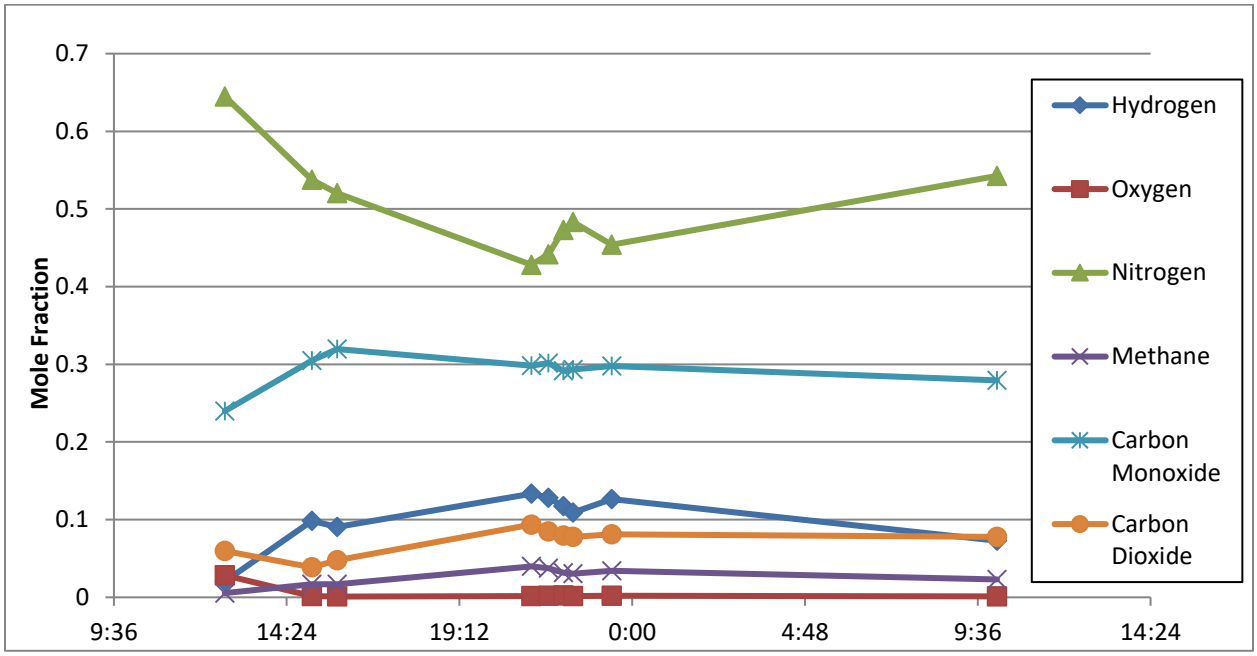
Source: West Biofuels, LLC

Figure 50: Minor Hydrocarbon Composition From Test #1, Location 7



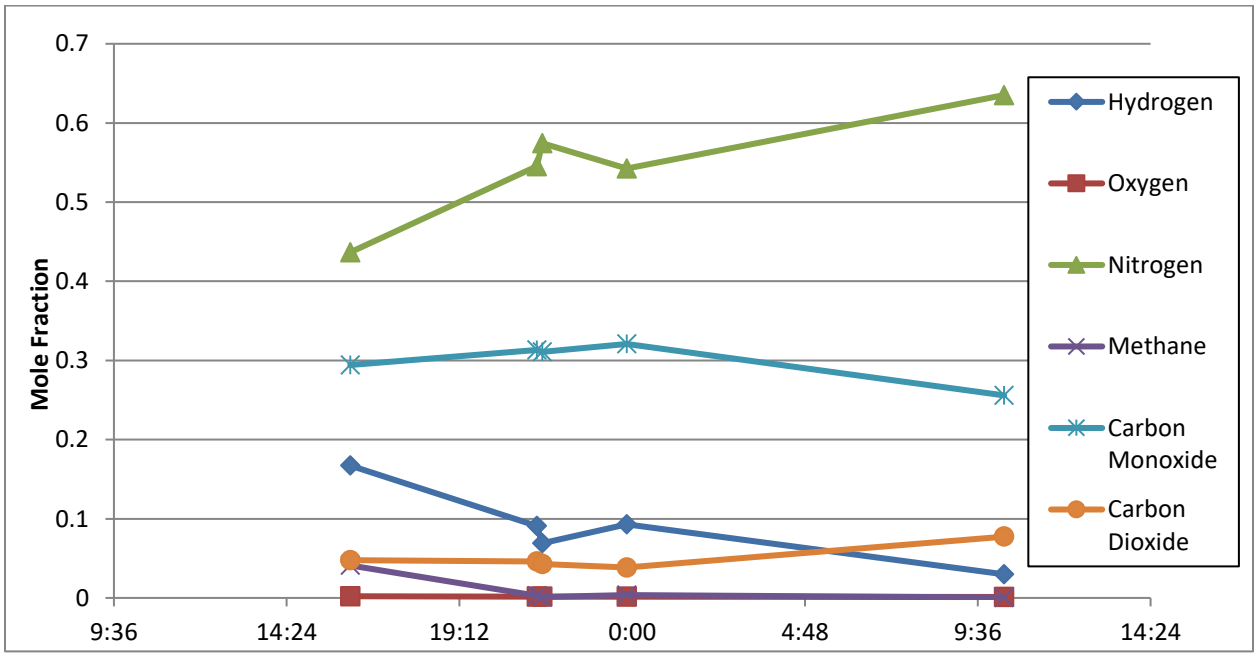
Source: West Biofuels, LLC

Figure 51: Major Gas Composition From Test #2, Location 7 Vs. Time



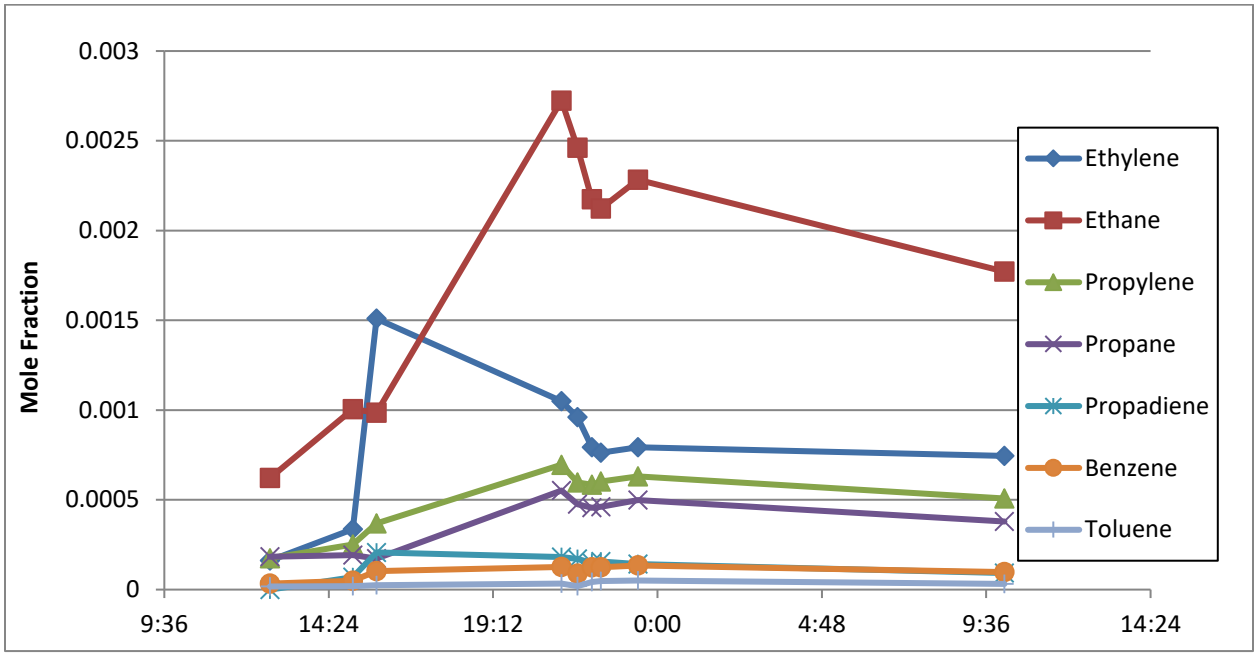
Source: West Biofuels, LLC

Figure 52: Major Gas Composition From Test #2, Location 4 Vs. Time



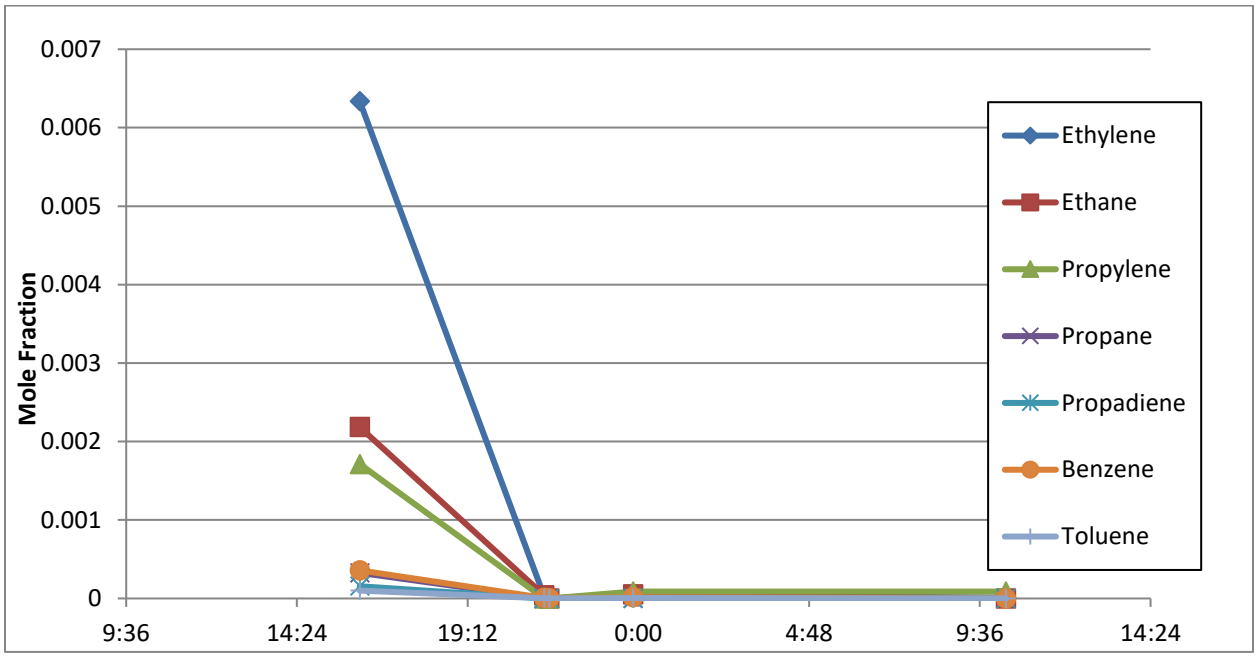
Source: West Biofuels, LLC

Figure 53: Minor Hydrocarbon Composition From Test #2, Location 7 Vs. Time



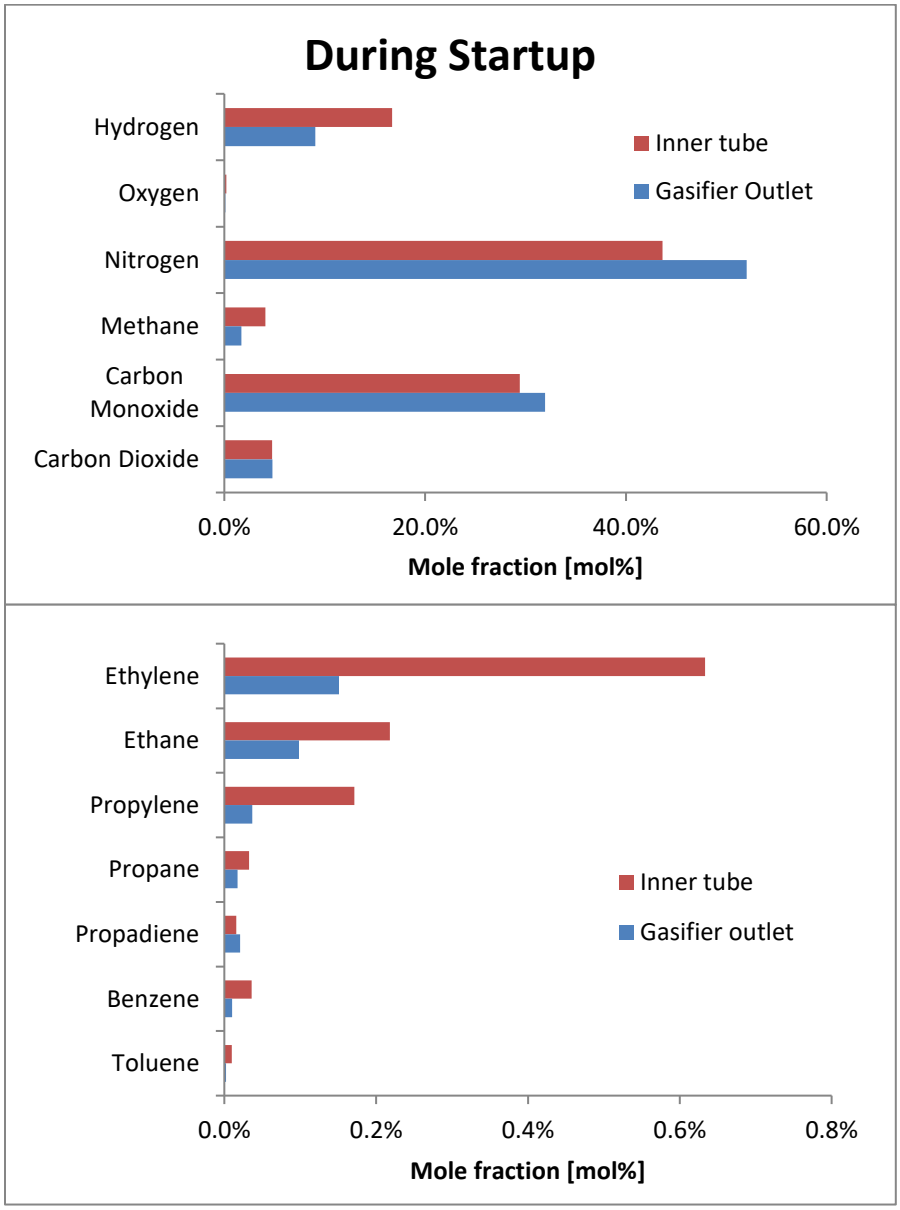
Source: West Biofuels, LLC

Figure 54: Minor Hydrocarbon Composition From Test #2, Location 4 Vs. Time



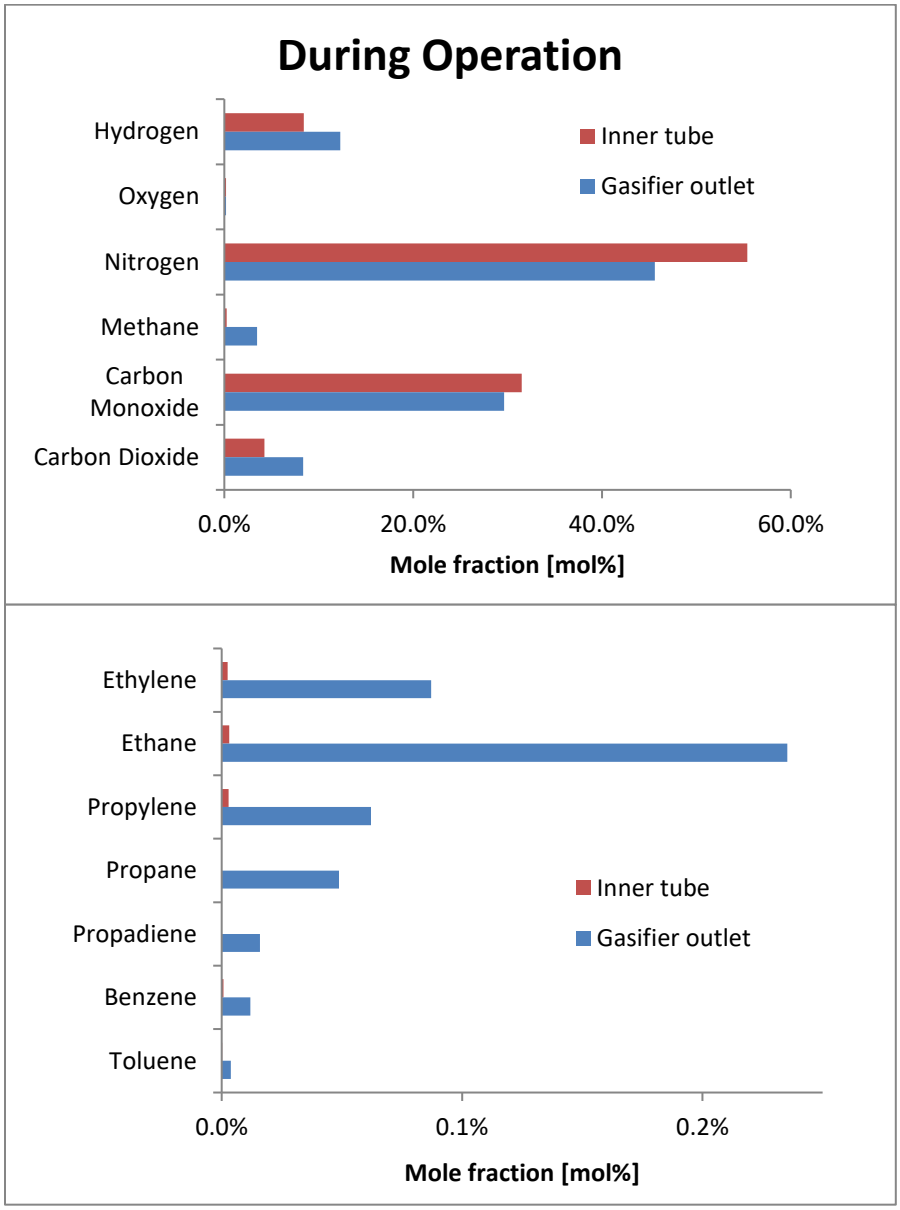
Source: West Biofuels, LLC

Figure 55: Gas Composition During Startup From Test #2, Loc 4 And Loc 7



Source: West Biofuels, LLC

Figure 56: Gas Composition During Operation For Test #2, Loc 4 and Loc 7



Source: West Biofuels, LLC

Forest Biomass Runs

The conditioned gas test runs demonstrated the performance of the gasifier on forest biomass feedstock in various stable operating conditions shown in Table 66. A summary of the total inputs and outputs for these complete test runs from plant startup to shutdown/idle is shown in Table 67. These testing periods included thirteen plant startups and shutdowns and the production of over 13 tons of producer gas containing 101 GJ of chemical energy (based on an average higher heating value of 6.29 MJ/kg) over many days of cumulative gas production.

Table 67: Summary Of Forest Biomass Runs With CircleDraft Gasifier System

Test Number	Test Descriptor	Gas Production Period (hr)	Biomass Input (kg)	Air Input (kg)	Steam Input (kg)	Producer Gas Generated (kg)	Biochar Produced (kg)	Gas Output (GJ)
3	June 2016 Run	37.5	4894	2871	749	4446	718	28.0
4	October 2016 Run	23.5	5295	2534	1511	3984	799	25.1
5	December 2016 Run	26.0	4268	2447	1299	3980	610	25.0
6	February 2017 Run	5.2	1181	507	266	1142	140	7.2
7	June 2017 Run	6.5	2476	925	597	1498	224	9.4
8	September 2017 Run	4.3	*1249	660	426	984	113	6.2

***Estimated based on equivalent raw wood input to a torrefier system prior to the gasifier**

Source: West Biofuels, LLC

For each testing period where the reactor reached the desired steady state condition, data was collected on all of the operating variables and inputs as well as the resulting gas composition and gas and biochar productivity. These results are shown in Table 68 for various testing days and the steady state period was at least 2 hours and up to 8 hours. The results for the average gas compositions for the stable testing periods are shown in Figure 57 and Figure 58. The producer gas produced always showed sufficient calorific content for engine usage primarily due to hydrogen and carbon monoxide but also some hydrocarbons. The production of higher hydrocarbons were much more variable than the major gasses and this could have been due to channeling in the reactor or pyrolysis zone inconsistency causing variable amounts of volatiles production.

UC researchers performed tar and particulate analysis during some of the test runs. Table 69 shows a summary of the results. They measured the tar loading with both SPE and gravimetric methods. Both methods measured bulk tar concentrations between 2,500 and 19,200 milligrams per normal cubic meter in the raw gas. The tar concentrations in the conditioned gas were between 800 and 2,500 with an average reduction on the order of 89 percent with the gas scrubbing system. However, these concentrations are still well above the levels set out in the objectives by an order of magnitude. The team expected that the gasification of torrefied wood would reduce these concentrations but the results were non-conclusive and did not indicate an improvement in the level of tar generation. This gasifier system will require substantial additional condensable reduction or removal to meet long-term gas engine performance specifications.

It is difficult to precisely measure tar dew point for the samples because of the large number of unidentified compounds of high molecular weight. Tar dew point is estimated with a compositional model that uses the constituent properties and concentrations. However, using reasonable assumptions about the mixture of these species, it can be concluded that tar dew point exceeds ambient temperatures which is a major concern for condensation of these

compounds inside all gas handling lines, the intake into the gas engine, the engine intercooler, and other places where temperatures are below the actual dew point.

Particulate concentrations were in the range of 500 to 800 milligrams per normal cubic meter in the cleaned gas which is also above the acceptable levels for introduction into a gas engine. This indicates that additional particulate control will be needed in a commercial system (for example filter or precipitator) to meet long-term performance objectives.

In analyzing the results some useful relationships were developed. One of the primary observations is how the productivity of the plant is clearly related to the air input. In Source: West Biofuels, LLC

Figure 59, it can be seen that there is a linear relationship with gas production and air flowrate. In Figure 60, the relationship between air input and biomass consumption and biochar production are shown. All of these relationships are helpful for having consistent performance of this system on biomass.

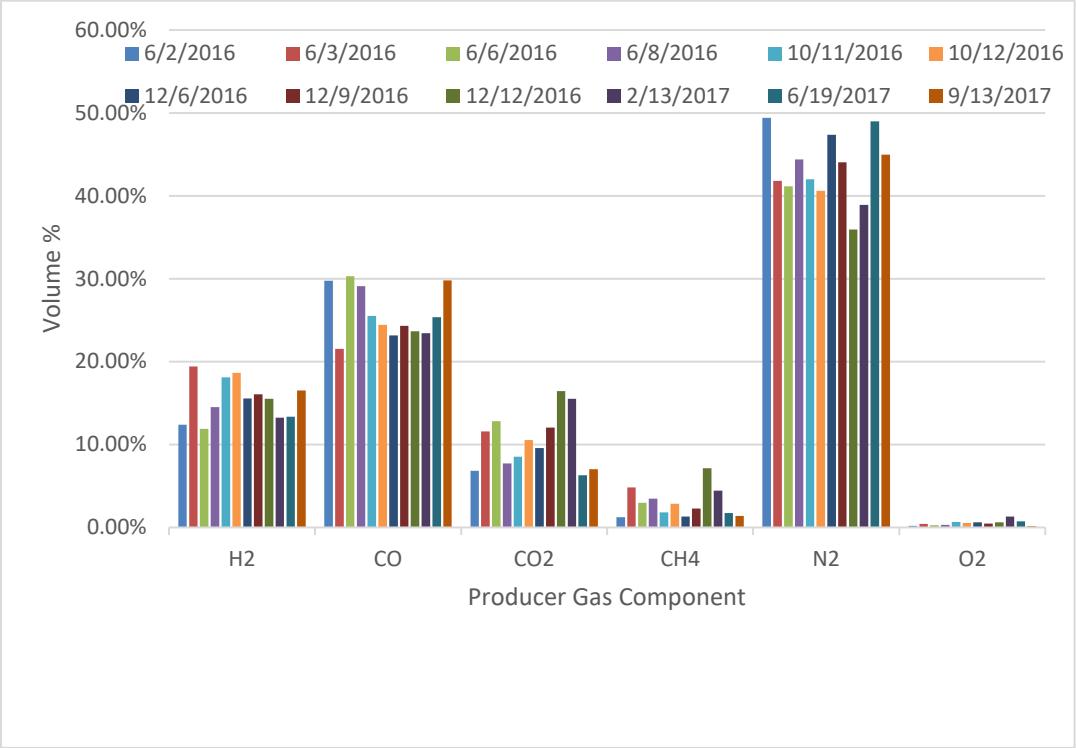
Table 68: Performance Results For Steady State Periods

Test Number	Date	Air Input (kg/hr)	Steam Input (kg/hr)	Biochar Removal (kg/hr)	Producer Gas Generation (kg/hr)	– (kW)	Biomass Consumption* (kg/hr)	– (kW)	Efficiency
3	6/2/16	140.1	19.9	7.6	196.4	282.8	87.7	450.4	0.63
3	6/3/16	147.2	20.0	22.3	230.5	443.2	111.5	573.2	0.77
3	6/6/16	59.8	19.7	12.2	104.3	170.7	56.0	287.9	0.59
3	6/7/16	56.4	19.7	22.1	85.8	155.9	42.8	220.1	0.71
3	6/8/16	58.1	19.7	22.5	88.4	160.6	44.1	226.7	0.71
3	6/9/16	64.3	16.7	26.2	97.8	177.7	48.8	250.9	0.71
4	10/11/16	124.9	77.6	30.1	191.6	317.5	87.2	448.3	0.71
4	10/12/16	122.8	74.4	36.9	198.0	348.4	94.8	487.3	0.72
5	12/6/16	159.6	54.1	23.8	226.3	313.7	93.9	482.4	0.65
5	12/7/16	108.5	64.9	24.4	161.7	235.4	70.9	364.5	0.65
5	12/9/16	148.6	31.2	25.6	233.4	356.1	107.9	554.6	0.64
6	2/13/17	159.6	50.0	26.9	288.0	490.8	150.8	774.8	0.63
7	6/19/17	359.8	34.6	29.6	505.3	663.6	185.2	998.1	0.66
8	9/13/17	153.5	38.5	32.5	227.0	372.8	128.1	668.8	0.56

***Biomass consumption is estimated from system carbon balance**

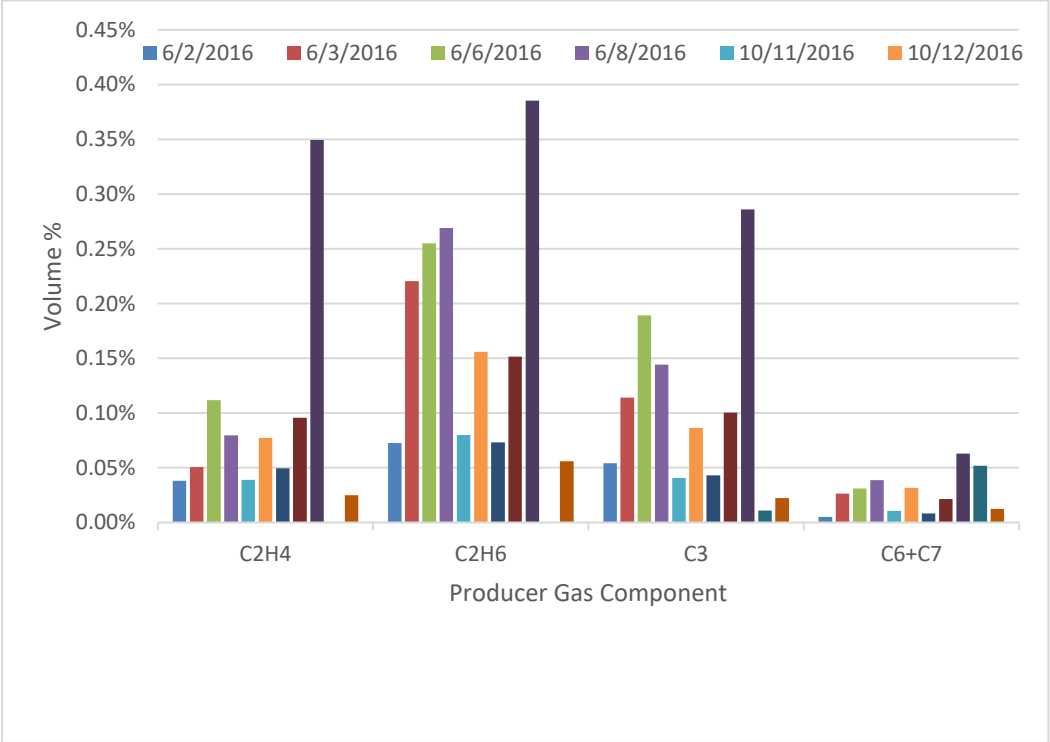
Source: West Biofuels, LLC

Figure 57: Producer Gas Composition For Steady State Periods, Major Gasses (vol%)



Source: West Biofuels, LLC

Figure 58: Producer Gas Composition For Steady State Periods, Minor HC Gasses (vol%)



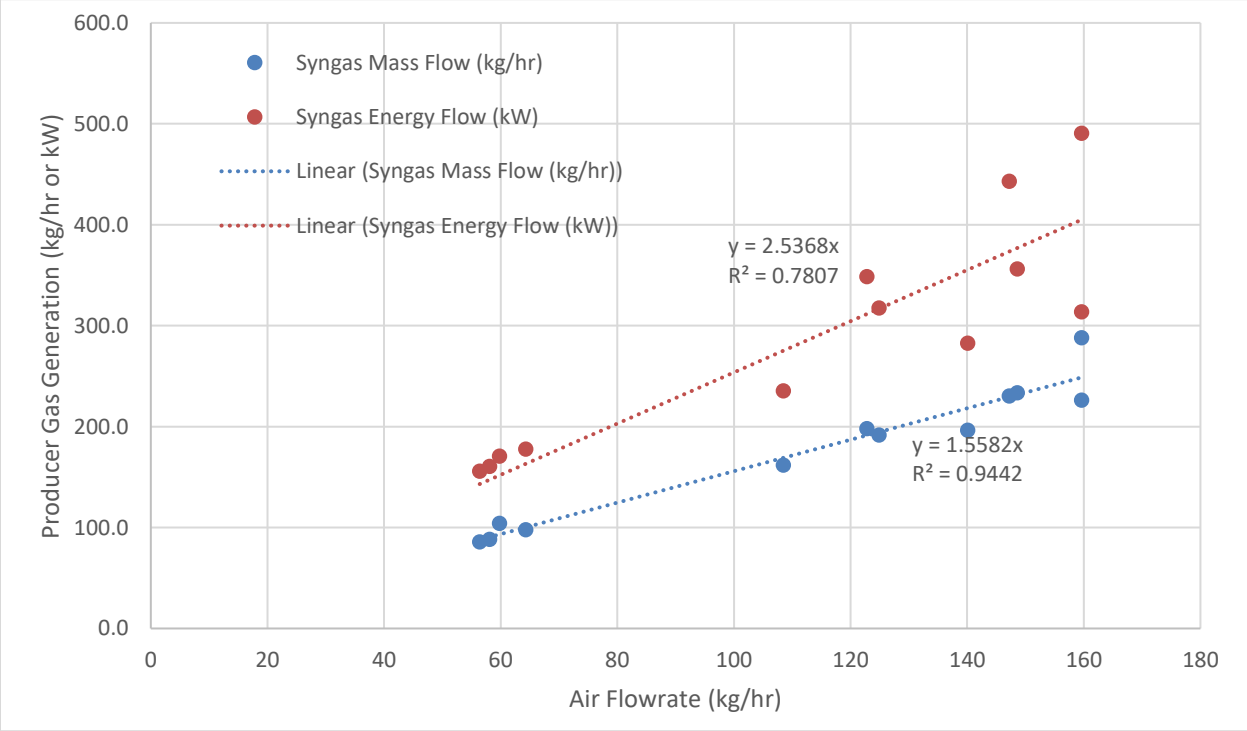
Source: West Biofuels, LLC

Table 69: Producer Gas Composition, Tars And Particulate Matter (mg/nm^3)

	Pre-Scrubber			Post-Scrubber			Average Reduction
(mg/Nm^3)	Min	Max	Average	Min	Max	Average	
Tar Species							
Benzene	723	1943	1266	423	600	499	61%
Toluene	394	1533	964	164	437	237	75%
Ethylbenzene	0	586	338	0	55	4	99%
Xylene	131	514	323	0	117	23	93%
Styrene	42	431	257	0	66	14	95%
Naphthalene	27	239	144	0	22	4	97%
*Unidentified	1237	13984	8320	194	1176	507	94%
Total Tar	*2554*	*19231*	*11613*	*781*	*2455*	*1287*	*89%*
Total Particulate				*536*	*829*	*683*	

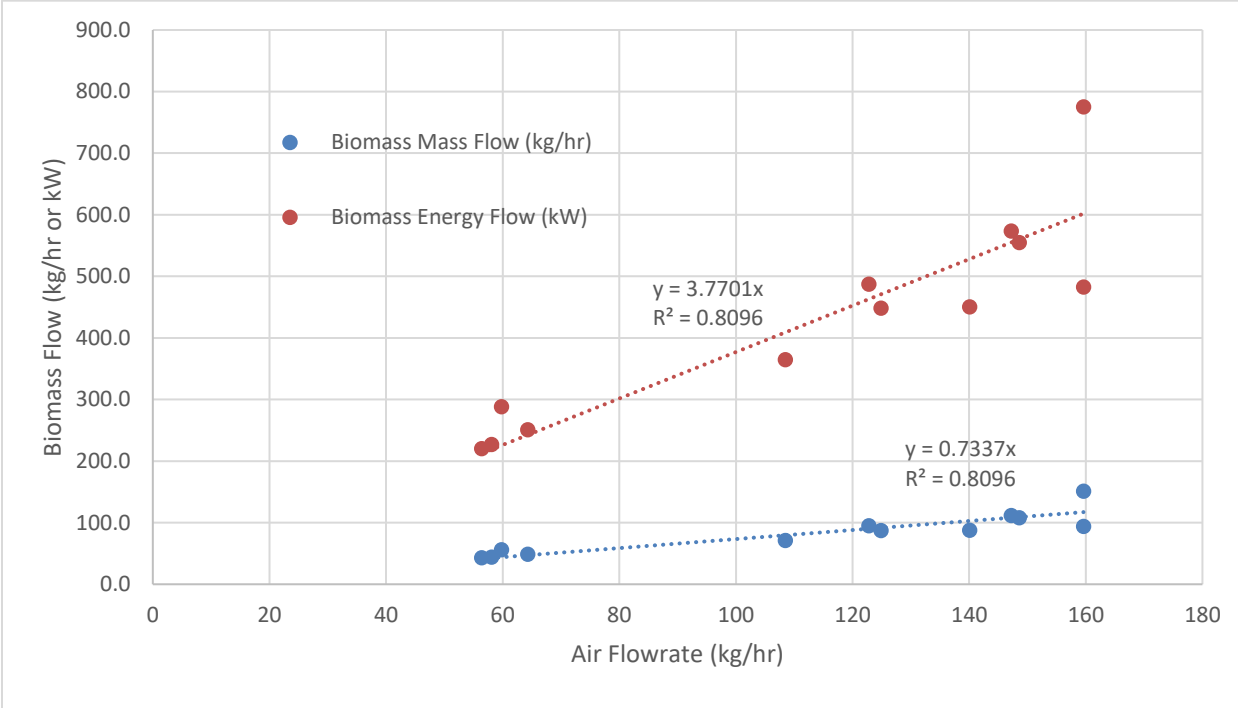
Source: West Biofuels, LLC

Figure 59: Producer Gas Mass And Energy Production Vs. Input Air Flowrate



Source: West Biofuels, LLC

Figure 60: Biomass Consumption Vs. Input Air Flowrate



Source: West Biofuels, LLC

System Modeling

Researchers developed simulations of the CircleDraft system to better understand the reactions occurring within the gasifier. The research team developed a three-dimensional CFD (computational fluid dynamics) model to simulate the circle-draft biomass gasifier. In this model, the MP-PIC (Multiphase Particle-In-Cell) method was applied to simulate gas-solid flows in the circle-draft biomass gasifier. The heterogeneous and homogeneous reaction kinetics were integrated with the momentum, mass, and energy transport equations to predict producer gas distribution and reactor temperature profile in the circle-draft biomass gasifier.

Model Description

The MP-PIC method is an Eulerian-Lagrangian method. This model was built in Barracuda VR (virtual reactor). The softward model couples the Navier-Stokes equation with LES to simulate the gas phase. The particulate phase is calculated with the particle acceleration equation (O'Rourke and Snider 2014), based on Newton's motion law for each particle parcel. The momentum transport equation was coupled with the mass and energy transport equations to simulate mass and energy transfer in the circle-draft biomass gasifier. The calculation of thermal radiation in the MP-PIC method was based on Stefan-Boltzmann law. The analysis uses the finite volume method to solve the discretized governing equations.

Governing Equations

The continuity and momentum equations for the gas phase are shown as follows:

$$\frac{\partial(\alpha_g \rho_g)}{\partial t} + \nabla \cdot \left(\alpha_g \rho_g u_g\right) = \delta m_p \qquad (1)$$

$$\frac{\partial(\alpha_g \rho_g u_g)}{\partial t} + \nabla \cdot (\alpha_g \rho_g u_g u_g) = -\nabla p - F + \alpha_g \rho_g g + \nabla \cdot \tau$$

(2)

$$\tau = \mu \left(\frac{\partial u_{g,i}}{\partial x_j} + \frac{\partial u_{g,j}}{\partial x_i} \right) - \frac{2}{3} \mu \delta_{ij} \frac{\partial u_k}{\partial x_k} \quad (3)$$

$$\mu = \mu_{lam} + \mu_{eddy} \quad (4)$$

μ_{eddy} is calculated by the sub-grid scale (SGS) model[30] as shown below:

$$\mu_t = \frac{1}{2} C \rho_g \Delta^2 \sqrt{\left(\frac{\partial u_{g,i}}{\partial x_j} + \frac{\partial u_{g,j}}{\partial x_i} \right)^2} \quad (5)$$

$$\Delta = \sqrt[3]{V} \quad (6)$$

C is a model constant of 0.01. The particle velocity is calculated with the particle acceleration equation as follows:[31]

$$\frac{du_p}{dt} = D_p (u_g - u_p) - \frac{\nabla p}{\rho_p} - \frac{\nabla \tau_p}{\rho_p \alpha_p} + g + \frac{\overline{u_p} - u_p}{2\tau_D} \quad (7)$$

The following equation models the solid stress tensor, τ_p:

$$\tau_p = \frac{10 P_s \alpha_p{}^{\beta}}{max[(\alpha_{cp} - \alpha_p), \varepsilon(1 - \alpha_p)]} \quad (8)$$

α_{cp} is the close-pack volume fraction of the particulate phase. In this work it was set as 0.42, based on experimental data. The following equation is used to model the solid volume fraction, α_p:

$$\alpha_p = \iiint f \frac{m_p}{\rho_p} dm_p du_p dT_p \quad (9)$$

The interphase momentum exchange between the gas and particle phase is given by:

$$F = \iiint f \left\{ m_p \left[D(u_g - u_p) - \frac{\nabla p}{\rho_p} \right] + u_p \frac{dm_p}{dt} \right\} dm_p du_p dT_p \quad (10)$$

The drag function of D is described as follows:[32]

$$D_{p1} = \frac{6}{8} C_d \frac{\rho_g |u_g - u_p|}{\rho_p d_p} \quad (11)$$

$$C_d = \begin{cases} \frac{24 \alpha_g{}^{-2.65}}{Re}, Re < 0.5 \\ \frac{24 \alpha_g{}^{-2.65}}{Re} (1 + 0.15 Re^{0.687}), \quad 0.5 \le Re \le 1000 \\ 0.44 \alpha_g{}^{-2.65}, \quad Re > 1000 \end{cases}$$

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[30] Smagorinsky, J. (1963), "General Circulation Experiments with the Primitive Equations," Monthly Weather Review, 91, 99-164.

[31] O'Rourke, P. J., and Snider, D. M. (2010), "An Improved Collision Damping Time for Mp-Pic Calculations of Dense Particle Flows with Applications to Polydisperse Sedimenting Beds and Colliding Particle Jets," Chemical Engineering Science, 65, 6014-602

[32] Gidaspow, D. (1994), "Multiphase Flow and Fluidization. Continuum and Kinetics Theory Description," Academic Press, Boston.

(12)

$$D_{p2} = 0.5\left(\frac{180\alpha_p}{\alpha_g Re} + 2\right)\frac{2\rho_g|u_g - u_g|}{d_p\rho_p} \quad (13)$$

$$D_p = \begin{cases} D_{p1} & \alpha_p < 0.75\alpha_{cp} \\ (D_{p2} - D_{p1})\left(\frac{\alpha_p - 0.75\alpha_{cp}}{0.1\alpha_{cp}}\right) + D_{p1} & 0.85\alpha_{cp} \geq \alpha_p \geq 0.75\alpha_{cp} \\ D_{p2} & \alpha_p > 0.85\alpha_{cp} \end{cases}$$

(14)

The mass and energy transport equations for the particulate phase are:[33]

$$\delta m_p = -\iiint f\,\frac{dm_p}{dt}\,dm_p du_p dT_p \quad (15)$$

$$\frac{dm_p}{dt} = \sum_{i=1}^{N}\frac{dm_{p,n}}{dt} \quad (16)$$

$$\frac{dm_{p,n}}{dt} = \frac{\alpha_g Mw_{p,n}}{\rho_p\alpha_p}m_p\frac{dC_{p,n}}{dt} \quad (17)$$

$$C_V\frac{dT_p}{dt} = \frac{1}{m_p}\frac{k_d Nu}{d_p}A_p(T_g - T_p) \quad (18)$$

Reaction Kinetics

In the circle-draft gasifier, biomass is fed at the top and then drops into the drying zone where moisture is released from biomass. Dry biomass continues to fall into the pyrolysis zone. Biomass pyrolysis reactions release volatiles and generate char. Char particles pass through the stabilization zone and reach gasification zone. Char particles react with air and steam injected from the bottom to generate syngas. The residual char and ash fall down into the bottom region where are removed from the gasifier with an ash auger. In this model heterogeneous reactions include biomass drying, pyrolysis, partial combustion of primary char, char and CO_2 reaction, char and steam reaction, and methane formation. The model also considers the homogeneous reactions such as water gas shift reaction and gas oxidation reactions.

Heterogeneous reactions:[34]

$\text{Moisture in Biomass}_{(s)} \rightarrow H_2O_{(g)}$ (R-1)

$r_1 = 5.13 \times 10^{10}\exp(\frac{-10585}{T_p})m_{biomass}$

$\text{Biomass} \rightarrow \text{Volatiles}_1(CO, CO_2, H_2, CH_4, C_2H_4, C_2H_6) + \text{Primary char} + \text{Tar}$ (R-2)

$r_2 = 1.49 \times 10^{5}\exp(\frac{-1340}{T_p})m_{biomass}$

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[33] Snider, D. M., Clark, S. M., and O'Rourke, P. J. (2011), "Eulerian–Lagrangian Method for Three-Dimensional Thermal Reacting Flow with Application to Coal Gasifiers," Chemical Engineering Science, 66, 1285-1295.

[34] Walker Jr, P. L., Rusinko Jr, F., and Austin, L. G. (1959), "Gas Reactions of Carbon," in *Advances in Catalysis* (Vol. Volume 11), eds. P. W. S. D.D. Eley and B. W. Paul, Academic Press, pp. 133-221.

Yu, J., et al. (2011), "Biomass Pyrolysis in a Micro-Fluidized Bed Reactor: Characterization and Kinetics," Chemical Engineering Journal, 168, 839-847.

Xu, J., and Qiao, L. (2012), "Mathematical Modeling of Coal Gasification Processes in a Well-Stirred Reactor: Effects of Devolatilization and Moisture Content," Energy & Fuels, 26, 5759-5768.

The reaction rate of primary pyrolysis was calculated with a single-step global reaction mechanism[35]. Using the best fit to the experimental data from this work, the researcher selected the pre-exponential factor of 1.49×10^5.

$$\text{Primary Char} + n_1O_2 \rightarrow n_2CO + n_3CO_2 + n_4H_2 + n_5H_2O + \text{Char} \quad \text{(R-3)}$$

$$r_3 = 8.68 \times 10^6 m_{prim.char} T_p \exp(\frac{-29160}{T_p})[O_2]$$

The primary char generated in biomass pyrolysis was defined as $CH_{1.286}O_{0.4585}$ according to experimental data. To simplify the model, char generated in the partial combustion of primary char is assumed to be pure carbon. Tar generated in biomass pyrolysis is defined as $CH_{1.331}O_{0.6979}$ (Ingram, et al. 2008).

$$C + CO_2 \leftrightarrow 2CO \quad \text{(R-4)}$$

$$r_{4f} = 1.272 m_c T_p \exp(\frac{-22645}{T_p})[CO_2]$$

$$r_{4r} = 1.044 \times 10^{-4} m_c {T_p}^2 \exp(\frac{-2363}{T_p} - 20.92)[CO]^2$$

$$C + H_2O \leftrightarrow CO + H_2 \quad \text{(R-5)}$$

$$r_{5f} = 1.088 m_c T_p \exp(\frac{-22645}{T_p})[H_2O]$$

$$r_{5r} = 1.044 \times 10^{-4} m_c {T_p}^2 \exp(\frac{-6319}{T_p} - 17.29)[H_2][CO]$$

$$C + 2H_2 \rightarrow CH_4 \quad \text{(R-6)}$$

$$r_6 = 1.18 \times 10^{-5} m_c T \exp(\frac{-17921}{T_p})[H_2]$$

Homogeneous reactions:[36]

$$CO + H_2O \rightarrow CO_2 + H_2 \quad \text{(R-7)}$$

$$r_7 = 2.75 \exp(\frac{-10079}{T_g})[CO][H_2O]$$

$$CO + 0.5O_2 \rightarrow CO_2 \quad \text{(R-8)}$$

$$r_8 = 1.00 \times 10^{10} \exp(\frac{-15155}{T_g})[CO][O_2]^2$$

$$H_2 + 0.5O_2 \rightarrow H_2O \quad \text{(R-9)}$$

$$r_9 = 2.2 \times 10^9 \exp(\frac{-13110}{T_g})[H_2][O_2]^2$$

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \quad \text{(R-10)}$$

---

[35] Yu, J., et al. (2011), "Biomass Pyrolysis in a Micro-Fluidized Bed Reactor: Characterization and Kinetics," Chemical Engineering Journal, 168, 839-847.

[36] Padban, N., and Becher, V. (2005), "Clean Hydrogen-Rich Synthesis Gas," CHRISGAS, fuel from biomass.

Gómez-Barea, A., and Leckner, B. (2010), "Modeling of Biomass Gasification in Fluidized Bed," Progress in Energy and Combustion Science, 36, 444-509.

Lu, X., and Wang, T. (2013), "Water–Gas Shift Modeling in Coal Gasification in an Entrained-Flow Gasifier – Part 2: Gasification Application," Fuel, 108, 620-628.

$$r_{10} = 2.8 \times 10^9 \exp(\frac{-24417}{T_g})[CH_4][O_2]^2$$

Simulation Setup

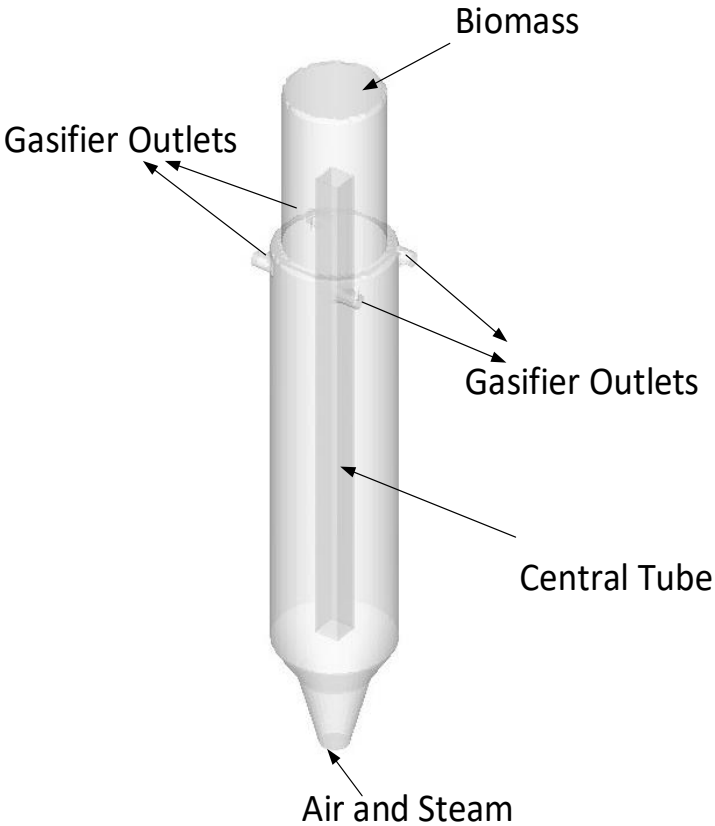
The CFD model was built in Barracuda Virtual Reactor® using the MP-PIC method to simulate a 2MWth circle-draft biomass gasifier at Woodland Biomass Research Center, Woodland, California. The height of the gasifier is 10.4 meters and the diameter of the gasifier is 1.7 meters.

The boundary settings of the circle-draft biomass gasifier are shown in Figure 61. The model defines biomass feeding points at the top, four gas outlets are set at the side, and steam & air injections are defined at the bottom of the gasifier.

A central tube is built in the center of the gasifier. Note that the structure of the central tube is in the shape of a rectangular box for simplicity, instead of the original cylindrical-tube shape. The total volume of the structure is still the same as that of the original central tube, which ensures that the shape of the central tube does not impact that the predicted flow pattern in the gasifier. In the Barracuda VR® software orthogonal grids are used to mesh the geometries. For round-shaped geometries, more gridlines and cells are needed to capture necessary geometry details. In comparison, geometries with straight edges require less gridlines and computational cells. Therefore, in this work a rectangular-box channel is built to simplify the geometry to achieve better computation efficiency.

The ultimate analysis data of biomass used in experiments are shown in Table 70 and the model settings of base case are listed in Table 71. A normal distribution with a standard deviation of $0.2d_p$ was applied to describe the size distribution of biomass particles. The thermal conductivity was set as 0.12 W/(mK) and the heat capacity of biomass was set as 1760 kJ/kgK.

Figure 61: Boundary Settings For The CircleDraft Gasifier



Source: West Biofuels, LLC

Table 70: Ultimate Analysis Of Biomass Feedstock

Elements	wt %
Moisture	17.23
C	43.16
H	5.06
O	33.26
N	0.10
Ash	1.19

Source: West Biofuels, LLC

Table 71: Base Case Settings

Description	Value
Biomass particle diameter (mm)	5.64
Biomass density (kg/m^3)	662.85
Initial solid packing	0.42
Outlet pressure (atm, abs.)	1
Biomass feeding rate (kg/h)	101.42
Air feeding rate (kg/h)	77.44

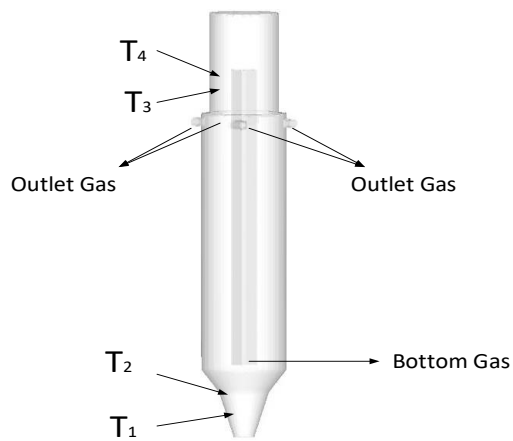
Source: West Biofuels, LLC

The model was solved with the control volume method. A computational grid with 111,537 grids was applied for the CFD model. A study used three computational grids with 88,750, 111,537, and 168,175 cells to determine optimal grid resolution. The difference of the simulation results between the three cases are less than 5 percent. Considering relative low computational cost and acceptable model accuracy, the grid with 111,537 cells was selected for the base case. The simulation time was set as 1000 seconds to reach the steady-state. The convergence criterions for volume, pressure, velocity, and energy were set as 10^{-6}, 10^{-7}, 10^{-6}, and 10^{-7}. The iteration numbers were set as 10, 2000, 50, and 100 for each transport equations, respectively. The size of time step is in the range of 10^{-3} to 10^{-5} seconds and is automatically controlled by the Courant-Friedrichs-Lewy (CFL) scheme[37] to achieve a converged solution. The model was computed using the GPU-accelerated computing technology on a computer with an Intel® i7 CPU @3.50 GHz and a GeForce GTX TITAN graphics card. The 1000-s simulation took about 5 days to be completed.

Modeling Results

Figure 62 shows the locations of temperature sensors and producer gas sampling points. Considering the air and steam inlet as the bottom surface, the model recorded the temperatures of T_1, T_2, T_3, and T_4 in the char gasification and pyrolysis zones at the heights of 0.95, 1.44, 8.68, and 9.17 meters. Producer gas was sampled from the bottom entry point of the central tube and 4 gas outlets as the bottom producer gas and the final producer gas output, respectively.

Figure 62: Temperature Sensor And Gas Sampling Locations



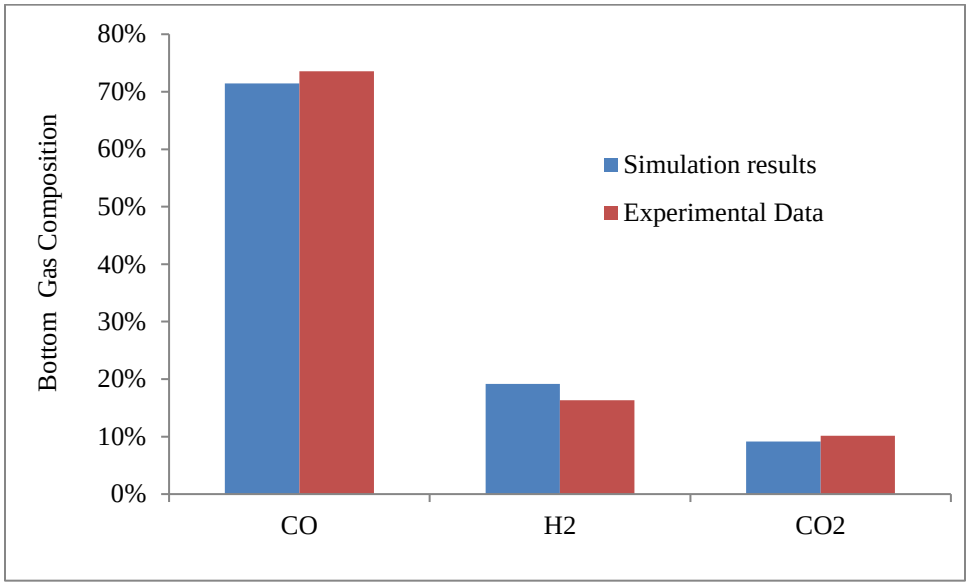
Source: West Biofuels, LLC

In Figure 63, the predicted producer gas composition in the bottom region is compared with experimental data. It is observed that the gas composition prediction in the bottom region is

[37] Courant, R., Friedrichs, K., and Lewy, H. (1967), "On the Partial Difference Equations of Mathematical Physics," IBM Journal.

consistent with experiment measurement. The bottom producer gas in experiments was sampled at the bottom surface of the central tube in the circle-draft gasifier.

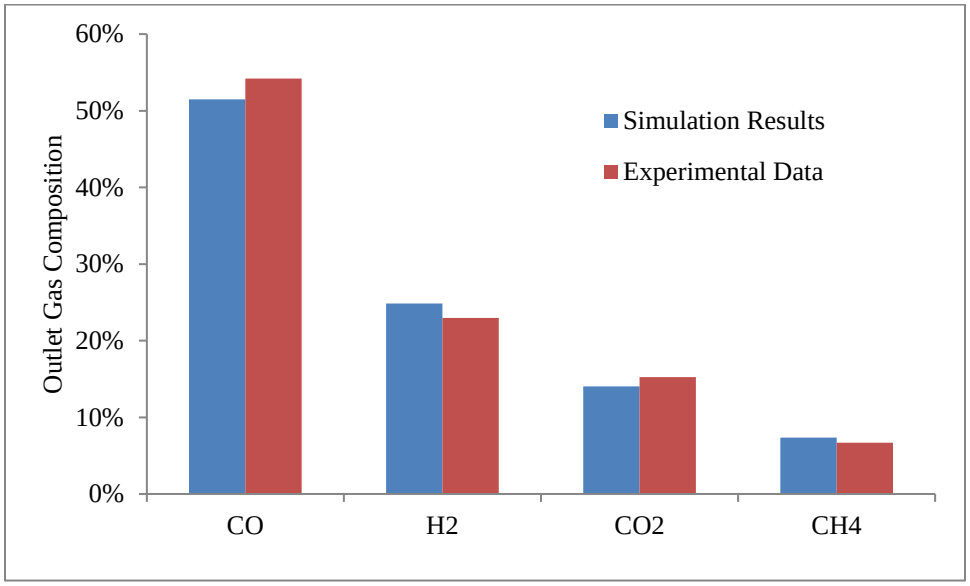
Figure 63: Comparison Of Bottom Producer Gas



Source: West Biofuels, LLC

The predicted outlet gas composition is also compared with experimental data. As seen in Figure 64, the difference between the simulation results and experimental data is averagely less than 3 percent.

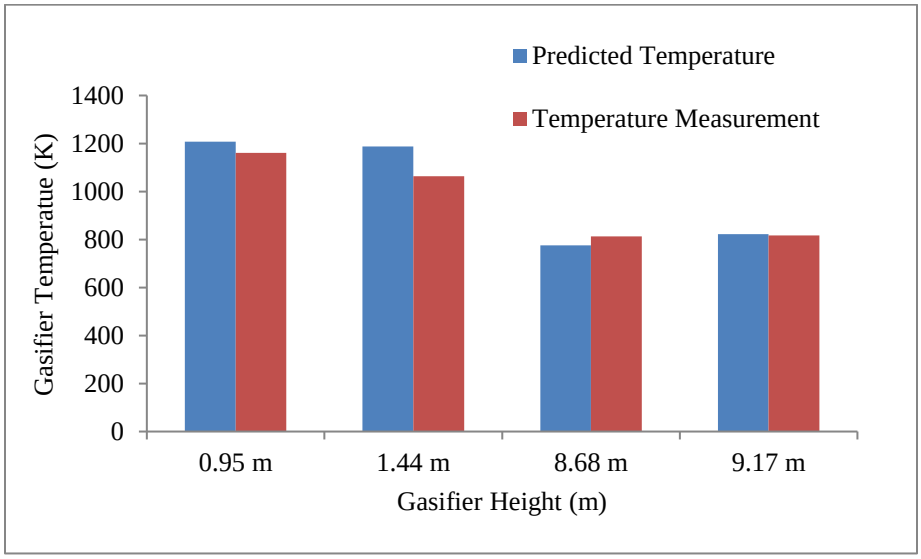
Figure 64: Comparison Of Outlet Producer Gas



Source: West Biofuels, LLC

Figure 65 demonstrates the comparison of the gasifier temperatures in biomass pyrolysis and char gasification zones. As seen in the figure, the temperature predictions agree well with temperature measurements.

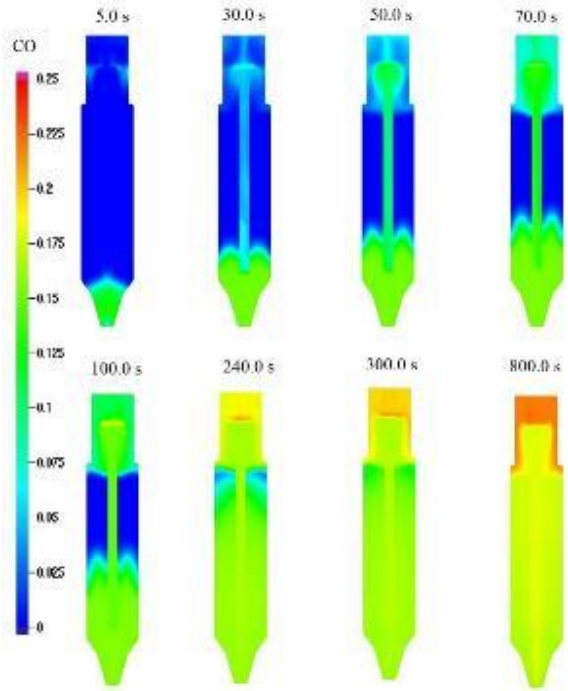
Figure 65: Comparison Of Gasifier Temperature



Source: West Biofuels, LLC

Figure 66 demonstrates the transient distribution of CO molar fraction in the circle-draft gasifier.

Figure 66: Transient CO Distribution

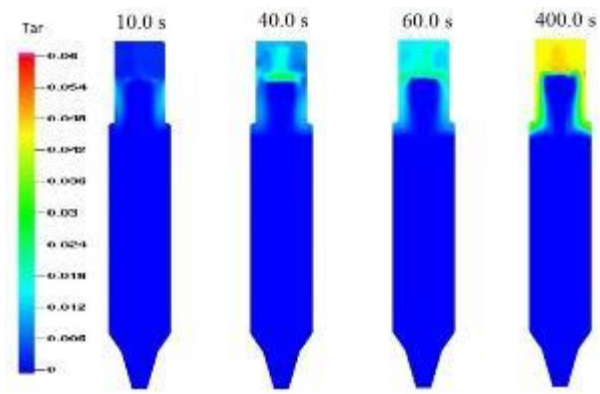


Source: West Biofuels, LLC

As shown in the figure, CO is generated in the bottom region due to gasification and then flows through the solid bed to reach the central tube. The gas rises through the central tube to the pyrolysis zone in the upper region of the gasifier, where more CO is generated from biomass pyrolysis. Two streams of CO from the bottom and upper regions merges and accumulates in the upper region of the gasifier. Meanwhile, the rest of CO generated in the bottom region gradually penetrates through the annular region surrounding the central tube and reaches the upper region. All of CO from the bottom and upper regions is eventually extracted from 4 gas outlets at the side of the gasifier.

Figure 67 shows transient tar distribution in the circle-draft gasifier. It is observed that tar is only generated in the pyrolysis zone which is in the upper region of the gasifier. Tar gradually accumulates in the region and finally leaves the gasifier through the gas outlets. As predicted in the model, since tar is generated in the upper region and is extracted together with other gases from the gas outlets, tar concentration in the final gas output is expectedly high, which matches our observations in the experiment.

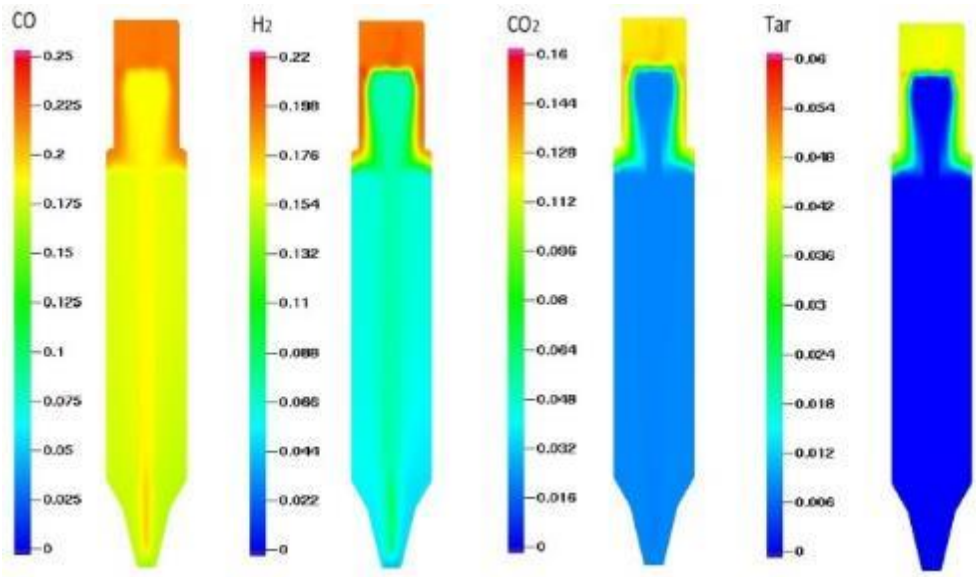
Figure 67: Transient Tar Distribution



Source: West Biofuels, LLC

The molar fractions of CO, H_2, CO_2, and Tar in the steady-state are shown in Figure 68. As seen in the figure, the char gasification and biomass pyrolysis zones both generate CO, H_2, and CO_2. CO and H_2 are concentrated in the central region, which is mainly due to producer gas production from water gas shift reaction. On the other hand, tar is only generated from the top region and is eventually extracted together with other gases through the gas outlets.

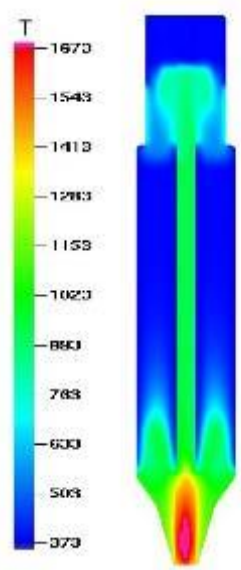
Figure 68: Steady-State Producer Gas Composition



Source: West Biofuels, LLC

The temperature distribution in the circle-draft gasifier is shown in Figure 69. As indicated in the figure, the central region in the bottom region is hot due to partial combustion of char and the temperature in the upper region is lower due to biomass gasification.

Figure 69: Temperature Distribution Of CircleDraft Biomass Gasifier



Source: West Biofuels, LLC

Results and Findings

Based on the current testing, the producer gas composition and operating range characteristics of the tested gasifier system are shown in Table 72.

Table 72: Measured Operating Characteristics of the CircleDraft Gasifier System

Gas Composition	Min	Max	Average
H_2 (vol %)	12.49%	20.28%	15.47%
CO (vol %)	23.52%	29.41%	26.59%
CH_4 (vol %)	1.47%	7.13%	3.55%
C_2H_4 (vol %)	0.00%	1.80%	0.35%
C_3+ (vol %)	0.06%	0.15%	0.10%
CO_2 (vol %)	7.39%	16.44%	10.68%
N_2 (vol %)	35.94%	46.06%	42.51%
Tars (mg/Nm^3)	781	2455	1287
Particulate (mg/Nm^3)	536	829	683
HHV(MJ/kg)	5.31	7.78	6.29
Cold Gas Eff. (%)	56.20%	78.50%	65.20%
Biochar Production (kg/dry kg)	0.09	0.21	0.15

Source: West Biofuels, LLC

The gasifier testing did not succeed at meeting many of the project targets and failed to meet certain critical targets. Table 73 shows the objective targets, the testing results, the expected performance at full capacity, and whether the target objective was achieved.

Table 73: Original Task Objectives Comparison

Objective	Original Target	Testing Results	Expected Performance at Full Capacity	Objective Achieved?
Thermal Efficiency:	≥70%;	63-77%	65%	NO
Throughput Rate:	≥ 900 dry lbs/hr;	140-620 dry lbs/hr	450 dry lbs/hr	NO
Producer gas Energy Content:	≥ 150 Btu per ft^3;	168-210 Btu per ft^3	190 Btu per ft^3	YES
Tar Content:	< 20 mg/Nm^3;	780-2455 mg/Nm3	1000 mg/Nm^3	NO
Tar Dew Point:	< 15°C;	> 40°C;	> 40°C;	NO
Particulates:	< 5 mg/Nm^3 and less than 1 micron;	536-829 mg/Nm^3	600 mg/Nm^3	NO
Hydrogen Sulfide:	< 50 ppm;	13-40 ppm	25 ppm	YES
Biochar Production:	≥ 72 dry lbs/hr	20-75 dry lbs/hr	75 dry lbs/hr	YES
Biochar Quality:	(IBI) Biochar Standards	See Appendix A	See Appendix A	YES

Source: West Biofuels, LLC

The thermal efficiency was slightly lower than the desired target, 65 percent instead of 70 percent. The throughput rate achieved was about half of the original target rate, meaning the production capacity of the system is about half of what was originally envisioned. The producer gas was satisfactory in terms of energy content and hydrogen sulfide concentration but failed to meet tar and particulate objectives required for long-term performance with a gas engine. The biochar production was satisfactory with the system and met objective targets.

The conclusion of this section is that the System 1 configuration (Figure 47) will not work at the capacity anticipated and will require substantial improvements to gas quality for tars and particulates to be coupled with a gas engine generator system. This is in addition to substantial operating issues with forest thinning residues in terms of bridging, nesting, and channeling within the reactor that required frequent shut-down and maintenance to return the system to operation. Maintenance time exceeded operating time during the project runs and the same is expected at the commercial scale. The pre-treatment of the material with torrefaction addressed the material flow issues but failed to achieve a measurable improvement in gas quality. For the System 2 configuration (Figure 48) is more feasible from an operating perspective but still relies on further improvement in gas quality in order to be coupled with a gas engine system.

CHAPTER 4:
Engine Performance

Engine Generator Test Plan

The Engine-Generator Test Plan provides a detailed account of the methodology that will be utilized to evaluate power production from an engine-generator system operating on the producer gas generated by the CircleDraft gasifier system with the stated objectives:

- Install and test an internal combustion engine generator under various operational settings to identify the optimal configuration for producer gas fuel. Targets include:
  - Electrical Efficiency: $\geq$ 35 percent
  - CHP Efficiency: $\geq$ 75 percent
  - Oil Change Frequency: >750 hours
  - Generator Fault Frequency: <1 fault per 250 hours
  - Operating Speed: 1,000 RPM to 2,000 PRM
  - Equivalence Ratio: $\leq$ 0.55
  - Compression Ratio: $\geq$ 11:1
- Demonstrate engine-generator emission controls that meet California Air Resources Board (CARB) and Regional Air District standards. Targets include:
  - Nitrogen Oxide (NO_x): < 0.07 pounds per MWh
  - Carbon Monoxide (CO): < 0.1 pounds per MWh
  - Volatile Organic Compounds (VOC): < 0.02 pounds per MWh
  - Particulate Matter (PM): < 0.31 pounds per MWh

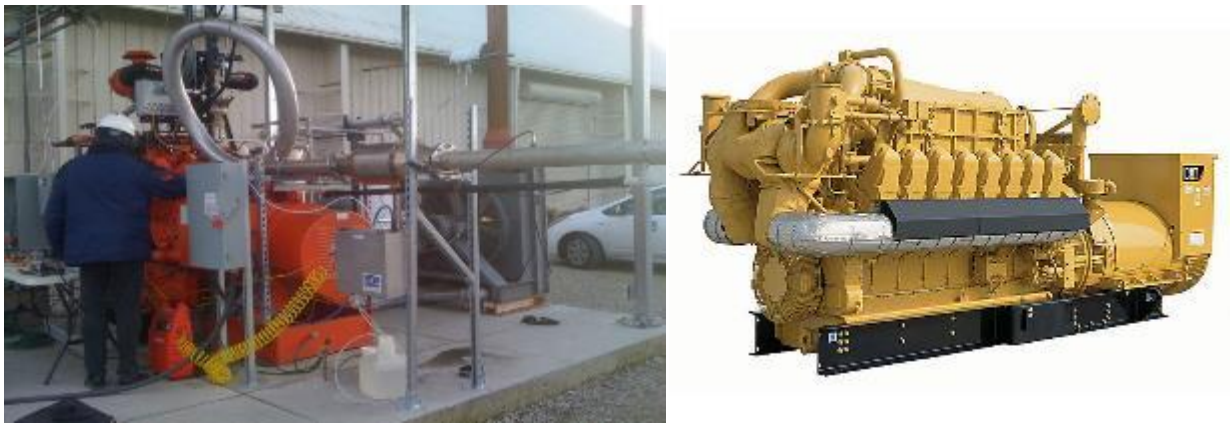
Engine-Generator Test Objectives and Technical Approach

Description of the Process

- Current Technology: West Biofuels has demonstrated engine performance on producer gas with a 200 kW Waukesha engine generator (Figure 70) at their site over a range of equivalence ratios. This engine generator is naturally aspirated and operates at a speed of 1200 rpm with a moderate electrical efficiency in the 20-25 percent range for converting gas to power. It is expected that many gasifier installations to date use similar simple engine systems giving room for efficiency improvements with higher performance engine systems. For emissions control, West Biofuels with partners have demonstrated engine emissions reductions of 95 percent or greater with both three-way catalyst and CompactSCR™ controls.
- Technological Advancement: West Biofuels and partners have been collaborating with Caterpillar Inc. and Holt of California to identify specifications for operating a modern

turbo-charged lean-burn engine generator on producer gas produced from biomass gasifier systems. Caterpillar wishes to qualify its 3500 series gas engine generators (Figure 70) with biomass generated producer gas which has a potential to achieve 35 percent efficiency or greater and also reduced exhaust emissions in lean-burn operation. The key to this integration effort will be demonstrating acceptable low contaminant loading in the producer gas to ensure long-lasting performance of the engine and components like the turbocharger and inter-cooler. While a commercial project may use a generator set of 1MWe or greater (Example G3516C), a smaller generator system (Caterpillar G3406) was be supplied for testing purposes (Figure 71). This 3400 series engine has similar operation to the larger 3500 series including turbocharger and modern controls so this system made a suitable test bed. The manufacturer specifications for the G3406 TA engine-generator running on natural gas are shown in Figure 72. The team felt that testing this smaller system would allow for the most cost-effective way to prove both the producer gas performance relative to another gaseous fuel (natural gas) and configuration and optimization of the exhaust cleanup system at a manageable scale.

Figure 70: (L) Waukesha Generator At West Biofuels Facility, 200 kWe. (R) Caterpillar Commercial Gas Engine G3516C, 1,000 kWe



Source: West Biofuels, LLC

Figure 71: Caterpillar G3406TA Engine Generator Utilized for Producer Gas Testing

Source: West Biofuels, LLC

Figure 72: Engine Generator Specifications For Caterpillar G3406TA

G3406 TA

GAS ENGINE TECHNICAL DATA

CATERPILLAR®

ENGINE SPEED:	1800	FUEL:	NAT GAS
COMPRESSION RATIO:	9.4:1	FUEL SYSTEM:	LPG IMPCO
AFTERCOOLER - MAX. INLET (°F):	130	WITH CUSTOMER SUPPLIED AIR FUEL RATIO	
JACKET WATER - MAX. OUTLET (°F):	210	FUEL PRESS. RANGE (PSIG):	1.5 - 5.0
COOLING SYSTEM:	JW+OC, AC	MIN. METHANE NUMBER:	80
IGNITION SYSTEM:	CDIS	RATED ALTITUDE (FT):	5000
EXHAUST MANIFOLD:	WC	AT AIR TO TURBO. TEMP. (°F):	77
COMBUSTION:	CATALYST	EXHAUST O2 EMISSION LEVEL:	0.2 %O2
		FUEL LHV (BTU/SCF):	905
		APPLICATION:	60 Hz GENSET

RATING AND EFFICIENCY		NOTES	LOAD	100%	75%	50%
ENGINE POWER	(WITHOUT FAN)	(1)	BHP	276	207	138
GENERATOR POWER	(WITH MECH FAN)	(2)	EKW	170	121	76
ENGINE EFFICIENCY	**(ISO 3046/1)**	**(3)**	**%**	**34.3**	**31.5**	**26.9**
ENGINE EFFICIENCY	(NOMINAL)	(3)	%	34.3	31.4	26.9
THERMAL EFFICIENCY	(NOMINAL)	(4)	%	53.2	56.4	61.3
TOTAL EFFICIENCY	(NOMINAL)	(5)	%	87.5	87.8	88.2

ENGINE DATA						
FUEL CONSUMPTION	**(ISO 3046/1)**	**(6)**	**BTU/bhp-hr**	**7418**	**8092**	**9472**
FUEL CONSUMPTION	(NOMINAL)	(6)	BTU/bhp-hr	7418	8092	9472
AIR FLOW (77 °F, 14.7 psi)		(7)	SCFM	385	311	238
AIR FLOW		(7)	lb/hr	1707	1376	1055
COMPRESSOR OUT PRESSURE			in. HG (abs)	48.5	45.2	40.8
COMPRESSOR OUT TEMPERATURE			°F	181	167	147
AFTERCOOLER AIR OUT TEMPERATURE			°F	132	131	130
INLET MAN. PRESSURE		(8)	in. HG (abs)	44.1	35.7	27.1
INLET MAN. TEMPERATURE	(MEASURED IN PLENUM)	(9)	°F	133	133	133
TIMING		(10)	°BTDC	29	29	29
EXHAUST STACK TEMPERATURE		(11)	°F	1007	945	883
EXHAUST GAS FLOW (@ stack temp.)		(12)	CFM	1176	909	668
EXHAUST MASS FLOW		(12)	lb/hr	1811	1461	1121

EMISSIONS DATA					
NOx (as NO2)	(13)	g/bhp-hr	14.85	14.69	13.33
CO	(14)	g/bhp-hr	14.8	15.04	15.03
THC (molecular weight of 15.84)	(14)	g/bhp-hr	1.86	2.22	3.19
NMHC (molecular weight of 15.84)	(14)	g/bhp-hr	0.28	0.34	0.48
EXHAUST O2	(15)	% DRY	0.2	0.2	0.2
LAMBDA			1.04	1.02	1.01

HEAT BALANCE DATA					
LHV INPUT	(16)	BTU/min	34150	27941	21805
HEAT REJECTION TO JACKET (JW)	(17) (22)	BTU/min	10906	10116	9145
HEAT REJECTION TO ATMOSPHERE	(18)	BTU/min	1366	1118	872
HEAT REJECTION TO LUBE OIL (OC)	(19) (22)	BTU/min	1724	1600	1446
HEAT REJECTION TO EXHAUST (LHV to 77°F)	(20)	BTU/min	8052	6094	4403
HEAT REJECTION TO EXHAUST (LHV to 350°F)	(20)	BTU/min	5543	4042	2775
HEAT REJECTION TO A/C (AC)	(21) (23)	BTU/min	387	228	81

CONDITIONS AND DEFINITIONS

ENGINE RATING OBTAINED AND PRESENTED IN ACCORDANCE WITH ISO 3046/1STD. REF. CONDITIONS OF 77°F, 29.6 IN HG BAROMETRIC PRESSURE, 500 FT ALTITUDE). NO OVERLOAD PERMITTED AT RATING SHOWN. CONSULT ALTITUDE CHARTS FOR APPLICATIONS ABOVE MAXIMUM RATED ALTITUDE AND/OR TEMPERATURE.

EMISSION LEVELS ARE BASED ON THE ENGINE OPERATING AT STEADY STATE CONDITIONS. EMISSION TOLERANCES SPECIFIED ARE DEPENDANT UPON FUEL QUALITY. METHANE NUMBER CANNOT VARY MORE THAN ± 3. PUBLISHED PART LOAD DATA REQUIRES CUSTOMER SUPPLIED AIR FUEL RATIO CONTROL.

ENGINE RATING IS WITH 2 ENGINE DRIVEN WATER PUMPS.

FOR NOTES INFORMATION CONSULT PAGE THREE.

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Source: West Biofuels, LLC

Rationale for the Tests

After completion of gasifier testing from Task 3, the gasifier will continue to be run and a portion of the product producer gas will be converted to electricity using the PSI engine generator equipped with a CompactSCR™ after-treatment system. Generator efficiency will be determined by comparing the energy flow of the gas to the engine to the generated power delivered to a load bank. Recoverable heat from the generator jacket water and exhaust will also be monitored to determine potential for heat utilization for CHP projects. The objective will be to demonstrate good performance over several hundred hours of engine operation to qualify the technology for a commercial demonstration project in the future.

In terms of emissions performance of the engine, there are several considerations. Large amounts of hydrogen in the product gas allows the engine to be operated leaner than on natural gas which has the potential to achieve lower NOx emissions. If the product gas contains fuel-bound nitrogen, such as NH3, this will increase NOx emissions. In order to meet regulatory emissions, either the SCR system needs to be able to remove the required amount of NOx, or the gas-scrubbing system needs to be working well enough to remove the required amount of NH3 from the product gas. Both impacts will be investigated to optimize the system.

The CompactSCR™ system is designed with catalysts specifically sized for the engine used in the testing. Carbon Monoxide and Hydrocarbon emissions from the engine are reduced first with an oxidation catalyst before the SCR catalyst as shown in Figure 73 and previously described by West Biofuels and EF&EE[38]. The operation of the urea-metering and control system for the SCR catalyst has been demonstrated in prior producer gas applications by the team. Sensors communicate the temperature, pressure, and NOx concentration upstream and the temperature and NOx concentration downstream of the SCR catalyst to the PLC control unit. An analog signal from the engine controller communicates the engine load. The controller calculates the NOx flow rate from the engine load and upstream NOx concentration, then calculates the urea injection rate required to fully react with that quantity of NOx. This injection rate is communicated to the metering pump, which mixes the required amount of urea solution with the compressed air stream flowing to the nozzle.

The downstream NOx sensor supplies feedback to the urea metering system. To optimize the urea injection rate, the Optimin™ control algorithm slightly varies the ratio of urea injected to estimated NOx flow, while observing the effect on downstream NOx concentrations. If a change results in lower average NOx concentrations downstream, change continues in the same direction. If average NOx concentrations increase, the direction of change is reversed.

In a secondary on-line measurement system, engine-out and tail-pipe emissions (NOx, CO, SOx) are measured a continuous online Horiba PG-250 gas analyzer using standard California Air Resources Board (CARB) Methods. Hydrocarbons and Particulate Matter will also be measured periodically using other standard CARB or US EPA approved methods. With these

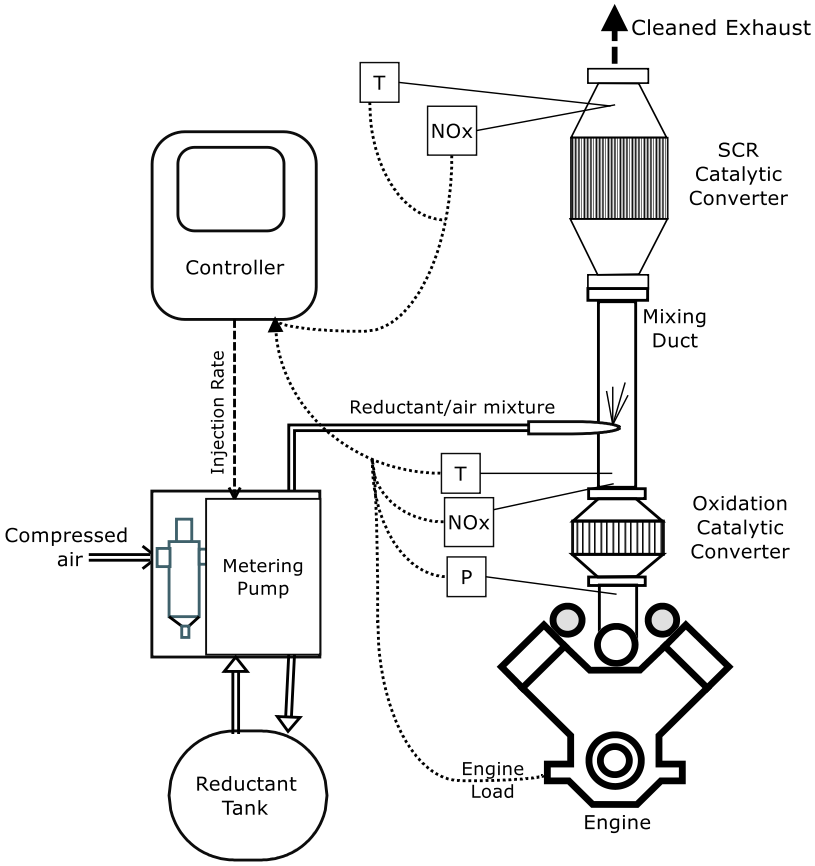
[38] Summers et. al. 2016.

measurements, the overall system emissions and the cleanup efficiency of the equipment can be quantified.

To determine the performance of the engine-generator on producer gas from the CircleDraft gasifier, West Biofuels will conduct a number of test runs and measure the inputs and outputs of the gasifier and the engine-generator simultaneously, to determine the overall system performance as well as the generator performance. These tests will be done on representative forest feedstocks that have been collected as part of Task 2. The gasifier will be operated in the optimum conditions determined during Task 3 testing where the gasifier and the gas cleanup system have been optimized on forest sourced material to produce the best producer gas for engine operation.

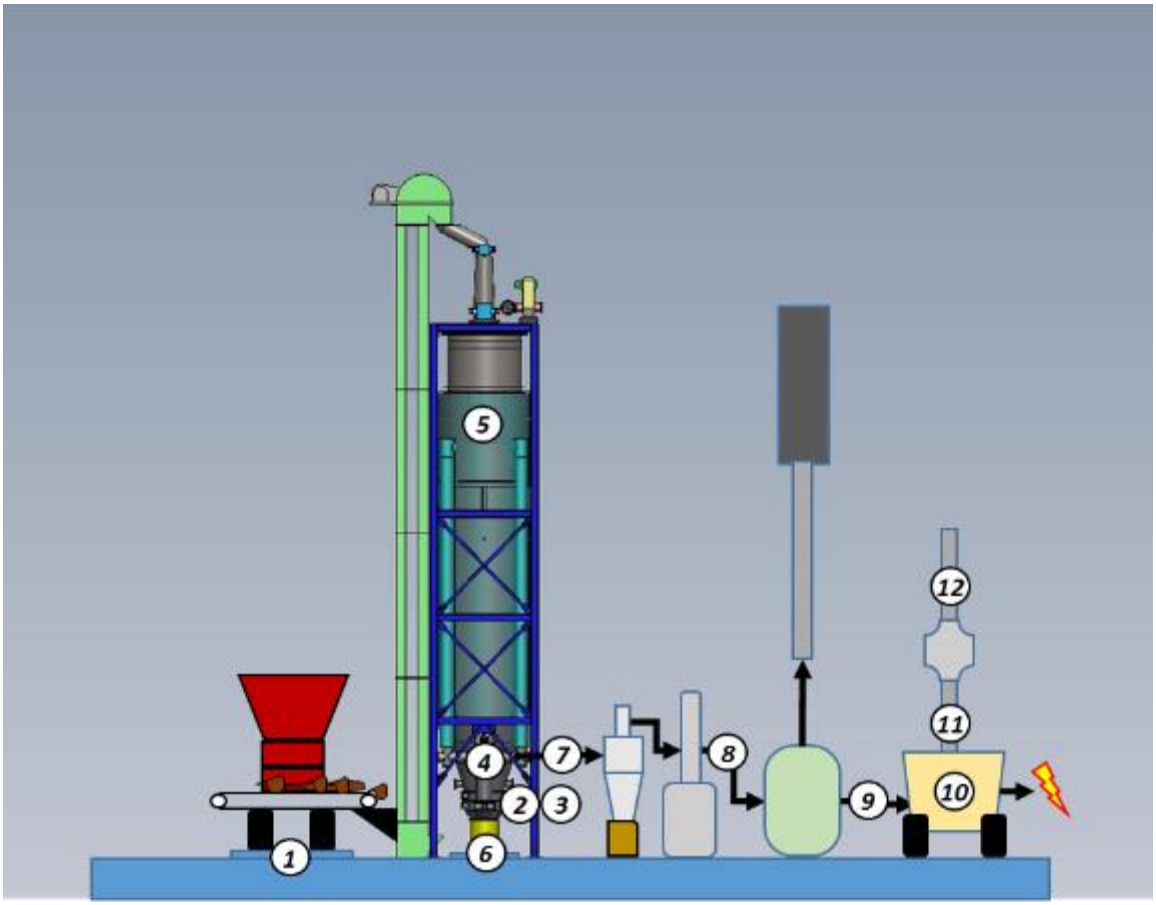
The sampling locations for this testing are shown in Figure 74. In this case the producer gas is cleaned in a two-stage cleanup system before it goes to a gas holder. The engine draws the amount of producer gas required to operate at the electrical load demanded by a controllable load bank. The remainder of the unused producer gas flows from the gas holder to the gas flare to balance the system. Three producer gas testing locations are available, raw gas and conditioned gas produced by the gasifier and conditioned gas delivered to the engine generator.

Figure 73: Engine-Generator With CompactSCR™ And Oxidation Catalyst System



Source: Engine, Fuel, and Emissions Engineering, Inc.

Figure 74: Sampling Locations For Engine Generator Testing



Source: West Biofuels, LLC

Test Matrix

The text matrix specifies the operating conditions of the engine-generator on producer gas from CircleDraft® gasifier and the measurement variables and techniques for fully characterizing the overall system performance from biomass introduction to power generation and emissions. Measuring the input/output mass and energy balances and the produced power and emissions are the main objective of the testing, but monitoring other variables such as settings, rates, pressures, and temperatures are also necessary to give a complete understanding of the operating conditions. Table 74 shows the sampling to be conducted at the locations shown in the schematic in Figure 74.

Table 74: Variables to be Sampled during Engine Testing

Loc #	Description	Units	Sensor Type	Expected Range	Precision
1	Biomass Feedrate	(kg/hr)	Load Cell, Continuous	300 - 500	10
1	Biomass Heating Value	(MJ/kg)	Lab Sample, Lower and Higher	17 - 20	0.1
1	Biomass Composition	(wt%)	Lab Sample, Proximate and Ultimate Analysis	Various	Various
2	Air Flow Rate	(Nm^3/hr)	Pitot Tube, Continuous	0 – 1000	10
2	Air Temp.	(°C)	Thermocouple, Continuous	0-50	0.5
2	Air Pressure	(mbar)	Pressure Transducer, Continuous	0-500	0.5
3	Steam Flow Rate	(kg/hr)	Pitot Tube, Continuous	0-200	1
3	Steam Temp.	(°C)	Thermocouple, Continuous	100-120	0.5
3	Steam Pressure	(mbar)	Pressure Transducer, Continuous	0-500	0.5
4	Gasification Zone Temp.	(°C)	Thermocouple, Continuous	800-1100	5
4	Gasification Zone Pressure	(mbar)	Pressure Transducer, Continuous	0-100	0.5
5	Filtration Zone Temp.	(°C)	Thermocouple, Continuous	0-400	5
5	Filtration Zone Pressure	(mbar)	Pressure Transducer, Continuous	0-100	0.5
6	Biochar Rate	(kg/hr)	Load Cell, Continuous	0-100	1
6	Biochar Composition	(wt%, var)	Lab Samples, Proximate and Ultimate Analysis, IBI Analysis	Various	Various
7	Raw Gas Flowrate	(kg/hr)	Ratio to Air Flow, Continuous	0-1000	10
7	Raw Gas Temp.	(°C)	Thermocouple, Continuous	0-200	0.5
7	Raw Gas Pressure	(mbar)	Pressure Transducer, Continuous	0-50	1
7	Raw Gas Composition	(vol %)	Lab Samples, Gas Chromatography	0-50	Various
7	Raw Gas Tar Content	(mg/Nm3)	SPE & CEN/TS 15439 Samples	500-5000	10
7	Raw Gas Particulate	(mg/Nm3)	Particulate Sampler	500-5000	10
8	Cond. Gas Flowrate	(kg/hr)	Pitot Tube and Ratio to Air Flow, Continuous	0-1000	10
8	Cond. Gas Temp.	(°C)	Thermocouple, Continuous	0-100	0.5
8	Cond. Gas Pressure	(mbar)	Pressure Transducer, Continuous	0-50	1
8	Cond. Gas Composition	(vol %)	Lab Samples, Gas Chromatograph	0-50	Various
8	Cond. Gas Tar Content	(mg/Nm3)	SPE & CEN/TS 15439 Samples	0-50	0.1
8	Cond. Gas Particulate	(mg/Nm3)	Particulate Sampler	0-20	0.1

Loc #	Description	Units	Sensor Type	Expected Range	Precision
9	Engine Gas Flowrate	(kg/hr)	Pitot Tube and Ratio to Air Flow, Continuous	0-1000	10
9	Engine Gas Temp.	(°C)	Thermocouple, Continuous	0-100	0.5
9	Engine Gas Pressure	(mbar)	Pressure Transducer, Continuous	0-50	1
9	Engine Gas Composition	(vol %)	Lab Samples, Gas Chromatograph	0-50	Various
9	Engine Gas Tar Content	(mg/Nm3)	SPE & CEN/TS 15439 Samples	0-50	0.1
9	Engine Gas Particulate	(mg/Nm3)	Particulate Sampler	0-20	0.1
10	Engine RPM	(RPM)	On-board Engine Controller	0-2000	1
10	Engine Coolant Temp. – Cold and Hot Side	(°C)	On-board Engine Controller	0-100	1
10	Engine Coolant Flow	(gpm)	Clamp-on Flowmeter	0-20	0.2
10	Engine Radiator Heat Removal	(kW)	Calculation	0-100	1
10	Generator Voltage – 3 Ph	(Volts)	On-board Engine Controller	0-500	1
10	Generator Current – 3 Ph	(Amps)	On-board Engine Controller	0-200	1
10	Generator Load	(kW)	On-board Engine Controller and/or Power Meter at Load Bank	0-150	0.2
11	Raw Exhaust Temp.	(°C)	On-board Engine Controller and Thermocouple, Continuous	0-500	1
11	Raw Exhaust Flow	(kg/h)	Pitot Tube and Calculated Based on Fuel and O_2, Continuous	0-2000	20
11	Raw Exhaust Composition	(% vol or ppmv)	Horriba 250X Continuous Gas Analyzer (O2, CO, CO2, NOx)	Various	Various
11	Raw Exhaust VOC Comp.	(ppmv)	Lab Samples, GCMS for species	0-500	10
12	Clean Exhaust Temp.	(°C)	On-board Engine Controller and Thermocouple, Continuous	0-500	1
12	Clean Exhaust Flow	(kg/h)	Pitot Tube and Calculated Based on Fuel and O_2, Continuous	0-2000	20
12	Clean Exhaust Composition	(% vol or ppmv)	Horiba PG-250 Continuous Gas Analyzer (O2, CO, CO2, SOx, NOx)	Various	Various
12	Clean Exhaust VOC Comp.	(ppmv)	Lab Samples, GCMS for species	0-500	10
12	NOx Emissions	(g/kWh)	CARB Method 100	0-0.250	0.002
12	CO Emissions	(g/kWh)	CARB Method 100	0-0.250	0.001
12	VOC Emissions	(g/kWh)	EPA Method 18	0-0.200	0.001
12	PM Emissions	(g/kWh)	CARB Method 5, Front Half	0-0.250	0.002

Source: West Biofuels, LLC

Table 75 shows the test matrix with operating parameters that will be tested for the engine-generator. The objective is to vary only the generator load and lambda and attempt to keep all operating conditions like gas pressure and gas composition equal for the tests to the extent feasible. During the tests, the gasifier will use the same forest sourced feedstock, constant airflow, steam input, and biochar removal rate and measure the input biomass feed rate to the gasifier in order to quantify overall system efficiency.

Table 75: Test Matrix For Engine Generator Testing

Parameter	Units	Test 1	Test 2	Test 3	Test 4
GASIFIER					
Biomass Type		Forest, HW	Forest, HW	Forest, HW	Forest, HW
Biomass Feed Rate*	(kg/hr)	400	400	400	400
Air Flowrate	(Nm3/hr)	850	850	850	850
Steam Input	(kg/hr)	140	140	140	140
Biochar Removal Rate	(kg/hr)	60	60	60	60
ENGINE GENERATOR					
Load	(kW)	60	120	60	120
Lambda		1.35	1.35	1.65	1.65
Producer Gas Flow Rate*	(kW)	205	345	205	345
Recoverable Heat Flow*	(kW)	85	135	85	135

***Estimates only. Actual rates to be measured.**

Source: West Biofuels, LLC

Instruments and Methods

Dry-gas composition of Producer Gas

The permanent gases will be measured with a gas chromatograph (Agilent 2000 Micro GC). The gas will be sampled through an impinger in an ice-bath, filled with either biodiesel or toluene. This removes most of the water and other condensable. Alternatively, sample bags or syringes can be used to collect a gas sample, and water/tars will condense in the bag or syringe.

- The following permanent gases will be measured: H_2, N_2, O_2, CH_4, CO, CO_2, C_2H_4, C_2H_6, C_3H_6, C_3H_8, and H_2S.
- Calibration: The instrument will be calibrated with three calibration-gas mixtures at the beginning of a test campaign, and double-checked with one calibration-gas mixture at the end of the campaign.

Tar content in the producer gas

Two methods will be used to measure tars in the producer gas, the SPE method (Solid phase extraction) and European tar protocol (CEN/TS 15439)

- SPE method:

Solid phase extraction (SPE) is a method of measuring tar compounds in the gas phase, originally developed by Brage et al. (1997)[39]. Gas sampling is performed by pulling 100mL of sample through a SPE column (Alltech Extract Clean™ Amino 500mg, 4mL) using a syringe pump. Tars are then extracted off the column using a simple procedure involving eluotropic polar (isopropyl alcohol) and non-polar (dichloromethane) solvent desorption separately. Extracted samples can then analyzed using GC-FID.

Calibration: GC chromatogram peaks are identified using Supelco EPA VOC Mix 2 and other external tar standards. EPA VOC Mix 2 contains 2000 µg/mL of the following compounds: benzene, bromobenzene, butylbenzene, ethylbenzene, p-isopropyltoluene, naphthalene, styrene, toluene, 1,2,3-trichlorobenzene, 1,2,4-trichlorobenzene, 1,2,4-trimethylbenzene, 1,3,5-trimethylbenzene, and m-xylene. Tar compound quantification of a compound within the external standard was calculated by multiplying the area of the analyte by the factor (cs / As).

$$c_x = \frac{(A_x c_s)}{(A_s)}$$

where, cx, cs are the concentrations of analyte and standard, respectively (µg/mL) and Ax, As are the peak areas for analyte and standard, respectively. The concentration of compounds not in the standard will be estimated by averaging the (cs / As) factor of the compounds in the standards.

- Tar protocol

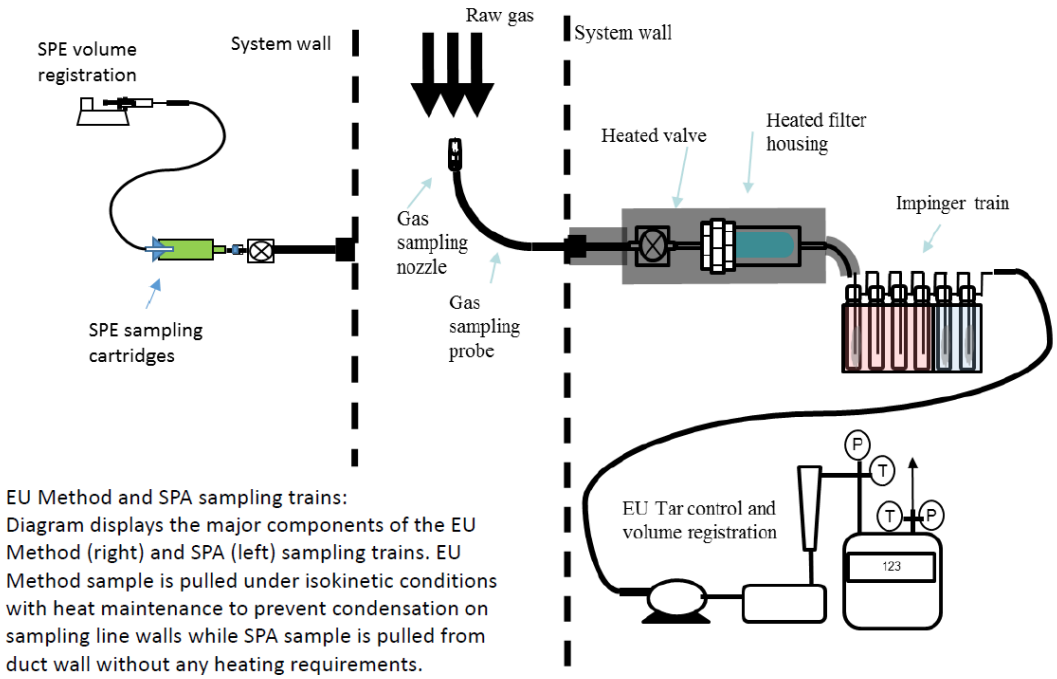
  The tar protocol follows CEN/TS 15439 and EPA Method 5, by isokinetically drawing a sample stream and flowing it through a set of six impingers filled with solvent (isopropanol). The first four impingers are in a water-bath held at 40C, the last two impingers ar in a water bath chilled to -20 C. The dry gas flow is measured with a dry test meter over a certain time period. After that, the impinger liquids are combined and analyzed in a gas chromatograph as well as gravimetrically by evaporating the solvent.

  The sampling nozzles and sampling flow rates are selected so that the velocity of the gas stream inside and outside of the nozzle are identical (isokinetic). The gas velocity will be calculated from the producer gas flow rate at sampling locations 7 and 8. The average gas velocity is calculated by dividing the gas flow rate by the cross section of the pipe. The tar-laden solvent will be analyzed in a gas chromatograph (Agilent 7820A with FID detector)

[39] Brage, C., Qizhuang Yu, Guanxing Chen, Krister Sjöström, Use of amino phase adsorbent for biomass tar sampling and separation, Fuel, Volume 76, Issue 2, January 1997, Pages 137-142.

Calibration: The gas chromatograph will be calibrated with EPA VOC Mix 2 (48777 Supelco) at the beginning of the test campaign. The calibration factors for unknown tar species will be derived from other known tar species.

Figure 75: Schematic Of Tar-Sampling Methods



Source: West Biofuels, LLC

Particulate Content in Producer Gas

The method follows EPA Method 5, by isokinetically sampling a gas stream and collecting particulates on a filter. The same setup as for tar sampling will be used, together with a heated filter (see Figure 74). After the collection of solids (and tars) on the filter, the filter will be washed in a Soxhlet extractor. The filter will be then be dried and weighed and compared to its original weight.

Water Content in Producer Gas

A gas-sample stream will be flow through an impinger filled with toluene immersed in an ice bath. The total sample-flow volume will be measured with a dry-test meter. At the end of the sampling, the liquid will be separated in a separation funnel. The amount of water will be measured in a graduated cylinder.

Sulfur Species in Producer Gas

Gas samples will be collected in Tedlar bags (2 L volume) and analyzed in a gas-chromatograph (GC) with sulfur-chemiluminescence detector (SCD). Teflon lines will be used to connect to the sampling bags during sampling.

Biomass Feed Rate

The feed rate of the biomass will be measured by load cells on the scale underneath the biomass supply bin. The weight and weight changes are recorded over the duration of the test to determine the average feed rate of the reactor.

Biomass Heating Value and Composition

Please refer to the Feedstock Test Plan for this project for more details on these analysis.

Air Flow Rate

The air flow rate into the combustor is measured using pitot tubes and a compressor flow curve.

Steam Flow Rate

The total steam flow rate will be measured by pitot tube flowmeter and confirmed by quantifying the total liquid water flow to the boiler system.

Producer Gas Flow Rate

The producer gas flow rate is measured with a pitot tube after sampling location 8 and sampling location 9. The sensor is calibrated with nitrogen. In addition, knowing the airflow to the gasifier and nitrogen content of the producer gas provides another means to confirm gas flow rate by nitrogen mass balance.

Temperature and Pressures

Temperatures are measured with Type-K thermocouples and pressures are measured with pressure transducers. The probes are located at various locations throughout the plant. The values are recorded with a National Instruments cRIO (NI-9074).

Engine Parameters

The engine generator has an onboard controller and data logger that records parameters like RPM, coolant temperature, oil temperature and pressure, exhaust temperature, etc. These parameters will be logged during all testing and analyzed for comparison between the tests. To the extent feasible, the sensors readings will be verified with an independent measurement.

Generator Parameters

The onboard controller/logger on the engine generator includes a power meter that measures voltage, amperage, and power for each leg/phase of the electricity produced by the generator. These parameters will be logged during all testing and analyzed for comparison between the tests. The power is also measured by the load-bank setting for comparison and confirmation of the generator measurements. To the extent feasible, the sensors readings will be verified with an independent measurement.

Engine Emissions Composition and Rates

Engine emissions compositions and rates are quantified using accepted engine stack measurement/air quality methods. Exhaust concentrations of NOx, CO, SOx, O2 and CO2 are measured with a Horiba PG-250 continuous logger during the testing that can monitor both the

raw and clean exhaust. Utilizing accepted engineering practices for power and flow measurement and CARB Method 100, emissions rates for each pollutant can be determined. For VOC and PM, EPA Method 18 and EPA Method 5 are utilized to quantify emissions of these compounds from the engine.

Data Analysis and Quality Assurance

Description of Data Analysis Procedures

Data is analyzed and averaged over the relevant testing period for both the continuous or periodically sampled data. The data is reviewed by the team to determine if there are any missing data, anomalies, or other possible errors in the instrumentation. Efficiencies and mass and energy flowrates are computed using standard accepted methodologies for engineering practice.

Quality Assurance Procedures and Contingency Measures

Instruments are calibrated as described above and data is reviewed for quality. Lab samples involve three replicates as described above. All samples are collected to be representative of the process by which they were generated and analysis will be run in triplicate. If the coefficient of variation for triplicate samples are larger than 10 percent, the test was repeated. Additional sample material will be preserved for re-testing as a contingency measure.

Predicted Performance

Test results are expected to meet the objectives identified for this task:

- Engine Generator Performance:
  - Electrical Efficiency: $\geq$ 35 percent
  - CHP Efficiency: $\geq$ 75 percent
  - Oil Change Frequency: >750 hours
  - Generator Fault Frequency: <1 fault per 250 hours
  - Operating Speed: 1,000 RPM to 2,000 PRM
  - Equivalence Ratio: $\leq$ 0.55
  - Compression Ratio: $\geq$ 11:1
- Engine Emissions Performance:
  - Nitrogen Oxide (NO_x): < 0.07 pounds per MWh (0.032 g/kWh)
  - Carbon Monoxide (CO): < 0.1 pounds per MWh (0.045 g/kWh)
  - Volatile Organic Compounds (VOC): < 0.02 pounds per MWh (0.009 g/kWh)
  - Particulate Matter (PM): < 0.31 pounds per MWh (0.140 g/kWh)

Generator Performance Report

The generator performance report provides a detailed analysis of the data collected to evaluate power production from a generator system operating on producer gas derived from a biomass

gasifier. The report evaluates an engine-generator system combined with the CircleDraft gasifier system as outlined tin the test plan. The project team also evaluated a thermal oil heater/organic rankine cycle (ORC) turbine system as an alternative generator system to a gas engine. Task 3 results showed that the gasifier system did not provide a suitable gas for long-term engine-generator performance requirements on forest sourced biomass. Therefore, two additional biomass power systems were developed and evaluated that utilize the alternative generator approach. This consistent with the overall project goal of developing a system for community scale power production from forest thinning residuals.

Description of Tests

The G3406TA engine generator was received at the West Biofuels site in early 2017 and was first thoroughly tested on natural gas to get baseline performance and emissions data. In an on-line measurement system, engine-out and tail-pipe emissions (NOx, CO, SOx,) are measured a continuous online Horiba PG-250 gas analyzer using standard California Air Resources Board (CARB) Methods. With these measurements, the overall system emissions and the cleanup efficiency of the equipment can be quantified.

The generator was then connected to the producer gas handling system with the configuration shown in Figure 74. The plan was that the gasifier would be operated at full capacity and a portion of the producer gas would be converted to electricity using the Caterpillar engine generator equipped with the EMIT™ catalyst after-treatment system. Generator efficiency would be determined by comparing the energy flow of the gas to the engine to the generated power delivered to a load bank. Recoverable heat from the generator jacket water and exhaust would also be monitored to determine potential for heat utilization for CHP projects. The objective was to demonstrate good performance over several hundred hours of engine operation to qualify the technology for a commercial demonstration project in the future.

However, after completion of gasifier testing from Task 3, it was apparent that the producer gas produced from the CircleDraft gasifier system on raw forest thinning biomass would not be suitable for extensive engine testing, if at all. Condensable tars and particulate in the gas after post-gasifier cleanup still exceeded targets by at least an order of magnitude. In spite of this challenge, the team decided to proceed with a single test of the engine on producer gas during the September 2017 run on torrefied biomass. Torrefied biomass has already removed low-temperature volatiles, which traditionally form tars in the producer gas. Using torrefied wood improved the ability to achieve a cleaner producer gas. In this configuration the producer gas produced in the gasifier is processed in a two-stage cleanup system before it goes to a gas holder. The engine draws the amount of producer gas required to operate at the electrical load demanded by a controllable load bank. The remainder of the unused producer gas flows from the gas holder to the gas flare to balance the system. Three producer gas testing locations are available, raw gas and conditioned gas produced by the gasifier and conditioned gas delivered to the engine generator.

Table 76 shows the target operating parameters that were used during the testing of the engine-generator on producer gas.

Table 76: Modified Test Matrix for Engine Generator Testing

Parameter	Units	Test Targets
GASIFIER		
Biomass Type		Forest Thinnings Torrefied
Biomass Feed Rate	(kg/hr)	130
Air Input	(kg/hr)	150
Steam Input	(kg/hr)	50
Biochar Removal Rate	(kg/hr)	20
ENGINE GENERATOR		
Load	(kW)	100
Lambda		0.99-1.01
Producer Gas Flow Rate	(kW)	370

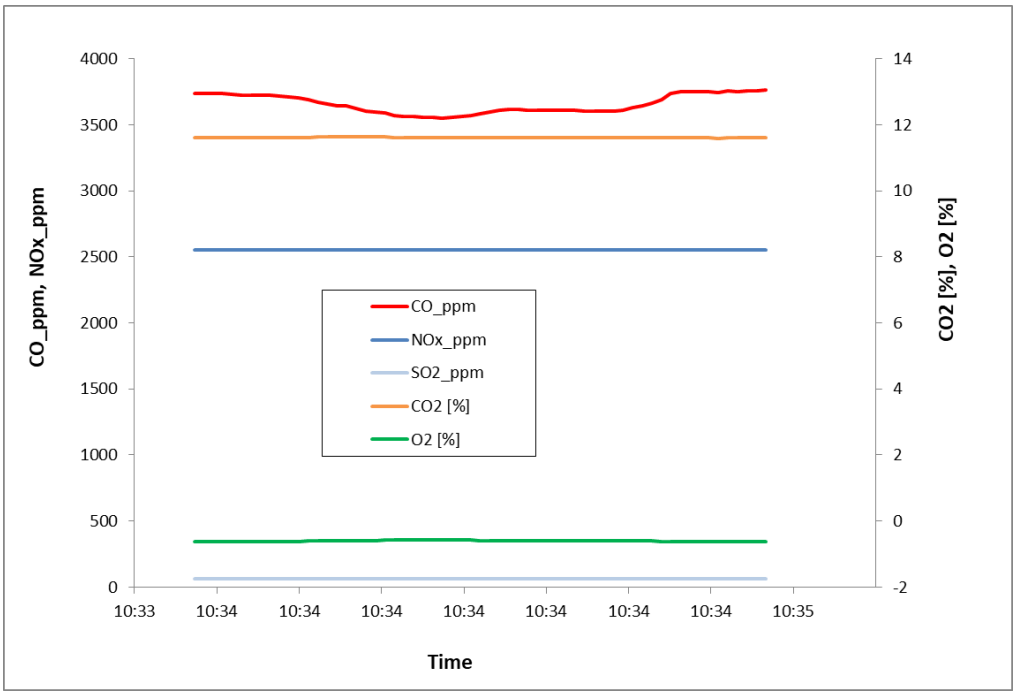
Note: Targets only, actual rates to be measured.

Source: West Biofuels, LLC

Engine-Generator Testing Results

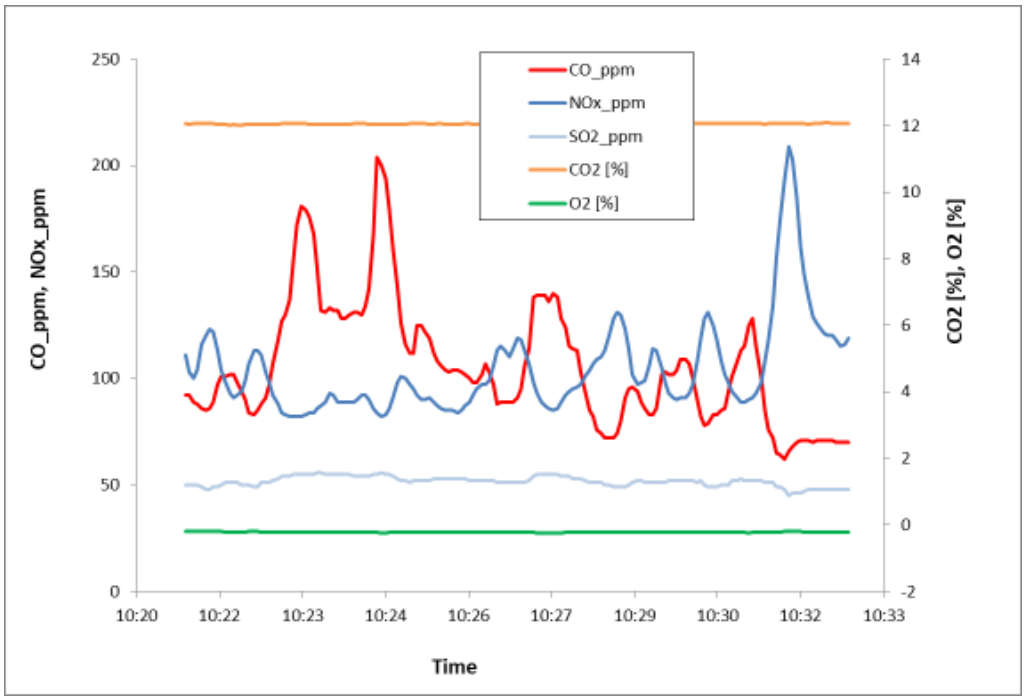
The first testing established the baseline engine emissions for the Caterpillar G3406TA generator utilized for the project. The generator was professionally serviced and then operated for several days to tune and optimize the performance on natural gas. After final adjustments, the emissions measurement equipment was calibrated and continuous measurements were made of the raw exhaust from the engine and the final exhaust after treatment with the catalyst system. The plots for NOx, SO2 and CO concentration measured during operation in the raw and final exhaust are shown in Figure 76 and Figure 77 respectively.

Figure 76: Measured NOx, SO2 And CO Concentrations In Raw Exhaust (G3406TA, Natural Gas Baseline)



Source: West Biofuels, LLC

Figure 77: Measured NOx, SO2 and CO Concentrations in Post-Catalyst Exhaust (G3406TA, Natural Gas Baseline)



Source: West Biofuels, LLC

The catalyst shows some level of variability for control for NOx and CO and it is expected that the algorithm of the EMIT™ control system needed to be tuned. However, the raw emissions were somewhat higher than desirable and above other data provided by Caterpillar (Figure 72). Additional tuning of the air/fuel ratio controller and possibly the timing would have likely lowered the raw emissions and stabilized the control, but this was beyond the scope of the project and capabilities of the team. The level of control provided by the catalyst system was still quite good on average, 96 percent for NOx and 97 percent for CO as shown in Table 74 and Table 77 along with the measurement results.

Table 77: Baseline Emissions Testing Results (G3406TA, Natural Gas Baseline)

	Raw Exhaust (pre-cat)			Final Exhaust (post-cat)		
Component	**Min**	**Max**	**Average**	**Min**	**Max**	**Average**
NO_x (ppm)	>2500	>2500	>2500	82	209	104
SO_2 (ppm)	60	61	61	45	56	52
CO (ppm)	3552	3760	3655	62	204	106
NO_x Control (%)				96.7%	91.6%	95.8%
SO_2 Control (%)				26.2%	8.1%	15.3%
CO Control (%)				98.3%	94.4%	97.1%

Source: West Biofuels, LLC

The catalyst is not designed to control SO2 although there appeared to be a small decrease after the catalyst. With optimization, it is believed that good emissions control results can be achieved with this system.

After baseline testing on natural gas, the engine generator was installed on the fuel train of the gasifier system. Testing on producer gas was performed during the September 2017 gasifier run on torrefied forest biomass. The properties of the gas that was tested are shown in Table 78 along with the energy flow results. While the gas energy content and flow amount were sufficient for operating the engine generator, the high tar and particulate loading were problematic for extended testing. The team limited testing period was limited to about one hour to not damage the engine generator. Even in this short time period, significant amounts of condensation occurred in the engine intake and filters and buildup began to occur in the turbocharger and intercooler as shown in Figure 78 and Figure 79.

Table 78: Bio-Energy System Performance Data During Engine Generator Testing

Parameters	Units	Values
GASIFIER		
Biomass Type		Forest Thinnings
Biomass Feed Rate	(kg/hr / kW)	128 / 668
Pre-treatment Steps		Drying/Torrefaction
Air Input	(kg/hr)	154
Steam Input	(kg/hr)	39
Biochar Removal Rate	(kg/hr / kW)	33 / 195
Gas Thermal Efficiency, HHV	(%)	56
PRODUCER GAS		
Higher Heating Value	(MJ/kg)	5.91
Tar Loading	(g/hr)	387
Particulate Loading	(g/hr)	171
Total Producer Gas Flow Rate, HHV	(kg/hr / kW)	227 / 373
ENGINE GENERATOR		
Net Power to Load	(kW)	65
Lambda		0.98-1.02
Producer Gas Flow Rate to Engine	(kW)	241
Recoverable Heat Flow	(kW)	98
Generator Electrical Efficiency	(%)	27
Generator CHP Efficiency	(%)	68

***Based on biomass input to process only, for example gas HHV**

Source: West Biofuels, LLC

Figure 78: Producer Gas Tar Condensation On Engine Intake Manifold And Filters

Source: West Biofuels, LLC

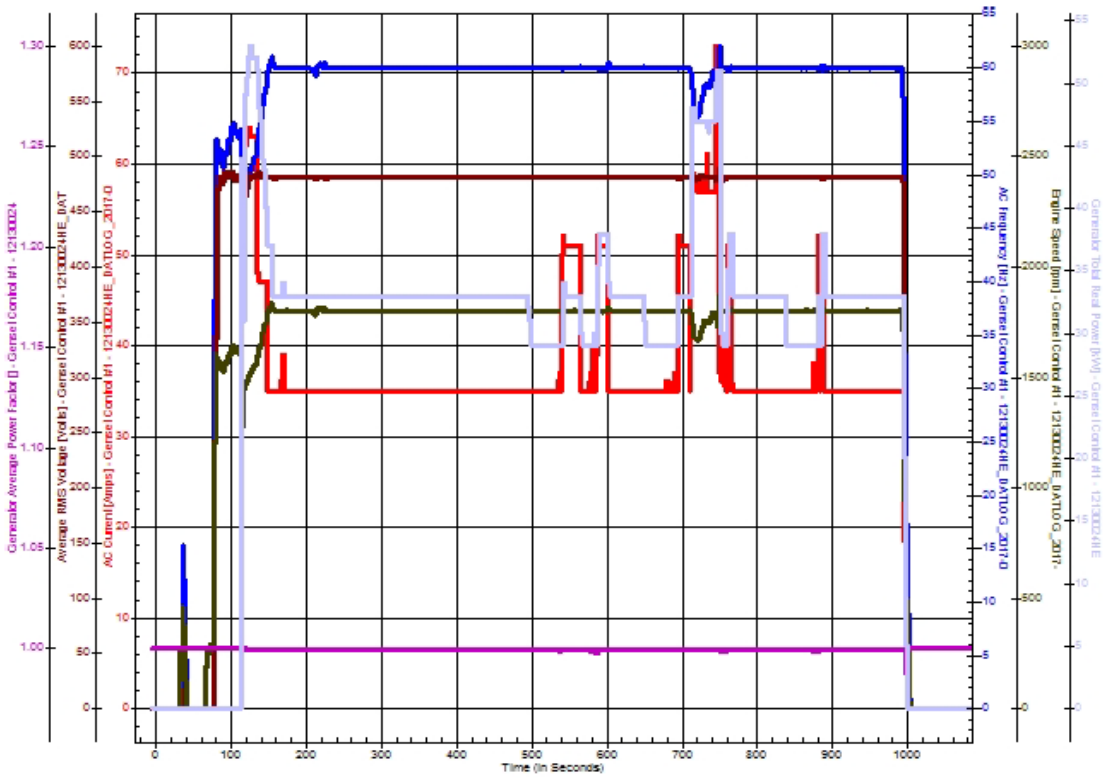
Figure 79: Producer Gas Condensation In Engine Turbocharger And Intercooler

Source: West Biofuels, LLC

The operation of the engine on producer gas was stable during the test period. Figure 80, shows the engine generator parameters during the test. However, it was difficult to stabilize the air fuel ratio during the test run. It is believed that the air fuel ratio was variable due to pressure fluctuations and heating value fluctuations. The heating value fluctuations are suspected to be from variations in the amount of high energy volatiles in the producer gas. Measurement of major gas composition was typically very consistent during gasifier testing.

It can be seen from the emissions testing results on producer gas that the control system for the catalyst had difficulty stabilizing on O2 concentration that impacted CO control primarily but also NOx as seen in Figure 81. Table 79 shows the measured emissions results and the estimated control relative to baseline. If stability could be achieved in the pressure and heating value, it is believed that the engine catalyst system could achieve good results on producer gas. However, this may not be relevant because the producer gas from the CircleDraft gasifier proved to not be suitable for an engine in long-term operation.

Figure 80: Engine Generator Operating Parameters (G3406TA, Producer Gas)



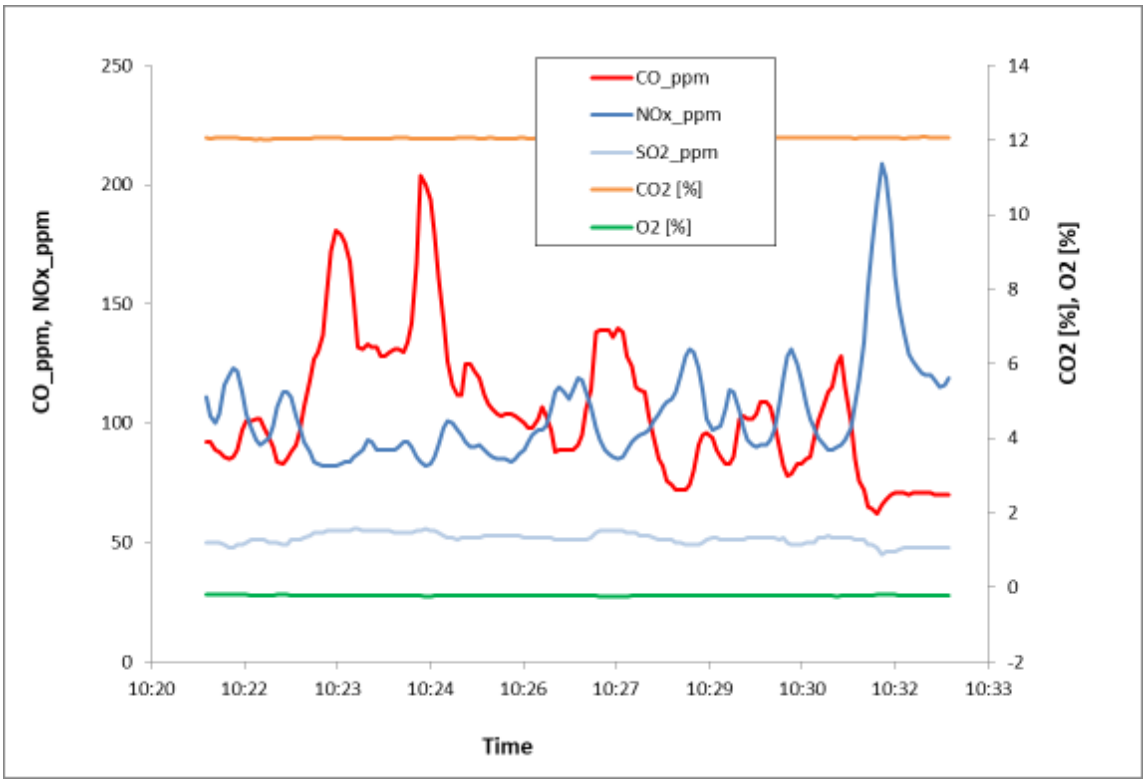
Source: West Biofuels, LLC

Table 79: Emissions Results For G3406TA Producer Gas Test

	Final Exhaust (post-cat)		
Component	**Min**	**Max**	**Average**
NO_x (ppm)	3	262	111
SO_2 (ppm)	8	90	13
CO (ppm)	208	650	294
NO_x Control (%)	99.9%	89.5%	95.5%
SO_2 Control (%)	86.9%	-47.5%	78.1%
CO Control (%)	94.3%	82.2%	92.0%

Source: West Biofuels, LLC

Figure 81: Measured NOx And CO Concentrations In Post-Catalyst Exhaust (G3406TA, Producer Gas)



Source: West Biofuels, LLC

Alternative Generator Testing and Evaluation

Description of the Processes

Since the producer gas produced by the CircleDraft gasifier did not meet engine manufacturer requirements, the project team evaluated alternative generator solutions in order to meet the overall goal of the project which was to deliver a reliable and financeable community-scale technology for production of energy from forest residues. The team conducted a number of project site visits in North America and Europe to look at alternative approaches. One technology stood out as a very reliable and easy to operate system on forest biomass at the scale of 1-5 MWe. With over 300 installations in Europe and several more in North America, the use of thermal oil (TO) heaters coupled with an organic Rankine cycle (ORC) turbine. The TO/ORC combination has shown itself to have high reliability and very low operations and maintenance costs over the life of a project relative to gas engine systems. For example, maintenance costs are typically 1 percent/yr[40] where engine maintenance costs are from 5 percent to 8 percent for engine systems operating on producer gas.[41] The capacity factor of

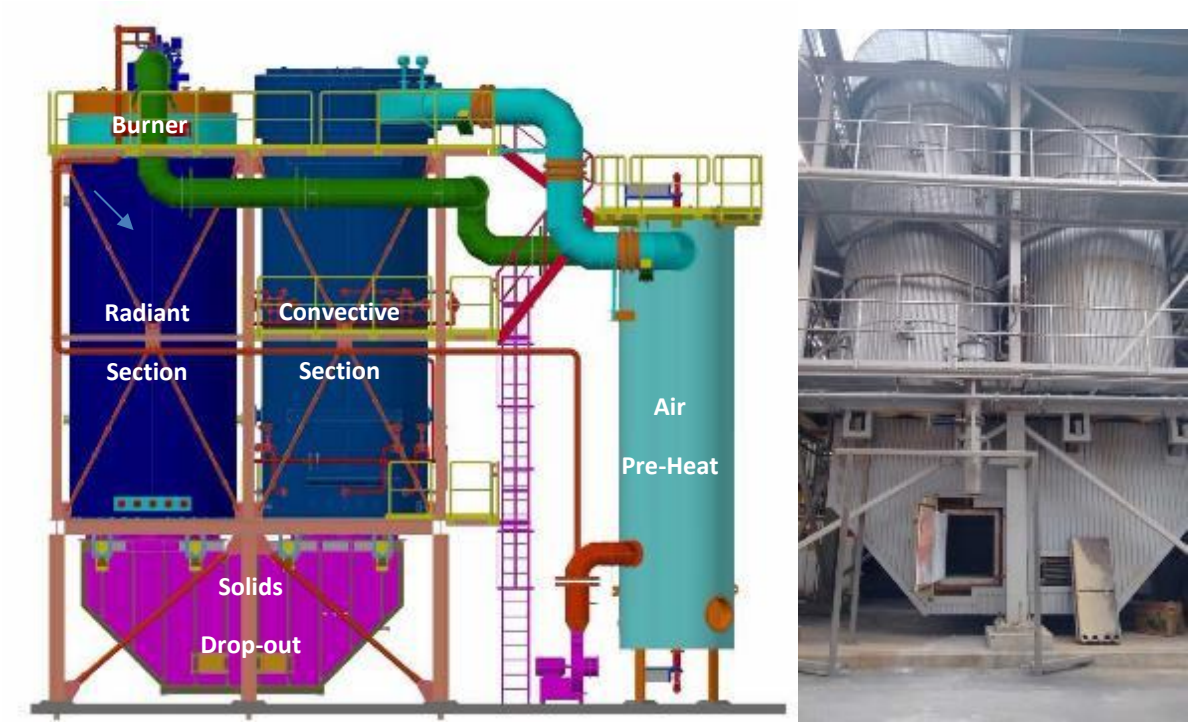
[40] Environmental Protection Agency Combined Heat and Power Partnership. "Waste Heat to Power Systems." https://www.epa.gov/sites/production/files/2015-07/documents/waste_heat_to_power_systems.pdf.

[41] Phone calls with Caterpillar, Dresser-Rand, and GE.

these systems is typically 80 percent - 90 percent[42] while engine generator systems operating on producer gas are 55 percent - 80 percent.[43] TO heaters have been configured with burner systems to convert low-BTU gas (LBG) like producer gas and these burners have very high tolerance for combustion of condensables and particulate matter unlike gas engines. They have a number of design advantages to engines because to combustion system design can be adapted to control combustion products by increasing flue gas residence time, multi-level air injection, exhaust gas recirculation, etc. and is very suited to addition of flue gas treatment technologies like particulate filtration, catalytic reduction, etc.

An LBG fired TO heater system suitable for heating thermal oil to supply a 3 MWe ORC system is shown in Figure 82.

Figure 82: LBG Thermal Oil Heater System



Source: West Biofuels, LLC

The system consists of a down-fired LBG burner with both a radiant and convective chamber section for heating the thermal oil. A clean-out is at the bottom to collect and solid deposits that may form on either section of the heat exchanger surfaces. Then flue gas exits the thermal oil section and enters an air preheater that heats the air prior to the burner. Flue gas can also be re-circulated to assist in optimizing flame characteristics and heat transfer within the system. For community-scale power systems from 1-3 MW, these units are modular and can be shipped over-the-road on a truck trailer. These systems are well established technology with hundreds of installations throughout the world and hundreds of thousands of operating hours.

[42] Phone call with Turboden sales representative and follow up with plant references

[43] Historic data from 15 years of a fluidized bed gasification plant operation in Austria

Most importantly, a number of established manufacturers of these systems are available and can give performance guarantees critical for obtaining funding for community-scale projects.

The ORC turbine generator uses the heat delivered by the thermal oil to generate power by cycling a hydrocarbon working fluid through the turbine instead of steam. These systems have proven to be very reliable and trouble free for many years of operation with an extremely low operating cost; only 10-20 percent of a comparable engine generator system operating on producer gas.[44] The team identified ORC suppliers that can supply these systems for commercial projects with a performance guarantee for power production. For example, one manufacturer, Turboden S.p.A. has supplied nearly 300 ORC systems for biomass power generation and co-generation applications throughout the world since 1999, all in the community scale range of 0.25 to 20 MW. A large portion of the systems are in the 1-5 MW range making them an optimal supplier California forest biomass projects. Turboden has installed two 3MW systems in North America in Canfor and Manning, British Columbia, Canada. A 3MWe ORC generator system shown in Figure 83 with nominal specifications shown in Table 80.

Figure 83: Commercial 3MW ORC Generator System

Source: West Biofuels, LLC

[44] ORC Data: Algieri, Angelo, and Pietropaolo Morrone. "Techno-economic analysis of biomass-fired ORC systems for single-family combined heat and power (CHP) applications." Energy Procedia 45 (2014): 1285-1294. https://ac.els-cdn.com/S1876610214001350/1-s2.0-S1876610214001350-main.pdf?_tid=41435b35-0138-4fb7-a723-f35ead356274&acdnat=1520897577_ffd14a8bc3160410ceca1ae1c4052fd6.

ICE Data: Vendor quotes for maintenance service contracts.

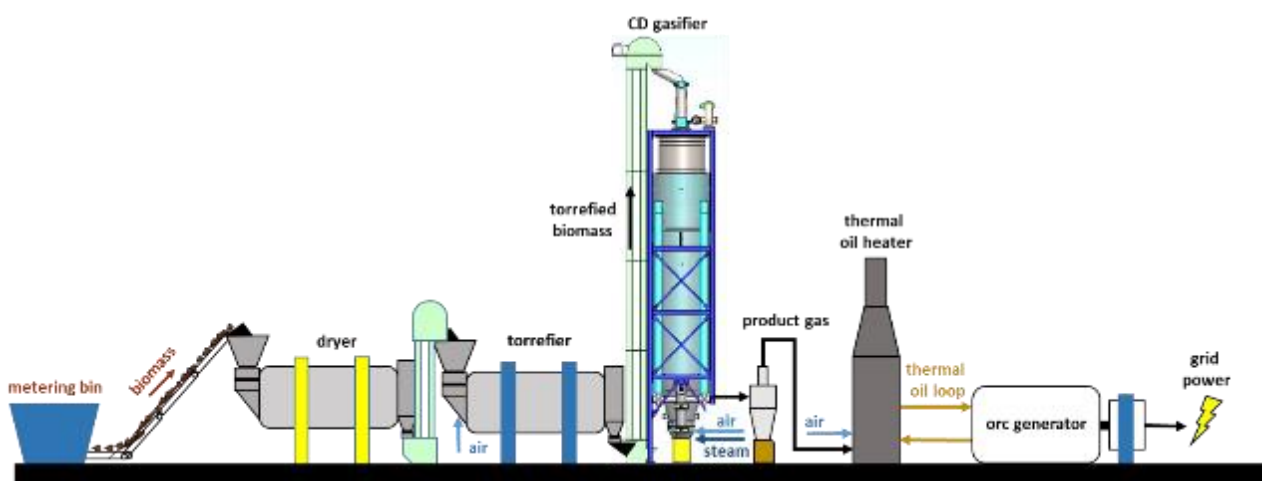
Table 80: Specifications for 3MWe ORC Power Generating System

Parameter	Units	Value
Thermal Oil Inlet Temp	°C	310
Thermal Oil Outlet Temp	°C	214
Thermal Oil Power Input	kW	13075
Cooling Water Inlet Temp	°C	25
Cooling Water Outlet Temp	°C	40
Cooling Water Flow	lpm	9448
Gross Electric Power	kW	3193
Parasitic Load	kW	125
Net Electric Power	kW	3067
Net Electric Efficiency	%	23.5

Source: West Biofuels, LLC

To evaluate the use of a TO/ORC system with a gasifier, a model was developed with the support of established vendors of these systems. The first configuration evaluated coupling the CircleDraft gasifier system with the TO heater and ORC generator as shown in Figure 84 (System 3, Systems 1 and 2 are described in Chapter 3). This system also includes a rotary drum torrefier prior to the gasifier to manage the issues with bridging and channeling in the CircleDraft system. The gas scrubber can be eliminated in this system as the raw gas is suitable to combust in the LGB burner.

Figure 84: System 3: Biomass Power Production System (including feedstock metering; dryer; torrefier; CircleDraft gasifier; TO heater, ORC generator)



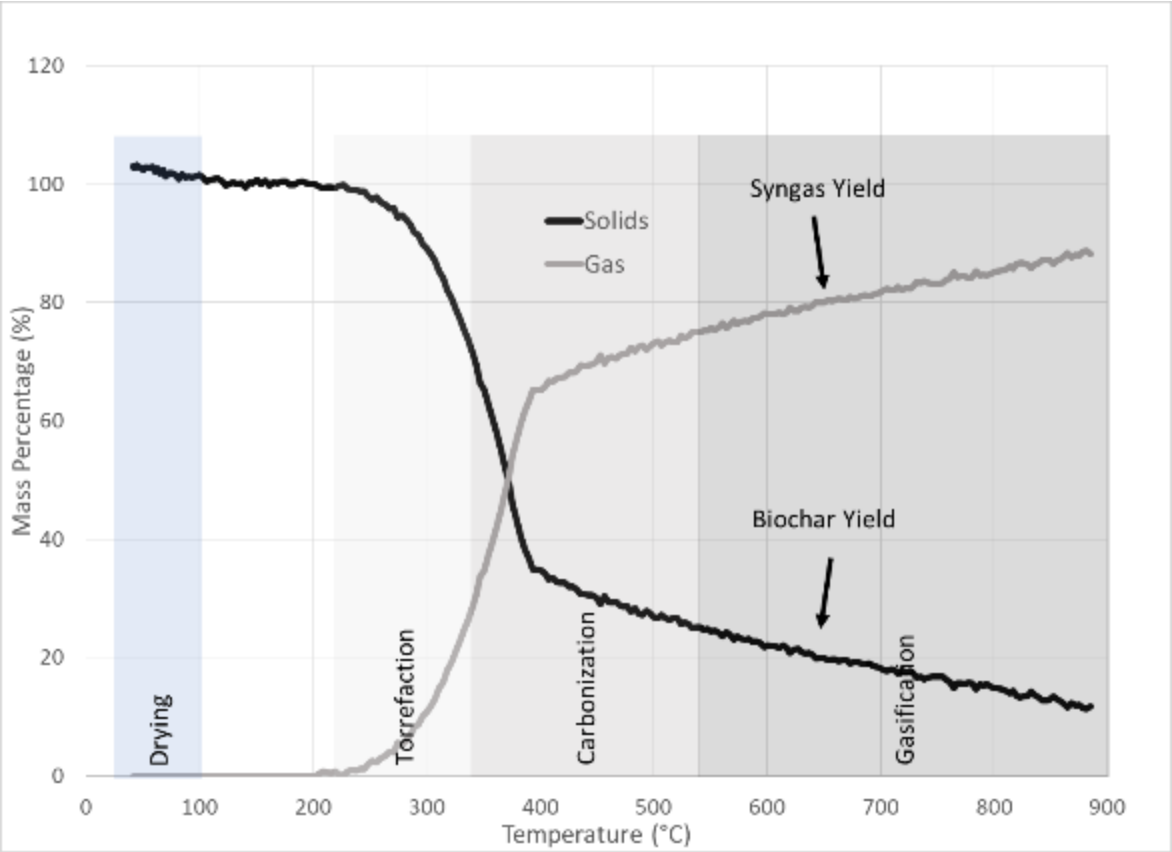
Source: West Biofuels, LLC

In the process of evaluating the torrefier and processing some torrefied forest residue samples for project testing, the team came up with another gasification approach that would eliminate the redundancy of having both the torrefier and the CircleDraft gasifier of System 3. This approach would also eliminate the problematic fixed-bed within the CircleDraft gasifier that still struggled to perform without blockages using the torrefied material. The team approached the

rotary torrefier vendor about increasing the process temperature into the carbonization range in order to carry the conversion to a higher level in order to produce enough gas and vapors for the TO heater as well as a high-quality biochar (instead of torrefied wood).

Figure 85 is a temperature scan of forest biomass from a thermogravimetric analyzer showing the amount of gas/vapor and torrefied wood/ biochar that can be produced as a function of temperature in a reducing environment without air. While torrefied wood is produced between 250°C to 340°C with up to a 0-30 percent mass loss, at higher temperatures from 340°C to 600°C and above, the same system will carbonize the wood with 70-85 percent mass loss to produce a high fixed-carbon biochar and more energetic producer gas and vapors. This system, dubbed the rotary gasifier, takes advantage of the well-established approach of convective heating of wood using a rotary drum. The systems are based on hundreds of very successful rotary drum thermal dryers for biomass that have been supplied by a number of vendors throughout the world.

Figure 85: Decomposition Of Forest Biomass Into Gas/Vapors And Biochar



Source: West Biofuels, LLC

Two self-contained rotary drum torrefier systems have been in operation since 2010 and have been operated for thousands of hours. TSI inc. designed the reactor, gas heating system, structure, material separation & cooling systems. Below are more details on the two completed projects for biochar and producer gas generation based on the rotary drum technology.

Figure 86: American Biocarbon Rotary Drum Torreactor System

Photo: Courtesy of TSI Inc.

American Biocarbon

TSI designed and built a 5'x30' torreactor system with a 7 MMBtu/h multi-fuel burner (Figure 86). This system was designed and built in late 2013 and operated in Rapid City SD using wood chips as the feedstock for several hundred hours at a variety of process temperatures. The system was relocated in 2014 to White Castle LA Cora Texas Sugar Mill to operate with bagasse (waste sugar cane) feedstock. This system has been operated approximately 7000 hours on bagasse. This system is operated 8 to 10 hours per day 5 days per week and has a 4,000 pph capacity.

Portable Torrefaction System

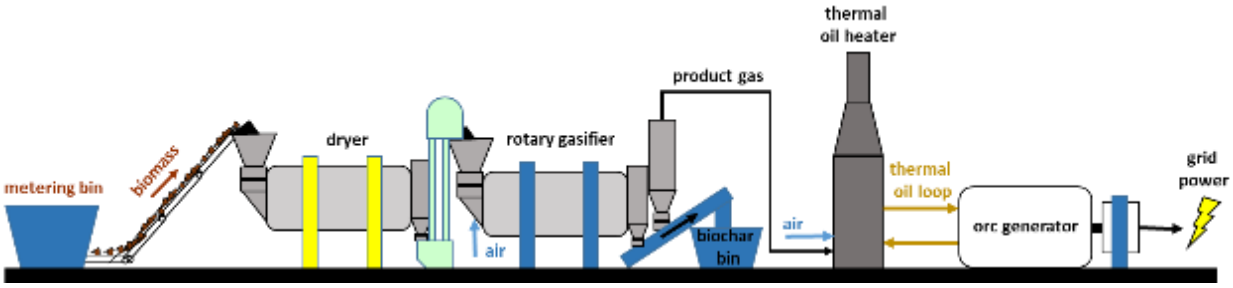
TSI designed and built a portable torrefaction system (Figure 87) in 2010 and has operated it as a pilot test unit since that time. This unit has processed hundreds of different materials over thousands of hours of operation. This system has a capacity of several hundred pounds per hour capacity depending upon the material. This system is used regularly to test feedstock material from around the world. The system was used by this project team as described in the next section for identifying the optimal conditions to maximize energy production from forest biomass.

Figure 87: TSI Portable Torrefaction Test System

Source: West Biofuels, LLC

The TO heater system is tolerant over a very wide range of combustible gas, vapors and char particulate so the team recognized that this combined with a rotary gasifier system is a good combination for electricity production. The project team developed a system that could use the gas and vapor stream from the rotary gasifier in the TO heater while producing high quality biochar as shown in Figure 88 (System 4). It includes a rotary dryer, rotary gasifier, TO heater, and ORC generator. The following section describes the experiments and analysis that the project team conducted to validate this system.

Figure 88: System 4: Biomass Power Production System (including feedstock metering; dryer; rotary gasifier; TO heater, ORC generator)



Source: West Biofuels, LLC

Description of the Tests

In order to properly model and analyze the TO heater/ORC generator system the team worked backward from the ORC manufacturer specifications (Table 80) for the temperature and flow of thermal oil required to operate the ORC system. The TO heater system supplier then helped model the burner and heat exchanger system needed to meet these thermal oil requirements. This included modeling the combustion characteristics of the input gas/vapor stream in the LBG burner for System 3 and 4. Once the team establish the gas requirements, they worked

back to the gasifier systems and the operating characteristics and throughput required to meet the TO heater needs. These models can then be compared directly with Systems 1 and 2 from Chapter 3 that established the performance of a gas engine system, notwithstanding that Systems 1 and 2 appear to be technically and economically infeasible.

The team also did a number of tests to establish the performance of the rotary gasifier system. The tests utilized the TSI test system (Figure 87) where the team conducted testing with forest biomass over multiple temperatures and conditions in order to characterize performance and optimize operating parameters for a commercial scale system that can produce sufficient gas and vapors for a thermal oil heater and ORC generator. The products were analyzed and a mass and energy balance were developed for the system. The test matrix for these tests is shown in Table 81.

Table 81: Test Matrix for Rotary Gasifier System

Parameter	Units	Test #1	Test #2	Test #3	Test #4	Test #5
Biomass Type		Forest, HW	Forest, HW	Forest, HW	Forest, HW	Forest, HW
Temperature Setpoint-Outlet Temperature	(°C)	260	288	316	343	371
Inlet Temperature	(°C)	343	371	400	427	454
Biomass Feed Rate	(kg/hr)	10	10	10	10	10
Heater Fire Rate	(%)	70	75	80	85	90
Gas Circulation Ratio		6:1	6:1	6:1	6:1	6:1
Drum Rotation Speed	(RPM)	5	5	5	5	5

Source: West Biofuels, LLC

In addition, the team utilized a laboratory scale drum reactor to do batch testing of forest biomass using the conditions of the rotary drum but within the controlled environment of an electric furnace. This system allows for controlled parameter variation testing and more precise measurement of the mass fractions between producer gas, condensable vapors, and biochar solids for each set of conditions. The team tested the concept of injecting a controlled amount of air into the system during carbonization to further reduce the biochar and higher molecular weight vapors and increase the producer gas production. This has a number of process advantages including eliminating the use of gas to externally heat the system, increasing the gas quantity, and making the product gas easier to combust. The test matrix for the lab scale system is shown in Table 82.

Table 82: Test Metrics for Lab Scale Simulation Of Air Injection

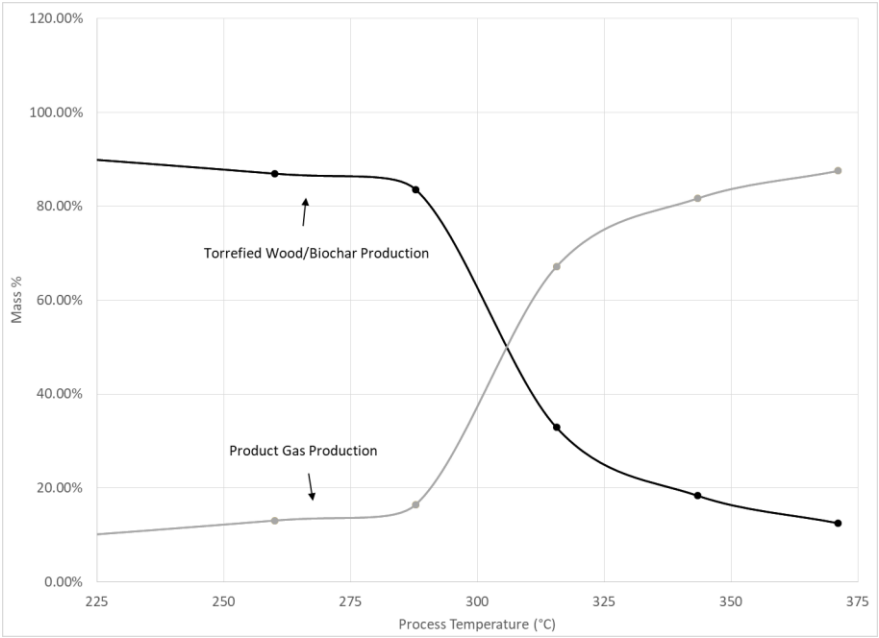
Parameter	Units	Test #1	Test #2	Test #3	Test #4	Test #5
Biomass Type		Forest, HW	Forest, HW	Forest, HW	Forest, HW	Forest, HW
Biomass Temperature Setpoint	(°C)	400	400	400	400	400
Furnace Temperature	(°C)	415	415	415	415	415
Biomass Batch Amount	(g)	70	70	70	70	70
Air:Fuel Ratio (dry mass)		0	0.1	0.3	0.5	0.7
Air Flow Rate	(l/min)	0	0.55	1.50	2.45	3.40
Air Flow Time	(min)	0	12	12	12	12

Source: West Biofuels, LLC

Alternative Generator Testing Results

The results of the rotary gasifier test were first needed in order to analyze and evaluate the alternative generator technology of the TO heater and ORC generator. The tests on the TSI test system were conducted in July of 2017 during a weeklong test campaign (approximately 30 hours of operating time). The mass fraction results showed the expected transition from wood torrefaction to carbonization between 250°C and 400°C (Figure 89) where a satisfactory energetic product gas mass yield of over 80 percent above 350°C.

Figure 89: Biochar And Product Gas Production Vs. Temperature in Rotary Gasifier



Source: West Biofuels, LLC

The resulting biochar also increases in fixed carbon with temperature from 20 percent to 70 percent over the same range. The full results with the actual process conditions can be seen in Table 83.

Table 83: Rotary Gasifier Performance Test Results with Forest Biomass

Nominal Temperature Setpoint (°C)	Outlet T (°C)	Inlet T (°C)	Fire Rate (%)	Drum RPM	Producer Gas Yield (%)	Biochar Yield (%)	Biochar Fixed Carbon (%)
260	261	330	72.8	5.0	13.1%	86.9%	22.1%
288	288	366	82.9	5.0	16.4%	83.6%	33.6%
316	316	408	71.5	4.0	67.1%	32.9%	64.8%
343	348	433	76.7	5.5	81.6%	18.4%	61.2%
371	374	461	70.8	4.5	87.5%	12.5%	70.1%

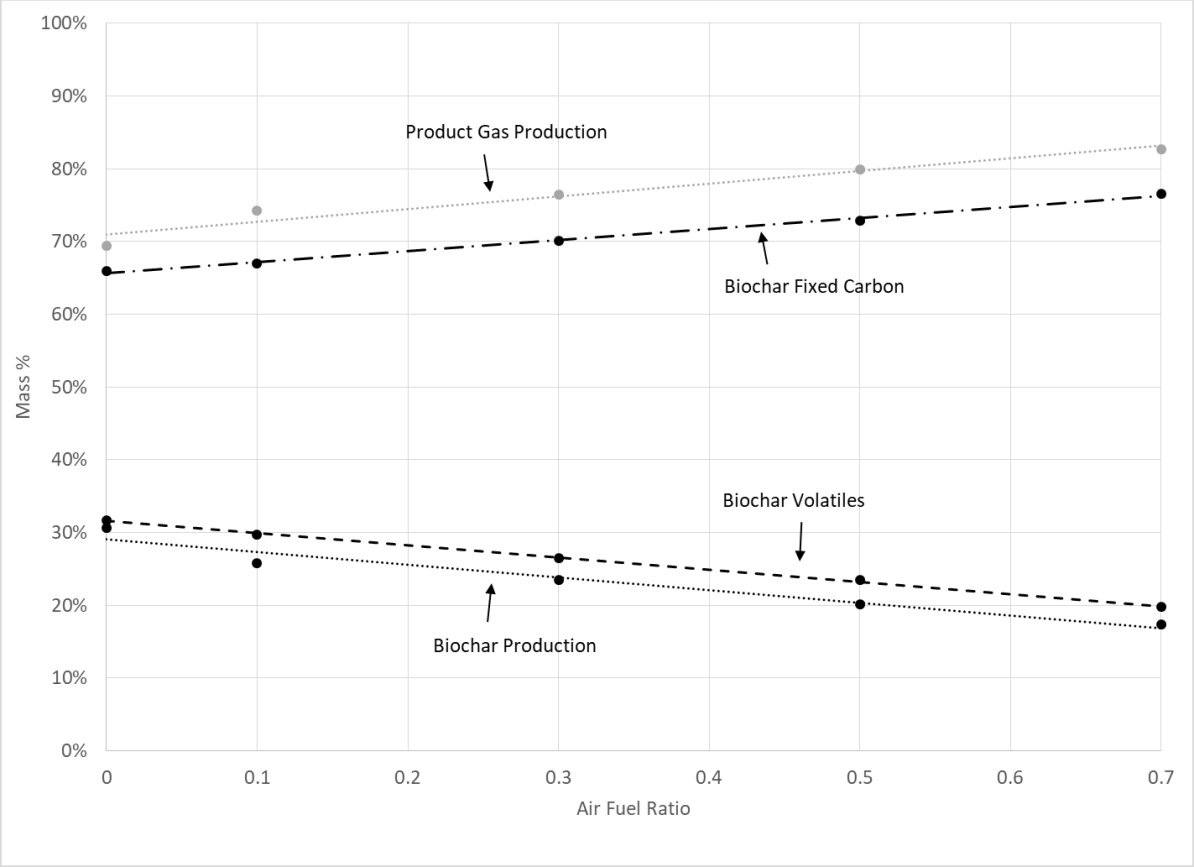
Source: West Biofuels, LLC

The lab scale testing allowed for better control of the air to the reacting biomass. In the test system, air leakage was not well controlled so there was concern that the resulting biochar reduction was greater than expected in a sealed system. The laboratory unit allowed for precise control of air addition to the reactor vessel and the testing focused on the relationship between air injection and solid and gaseous/vapor product fractions. Figure 90 shows the relationship between air to fuel injection ratio (mass air to mass of dry biomass) and the fractions of biochar and gaseous products in the reactor. Between 0.0 and 0.7 air injection the biochar fraction drops from 30 percent down to 17 percent in a very linear relationship with air rate and the product gas increases from 70 percent to 83 percent. In addition, it shows that the additional air is consuming the volatiles in the biochar making it higher quality as the amount of volatiles decreases by the same amount as the biochar. The testing shows that selective controlled air injection can enhance product gas production and improve the biochar carbon content at carbonization temperatures of 400°C.

The two test studies on the rotary gasifier system showed that it is feasible to get comparable performance between the rotary gasifier system and the CD gasifier system in terms of energetic gas and biochar production. Table 84 shows the comparison between the CD system operating on torrefied wood (from Chapter 3 results) compared with the rotary gasifier system without and with air injection. The efficiency of the rotary gasifier system without air injection is 5 percent less than the CD system but the rotary system produces nearly double the amount of biochar per unit of forest residue input. The rotary gasifier system with air injection is 14 percent more efficient than the CD gasifier system and produces a comparable amount of biochar. The advantage of the rotary gasifier system is that it is a single vessel with a proven history of consistent forest biomass feeding without bridging and channeling like the fixed bed CD system. Also, the process operates at much milder process conditions of 400°C compared

with 1000°C in the CD system eliminating the need for refractory and making slagging and agglomeration non-issues as well.

Figure 90: Product Fractions from Forest Biomass with Air Injection At 400°C



Source: West Biofuels, LLC

Overall Findings

The final analysis and findings from the engine generator and alternative TO heater/ORC generator system require looking at each of the four system configurations that have been proposed in the last two chapters. This section examines how well both the gasifier systems and the coupled generation systems perform in meeting the objectives and where any fatal flaws may exist in terms of integration of these systems. Table 85 goes through each of the objective categories from Chapter 3 and Chapter 4 and compares how well each system performs among these categories. The values in the table are for a commercial scale 3MWe system but can be scaled appropriately for any size system.

The cells that critically fail the objectives are highlighted and in bold. The comparison shows that there are several critical areas where Systems 1 and 2 do not meet the objectives in terms of requirements for an engine generator. These are primarily in terms of tar and particulate loading but also objectives set out for oil change frequency and generator faults. Caterpillar says that the oil change frequency should not exceed 500 hours and maybe less if the gas

contaminants are high. And we expect there to be frequent faults because of the gas fouling and condensation.

Table 84: Product Gas And Biochar Generation From Forest Biomass, Comparison Of Technology

Parameters	Units	CircleDraft Gasifier w/ Torrefied Wood @5%mc	Rotary Gasifier w/Wood @10%mc	Rotary Gasifier w/Wood @10%mc and Air Injection
Producer Gas Composition				
CO	(dry vol%)	29.8%	37.5%	21.0%
H2	(dry vol%)	16.5%	0.4%	0.3%
CH4	(dry vol%)	1.4%	5.6%	2.3%
N2	(dry vol%)	45.0%	0.3%	37.3%
CO2	(dry vol%)	7.0%	54.2%	34.8%
C2H4	(dry vol%)	0.0%	0.1%	1.0%
C2H6	(dry vol%)	0.1%	0.3%	0.0%
Producer Gas HHV	(MJ/kg)	5.9	4.0	2.7
Mass/Energy				
Producer Gas Generation	(mass% of dry input)	52%	27%	45%
Vapors Production*	(mass% of dry input)	2%	42%	38%
Biochar Production	(mass% of dry input)	16%	31%	17%
Producer Gas + Vapors HHV	(MJ/kg)	6.1	13.0	10.7
Biochar HHV	(MJ/kg)	24.3	21.6	24.0
Producer Gas + Vapors Energy	(MJ/kg of dry input)	11.3	9.6	12.1
Process Thermal Efficiency		***0.56***	***0.53***	***0.64***

*Consists of water and combustible C3+ compounds that are condensable at or above ambient temperature

Source: West Biofuels, LLC

Systems 3 and 4, while they don't meet the requirements for an engine generator, do meet the requirements for the TO heater which has a very broad range of tolerance for condensables and char particles in the LBG burner system. However, the efficiency of the TO Heater/ORC combination is lower than the gas engine and therefore more feedstock is required for a 3MWe output. This higher feed-rate also means additional biochar production which could offset the cost of the woody feedstock. If this is the case, the efficiency of this system may not be as critical as originally envisioned. In terms of lowering capital and maintenance costs and increasing reliability, System 4 would be the optimum choice from a technical risk standpoint.

Table 85: Performance Comparison Of System Configurations (based on 3MWe power production)

Objective	Units	System 1	System 2	System 3	System 4
Gasifier Objectives					
Thermal Efficiency:	(%)	65%	56%	56%	64%
Throughput Rate:	(dry kg/hr)	3000	3490	4970	4350
LBG Energy Content:	(MJ/kg)	6.1	6.1	6.1	10.7
Tar Content:	(mg/Nm^3)	*1,000*	*1,000*	14,700	>15,000
Tar Dew Point:	(°C)	*> 40*	*> 40*	> 100	> 300
Particulates:	(mg/Nm^3)	*600*	*600*	600	ND
Hydrogen Sulfide:	(ppm)	25	25	25	44
Biochar Production:	(% dry mass)	16%	16%	16%	17%
	(dry kg/hr)	481	558	795	739
Biochar Quality:	(% fixed carbon)	83%	83%	83%	78%
Generator Objectives					
Electrical Efficiency:	(%)	27%	27%	19%	19%
CHP Efficiency:	(%)	68%	68%	NA	NA
Oil Change Frequency:	(hours)	*500*	*500*	NA	NA
Generator Fault Freq.:	(per 250 hr)	*>1*	*>1*	<<1	<<1
Operating Speed:	(RPM)	1800	1800	3600	3600
Equivalence Ratio:	()	<0.55	<0.55	NA	NA
Compression Ratio:		9.4:1	9.4:1	NA	NA
Emissions Performance					
Nitrogen Oxide (NO_x):	(% control)	95.5%	95.5%	>90% est	>90%
Carbon Monoxide (CO):	(% control)	92.0%	92.0%	>90% est	>90%
Vol. Org. Comp. (VOC):	(% control)	ND	ND	ND	ND
Particulate Matter (PM):	(% control)	ND	ND	ND	ND

ND = Objective Not Determined; NA = Objective Not Applicable

Source: West Biofuels, LLC

CHAPTER 5: Feasibility Study

Community-scale modular biomass-to-electricity systems represent an important part of the state's solution. Supported by the California Public Utility Commission's (CPUC) Biomass Market Adjust Tariff (BioMAT), California has created an environment to support community-scale development. The Modular Biopower Feasibility Study explores the opportunities to place 10 CircleDraft biopower systems in areas of high fire risk for the management and risk reduction of forest fuels.

The objective of this report is to evaluate the technical feasibility of the modular gasification based on the data developed in Task 3 and Task 4 for utilization in a financial model to determine economic feasibility.

Technical Feasibility of Modular Biopower Systems

Gasification System Performance

The research and development efforts conducted in Task 2, Task 3, and Task 4 of this contract have evaluated critical performance items that impact the economic analysis of the modular system. Critical performance criteria include:

- Capacity Factor: Capacity factor is the ratio of actual energy output over a fixed time period to the maximum possible energy output over the same fixed time period. This ratio should account for operation and maintenance requirements and is necessary to estimate total annual energy production.
- Heat Rate: Heat rate is a measure of system efficiency recorded as total energy of incoming feedstock to total energy of outgoing product (in this case electricity).

Capacity Factor

Capacity factor is a combination of performance characteristics of the gasifier and the generator. Task 3 and Task 4 identified operational challenges running the CircleDraft fixed bed system with ground material as seen with forest-sourced feedstock. Challenges with material flow reduced the ability to consume feedstock and produce uniform high-quality producer gas, resulting in relative low performance. Significant discussion about how to improve material flow and gasifier performance is detailed in the Task 3 report. Overall, four systems were assessed to meet the needs of a modular system for forest feedstock.

- System 1: CircleDraft and Gas Engine
- System 2: Torrefier with CircleDraft and Gas Engine
- System 3: Torrefier with CircleDraft, Thermal Oil Heater, and ORC Generator
- System 4: Rotary Gasifier, Thermal Oil Heater, and ORC Generator

System 1: CircleDraft and Gas Engine

Using data collected from Task 3, West Biofuels was able to evaluate the impacts of feedstock bridging and channeling with the CircleDraft's fixed bed system. Across 12 days of testing at steady state conditions, the CircleDraft performed with a weighted average capacity factor of 80.5 percent of nameplate rating with a range from 75.4 percent to 121.1 percent.

Table 86: Capacity Factor from Gasifier Testing

Test Number	Test Date	Capacity Factor
3	6/2/2016	79.1%
3	6/3/2016	100.6%
3	6/6/2016	76.1%
3	6/7/2016	66.4%
3	6/8/2016	68.4%
3	6/9/2016	86.9%
4	10/11/2016	78.7%
4	10/12/2016	85.5%
5	12/6/2016	75.4%
5	12/7/2016	66.7%
5	12/9/2016	86.7%
6	2/13/2016	121.1%
Weighted Average:		**80.5%**

Source: West Biofuels, LLC

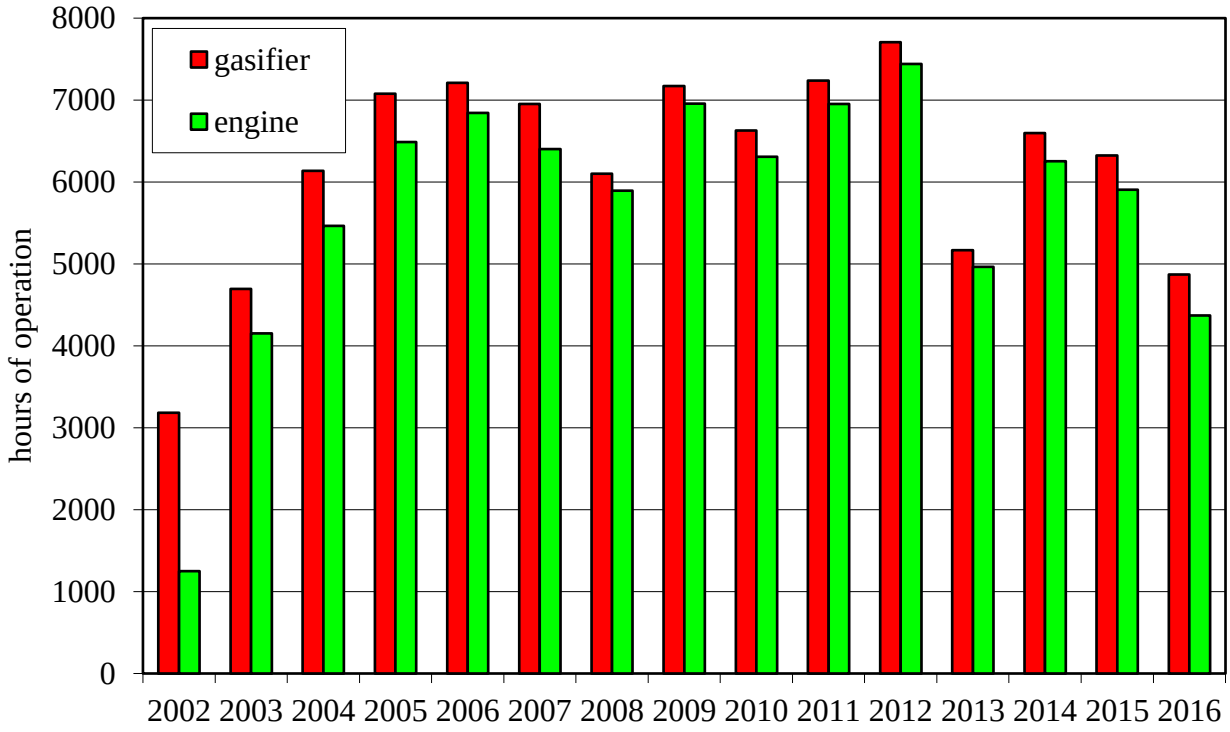
However, when bridging occurred with a severity that could not be resolved over the course of normal operations, the CircleDraft system required a full shut down and cool down to allow access to the gasifier to break the bridge. This exercise requires a six-day cool down period to ensure the system is sufficiently cool to expose the biomass to oxygen, two days of cleaning and one day to prepare for startup. Assuming the bridging occurs at a once a month frequency, the total downtime from bridging is expected to be 2,592 hours. Combining the gasifier derating to 80.5 percent and the downtime for bridging yields a system operation of 50.9 percent capacity.

System 2: Torrefier with CircleDraft and Gas Engine

While West Biofuels was not able to validate long-term operational performance with a torrefaction system, West Biofuels was able to demonstrate that the use of torrefied wood in the reactor improved flow dynamics. With the assumption that torrefaction as a pre-processing step will resolve the material flow challenges, a capacity factor can be estimated based on historical performance of gasification systems in Europe. One of the longest running gasification system—a Dual Fluidized Bed system in Güssing, Austria with a set of gas engines—shows an operating range between 5,463 and 7,4441 operating hours a year with an

average of 6,446 hours per year (Figure 91).[45] This average capacity factor of 73.6 percent should be considered a maximum capacity factor for a gasifier with gas engine as this fluidized bed system is designed to produce a high-quality producer gas without as many material handling issues as the fluidizing agent helps ensure feedstock moves through the system.

Figure 91: Operating Performance Of A Dual Fluidized Bed Gasifier In Güssing, Austria



Source: West Biofuels, LLC

System 3: Torrefier with CircleDraft and ORC Generator

This system changes the generator technology from System 2. ORC generators are less sensitive to producer gas inputs as gas engines. Therefore, the capacity factor is expected to improve to match more closely with gasifier operations, ranging from 6,102 hours per year to 7,707 hours with an average of 6,831 hours per year (78.0 percent).

System 4: Rotary Gasifier with ORC

One of the large advantages of the rotary gasifier system is that its operations are based on rotary dryers, which have design parameters of up to 8,000 hours per year (91.3 percent). However, producer gas production and energy production are expected to incur additional operational and maintenance requirements that will reduce the overall system capacity factor. To estimate the maximum capacity factor that should be expected, the operational performance

[45] Based on data from 2004 through 2015, excluding 2002 and 2003 as startup, 2013 for engine overhaul, and 2016 as an incomplete year due to utility contract expiration.

of existing biomass power plants in California were reviewed. Table 87 shows publicly-available information regarding operational biomass contracts in California.[46]

Table 87: Capacity Factor of Existing Biomass Power Plant Contracts

IOU	Installed Year	Project name	Contract Length (Years)	Contract Capacity	Expected Annual Generation	Capacity Factor
PG&E	1985	Burney Forest Products	30	31	212.555	78.3%
PG&E	2005	Chowchilla Biomass Facility	22	9	72	91.3%
SCE	1985	Desert View Power, Inc.	30	49.9	354.05	81.0%
PG&E	2008	DTE Stockton	25	44.5	315	80.8%
PG&E	2005	El Nido Biomass Facility	22	9	72	91.3%
SDG&E	2016	HL Power Company	5	24	175	83.2%
SDG&E	2016	HL Power Company LP	5	24	175	83.2%
PG&E	2007	Mt. Poso	15	44	328	85.1%
PG&E	2009	Ortigalita Power Company	15	0.75	5.585	85.0%
SCE	2016	Pacific Ultrapower Chinese Station	18	18	129	81.8%
SCE	2016	Rio Bravo Fresno	5	24.3	182	85.5%
SCE	2016	Rio Bravo Rocklin	5	24.4	182	85.1%
PG&E	2011	SPI Biomass Portfolio	20	58	346	68.1%
PG&E	1985	Thermal Energy Dev. Corp.	30	21	142.518	77.5%
PG&E	2006	Wadham Energy LP	10	26.5	141	60.7%
PG&E	1984	Wheelabrator Shasta	30	54.9	388.822	80.8%
PG&E	2009	Woodland Biomass	10	25	175	79.9%
			Average			**81.1%**

Source: West Biofuels, LLC

To estimate the capacity factor of a rotary gasifier, a conservative capacity factor of 81.1 percent is used, consistent with existing power plant contracts.

Heat Rate

Heat rate is a measure of conversion efficiency throughout the gasification system, including the generator. Heat rate is calculated based on the operational tests of the CircleDraft and Rotary Gasifier

CircleDraft Gasifier

The efficiency for the CircleDraft gasification system is shown in Table 88, calculated based on the data collected in Task 3.

[46] http://www.cpuc.ca.gov/RPS_Reports_Data/

Table 88: Gasifier Efficiency from CircleDraft Tests

Test Number	Test Date	Gasifier Efficiency
3	6/2/2016	62.8%
3	6/3/2016	77.3%
3	6/6/2016	59.3%
3	6/7/2016	70.8%
3	6/8/2016	70.8%
3	6/9/2016	70.8%
4	10/11/2016	70.8%
4	10/12/2016	71.5%
5	12/6/2016	65.0%
5	12/7/2016	64.6%
5	12/9/2016	64.2%
6	2/13/2016	63.3%
	Weighted Average:	**67.8%**

Source: West Biofuels, LLC

Using a gasifier efficiency of 67.8 percent and an internal combustion engine efficiency of 33.1 percent (based on technical specification of a Dresser Rand SFGLD 560 producer gas-rated engine), the total system efficiency is calculated to be 22.4 percent, which equals a heat rate of 15,232 Btu/kWh. This heat rate would be expected for System 1 and System 2.

System 3 used a different generation system, which includes a thermal oil heater and ORC system. Using a 75 percent efficient thermal oil heater and a 23.5 percent (per Turboden 32 HRS without split specification), the total system efficiency is calculated to be 11.9 percent, which equals a heat rate of 28,672 Btu/kWh.

System 4 uses a different gasification system, the rotary gasifier. West Biofuels tested the rotary gasification system to evaluate conversion efficiency. Batch testing, as described in Task 3, resulted in a producer gas production efficiency of 72.9 percent. Using the same efficiencies for the thermal oil heater and the ORC results in a total system efficiency of 12.8 percent, which equals a heat rate of 26,656 Btu/kWh.

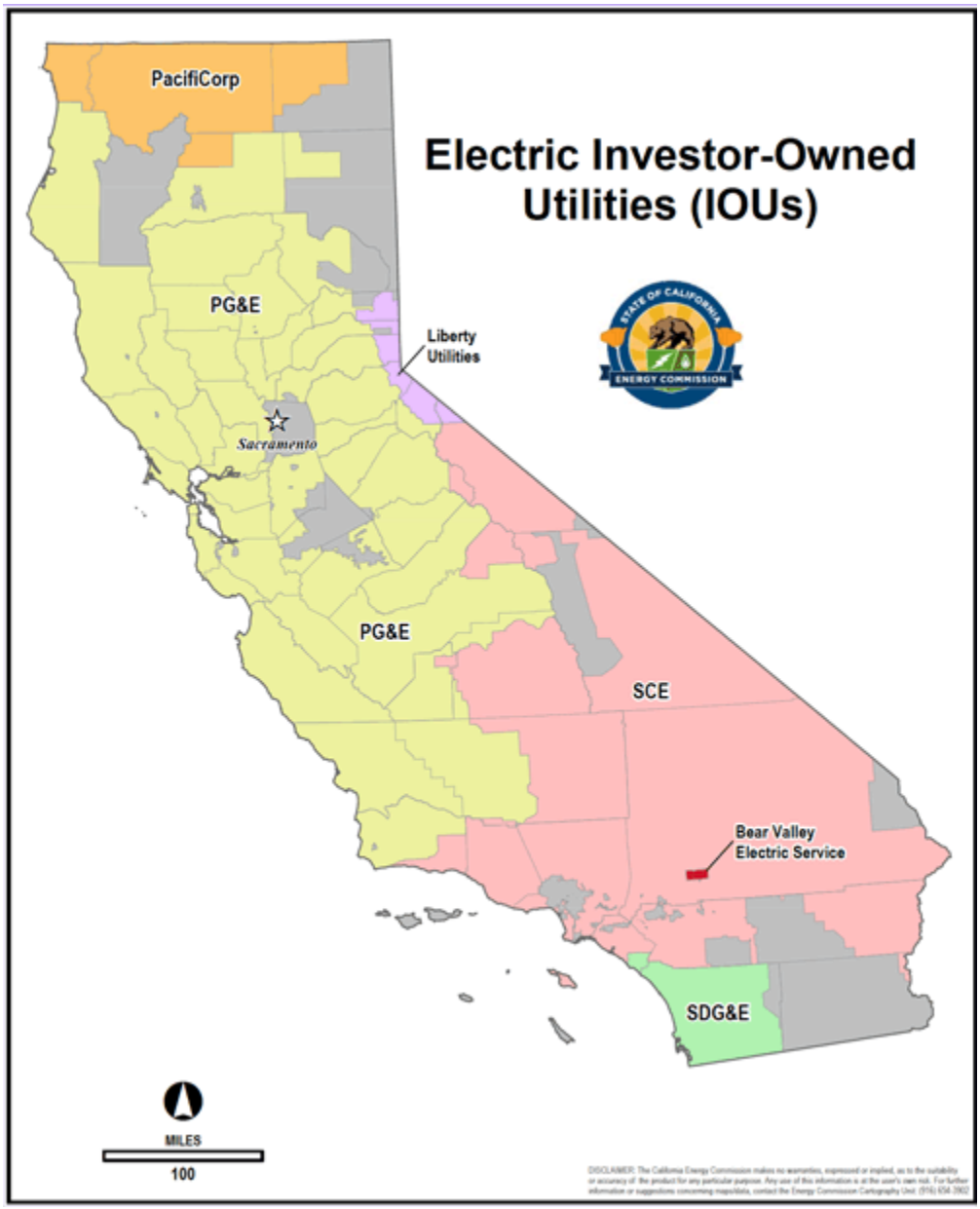
Grid Interconnection

Interconnection is a critical issue for the economic viability of a project. Forest projects are largely located in rural areas with small distribution systems that can be fed by a gasification project alone. Significant costs can be attributed to a project to ensure safe reliable grid operations after the distribute generation project is brought online.

Electric Rule 21 (Rule 21) is the process by which an electricity generating facility can export its energy to any of California's three major investor owned utilities (IOUs), Pacific Gas & Electric (PG&E), Southern California Edison (SCE), and San Diego Gas & Electric (SDG&E). These three

utilities serve approximately three-quarters of the electricity supply in California and the majority of the forested landscape, as shown in Figure 92. These IOUs are the only utilities offering the BioMAT program, targeting the development of community-scale biomass power project.

Figure 92: Electric Investor-Owned Utilities in California



Source: West Biofuels, LLC

Interconnection Study Process

The interconnection study process is outlined in the IOU Electric Rule 21[47] (specific to each IOU) or the Wholesale Distribution Tariff (WDT). The two processes are very similar; however, differ by the governing body. Rule 21 is maintained by the California Public Utility Commission (CPUC) and WDT is maintained by the Federal Energy Regulatory Commission (FERC). Lastly, a project developer can choose to directly interconnect to the transmission grid and conduct an interconnection study directly with the California Independent System Operator (CAISO).

Community-scale distributed generation projects are unlikely to connect directly to the transmission grid because of the relatively small size and the expense of transformers required to export to 60 kilovolt (kV) transmission lines. Additionally, to participate in the BioMAT program, a project must connect to the distribution network.

Rule 21 and WDT provide detailed guidelines for the approval for the interconnection of renewable energy projects into the utility's network. These tariffs increase transparency in the interconnection process, reducing the possibility of arbitrary decision making by the IOU. This formal review process determines if a proposed generation unit will cause negative impacts in the distribution network and the mitigation strategies necessary to ensure reliability and safety.

Prior to filing an Electrical Generation Interconnection (EGI) request, site developers may evaluate readily-accessible information about a potential site. IOUs offers two levels of pre-application reports to provide access to network information. To continue the application process, an applicant must submit an Electrical Generation Interconnection Request (EGI) to determine which kinds of studies are needed for the Distribution Provider (the way the rules refer to the IOU) are necessary.

Pre-Application Report

The Pre-Application Report request provides essential basic information that a qualified electrical engineer can use to help estimate the potential impacts and costs of interconnecting a project to the Utility grid. Three levels of Pre-Application Reports are available:

- **A. Standard Pre-Application Report**: Provides a readily-availability level of Distribution System data that requires little to no analysis on the part of distribution engineer providing the report.
- **B. Enhanced Pre-Application Report – Primary Service Package**: Provides a detailed level of Distribution System data that requires analysis on the part of the distribution engineer providing the report.
- **C. Enhanced Pre-Application Report – Behind the Meter Interconnection Package**: Provides distribution system level data that is relevant to a "Behind the Meter" interconnection, as well as Secondary or Primary service characteristics that are confirmed in the field.

[47] PG&E: https://www.pge.com/tariffs/tm2/pdf/ELEC_RULES_21.pdf
SCE: https://www.sce.com/NR/sc3/tm2/pdf/Rule21_1.pdf
SDG&E: http://regarchive.sdge.com/tm2/pdf/ELEC_ELEC-RULES_ERULE21.pdf.

Costs for the Pre-Application Report are shown in Table 89.

Table 89: Pre-Application Report Cost

Package Option	Cost
A	$300
B*	$325
C*	$900
AB	$525
AC	$1,100
BC*	$1,125
ABC	$1,325

Source: West Biofuels, LLC

The Pre-Application Report request includes 1) the precise location point of interconnection, 2) the fuel use (for example biomass), and 3) the conversion technology. The point of interconnection is defined by latitude and longitude, site map, street address, utility equipment number, meter number, and/or account number as available.

Electrical Generator Interconnection (EGI)

The EGI is the formal application process to begin the interconnection study.[48] Unlike the Pre-Application Report, site exclusivity is required for this formal process. Site exclusivity can be demonstrated by:

1. For private land:
    a. Ownership of, a leasehold interest in, or a right to develop property upon which the Generating Facility will be located consisting of a minimum of 50 percent of the acreage reasonably necessary to accommodate the Generating Facility; or
    b. An option to purchase or acquire a leasehold interest in property upon which the Generating Facility will be located consisting of a minimum of 50 percent of the acreage reasonably necessary to accommodate the Generating Facility.
2. For public land, including that controlled or managed by any federal, state or local agency:
    a. A final, non-appealable permit, license, or other right to use the property for the purpose of generating electric power and in acreage reasonably necessary to accommodate the Generating Facility, which exclusive right to use public land under the management of the federal Bureau of Land Management shall be in a form specified by the Bureau of Land Management.

The demonstration of site exclusivity, at a minimum, must be through the commercial operations date of the new generating facility.[49] In the EGI submission, the applicant will be able to select to pursue the Fast Track option or the Detailed Study Process. The results of the Pre-

[48] PG&E: https://www.pge.com/en_US/business/services/alternatives-to-pge/generate-your-own-power/electric-generation-interconnection.page.

[49] More information is available in Sheets 15-32 of the Rule.

Application Report will help determine the appropriate pathway. Additionally, the applicant can select the “Cost Envelope” option.

The distribution provider has 10 business days to review the EGI to determine completeness or 20 business days if the cost envelope option is selected. If anything is missing, the applicant receives a notice of deficiency at which time the applicant has 10 business days to correct the deficiency. Extensions to the timelines are allowed if necessary, upon request.

Cost Envelope Option

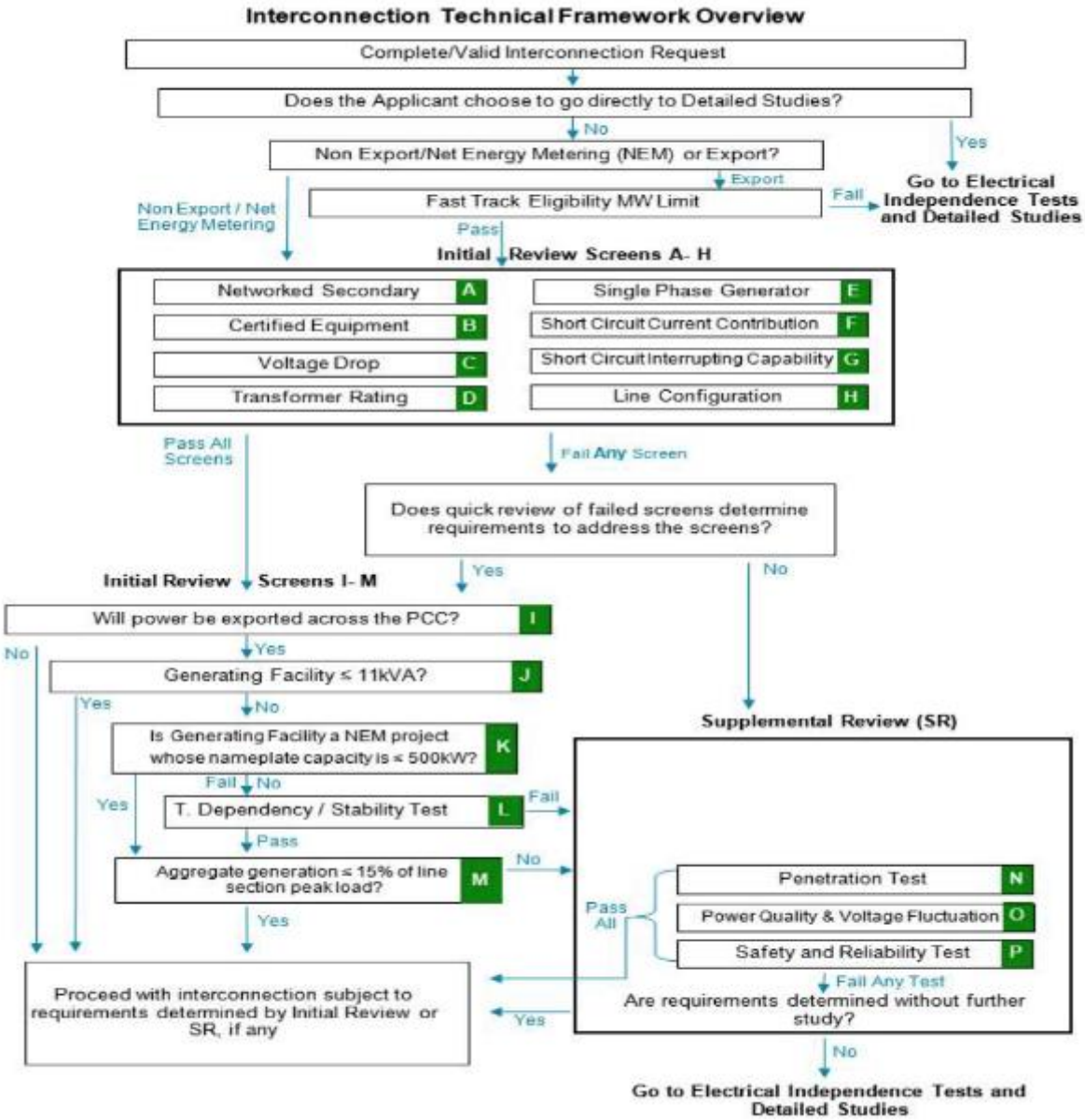
The CPUC has recently adopted a new program to help support cost certainty throughout the interconnection process, called the “cost envelope” option. This option is available to projects that pass the Fast Track study or the Independent Study process, one of the pathways within the Detailed Study Process. Selection of the cost envelop requires the payment of additional fees.

The cost envelop is a financial management tool that helps mitigate the risk of cost increases after the interconnection study has been concluded. An applicant is only responsible for the actual cost of the portion of interconnection facilities and/or distribution upgrades subject to the cost envelope within the range of plus or minus 25 percent of the estimated cost of such facilities identified in the cost envelope estimate. The applicant’s cost responsibility for that portion of the interconnection facilities and/or distribution upgrades subject to the envelope are capped at 25 percent above the estimated cost, and the applicant will not be responsible for the portion of the actual cost that exceed the 25 percent upper boundary. Correspondingly, any portion of the cost below 25 percent of the estimate will not be refunded to the applicant.

Fast Track

Sheet 137 in PG&E Electric Rule 21 shows a block diagram of the screens and technical parameters relevant to the eligibility for fast track. This block flow diagram is replicated in this report to further clarify the process (Figure 93).

Figure 93: Interconnection Technical Framework



Source: Sheet 137 of PG&E Electric Rule 21

Projects with a gross nameplate rating of 3 MW or less and are on a 12 kV or higher interconnection voltage point are eligible for Fast Track. The Fast Track process consists of a series of engineering evaluations called "Screens." Generally, proposed forest biomass projects are not able to pass these screens, due mainly to Screen M, which evaluates the project size against the distribution circuit's peak load, as depicted in Table 90. To determine if there is a potential for islanding, a phenomenon that occurs when an electricity generating facility is sufficiently large relative to the circuit loads that it alone can power the system, even if the rest of the network is down. This can cause serious safety concerns for line workers repairing the

network since it raises uncertainty as to whether or not a line is live. The pre-application report typically provides enough information to for an applicant to determine if this will be an issue.

Three existing forest biomass project Pre-Application Reports are summarized in Table 90 and show a common theme for forest biomass projects located in rural areas.

Table 90: Example Pre-Application Report Data Addressing Screen M

Project Name	Proposed capacity	Peak Load	15% of Peak Load
Blue Mountain Electric Company	3000 kW	4619 kW	692.5 kW
Indian Valley Biomass Project	3000 kW	1360 kW	204 kW
Burney Hat Creek Bioenergy	2880 kW	3660 kW	549 kW

Source: West Biofuels, LLC

In each of these examples, the proposed facility was substantially larger than 15 percent of peak load, indicating that Fast Track would not be a good option for these sites. The relative size of the proposed projects compared to the load in the circuit raises concerns about the operation of the system, namely loading of the assets, power quality issues related to voltage, protection coordination and islanded operation of the power stations.

If an applicant elects to pursue the Fast Track process, the IOU will provide the outcome of the Fast Track screens within 15 business days. If successful, the Distribution Provider will provide a template Generator Interconnection Agreement (GIA). If the cost envelope option is selected, the IOU will provide the Cost Envelope Estimate within 20 business days of receiving the study deposit.

If a project does not pass Fast Track, it will move to the Supplemental Review Process.

Supplemental Review Process

The supplemental review process is exclusively for projects that do not pass Fast Track. The supplemental review process includes three more screens to better determine the potential impacts of interconnection. If mitigation measures can be determined during this study period, the project will pass and will move forward with a GIA. However, if mitigations cannot be determined without further study, the project will move into the detailed study process. The supplemental review process takes approximately 20 business days upon receipt of payments.

Detailed Study Process

The first part of the detailed study process is the Electrical Independence Test (EIT). The EIT determines which of the three detailed study processes are appropriate:

- Independent Study Process: For projects that are electrically independent from all other projects currently being studied.
- Distribution Group Study Process: For projects that are electrically dependent of another project on the distribution circuit.

- Transmission Group Study Process: For projects that are electrically dependent of another project on the transmission circuit.

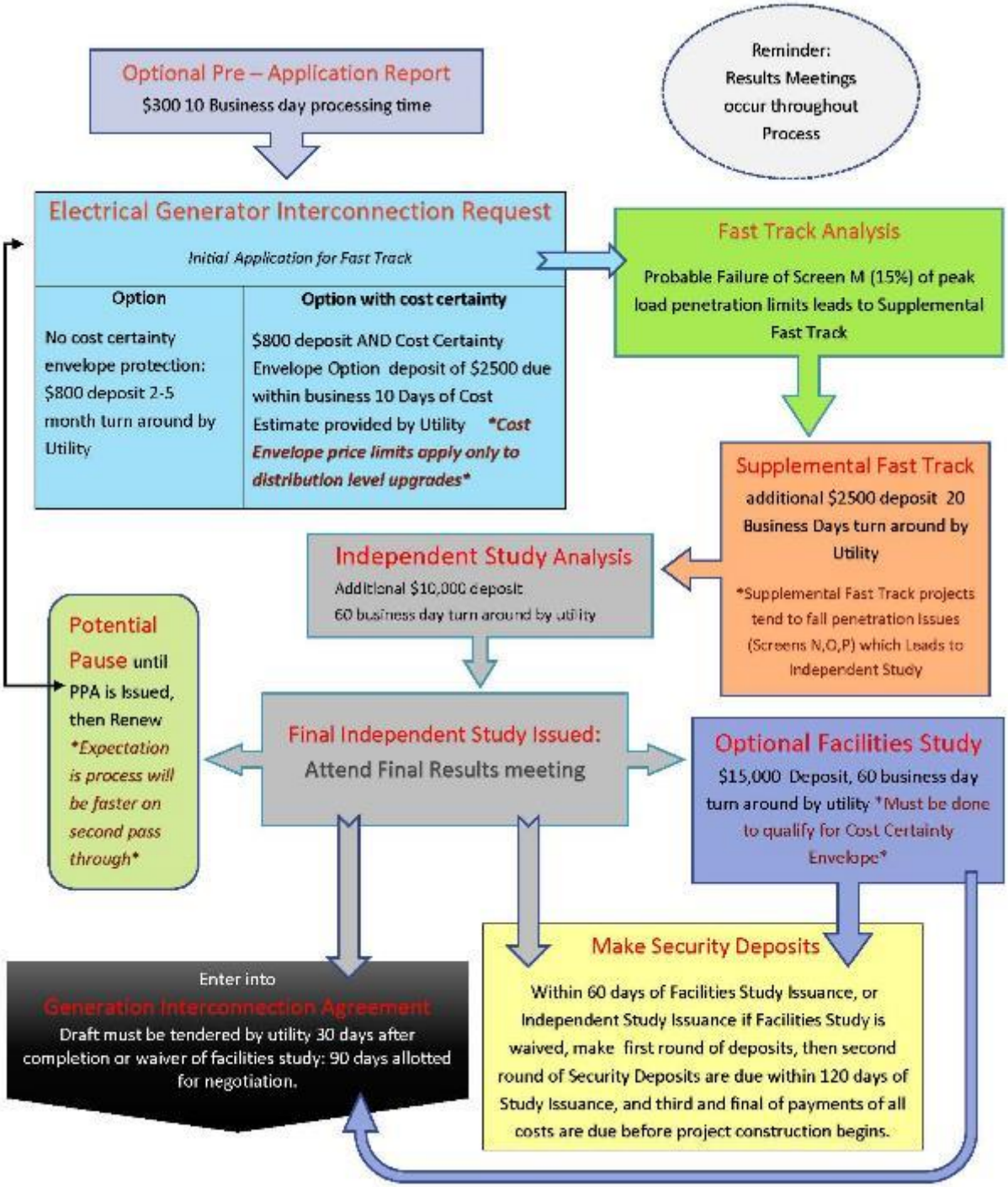
The majority of projects will directed towards the independent study process, particularly in rural areas. Although, for projects with large generating capacities relative its distribution circuit, there is a chance of entering the Transmission Group Study Process.

Each of the pathways contains two phases:

- Independent Study Process
    - System Impact Study
    - Facilities Study
- Distribution Group Study Process
    - Phase 1
    - Phase 2
- Transmission Cluster Study Process
    - Phase 1
    - Phase 2

The detailed study pathways all contains strict timelines that must be followed by the applicant to avoid withdraw. While Rule 21 and WDT also identify strict timelines for the utility provider, theses timelines can be extended by the IOU without recourse. These study processes traditionally take several months and result in the final cost estimate. Figure 94 shows a summary of the timelines associated with the study process.

Figure 94: Summary of Rule 21 Timelines



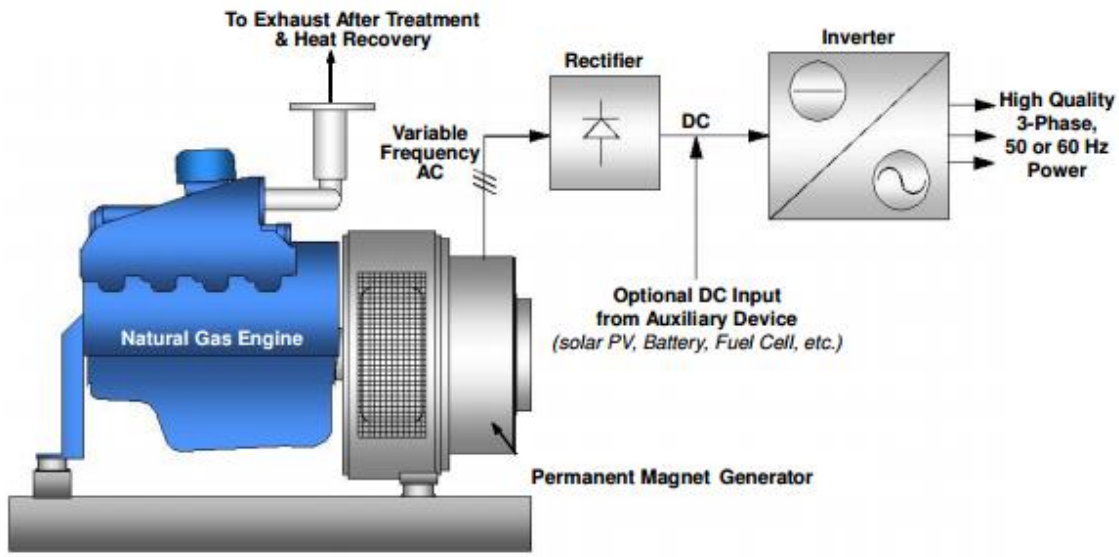
Source: West Biofuels, LLC

Interconnection with Synchronous vs. Inverter-Based Generators

West Biofuels worked with several electrical engineers to evaluate the potential to use inverter-based interconnection technology to connect to the grid. This research attempts to address an important interconnection challenge specific to projects in PG&E service territory, Direct

Transfer Trip (DTT). DTT is the most common anti-islanding mitigation utilized by PG&E to mitigate the impacts on the distribution network and transmission networks. DTT is frequently a very expensive technical solution, one that is notably not required in SCE service territory. Inverter-based systems used commonly in solar photovoltaic installations already have approved anti-islanding equipment and therefore do not traditionally require these expensive upgrades. Figure 95 shows a conceptual design of an inverter-based engine generator for a natural gas project, which could be replicated with a producer gas engine.

Figure 95: Conceptual Design of Inverter-Based Engine Generator



Engine/Generator Output

RPM	Volts	Freq (hz)	KW
1000	98	135	39
2200	207	297	93
3000	258	405	130

Power Conversion

Delivered kW

Volts	Freq (hz)	KW
480	60	37
480	60	88
480	60	123

Source: Tecogen[50]

West Biofuels evaluated the potential to develop an internal combustion engine generator set to utilize an inverter-based connection scheme. While this study was limited in scope and did not include actual interconnection applications with PG&E to compare the two systems at a given interconnection site, West Biofuels identified two manufacturers of these systems that could prove valuable to reduce the cost of interconnection in rural environments.

- Innovus Power: www.innovus-power.com
- Techogen: www.techogen.com

[50] Panora, R. and Roy, J. "Top 10 Reasons to Choose Inverter-Based Engine CHP". Tecogen. http://bpe-ne.com/wp-content/uploads/2012/07/top10-reasons-to-choose-inverter-based-engine-chp.pdf

Economic Feasibility of Modular Biopower Systems

Biomass Market Adjusting Tariff (BioMAT)

The BioMAT program is currently driving the market for community-scale biomass power in California. The feed-in tariff concept began in 2007 with the idea that under the Renewable Portfolio Standard (RPS) Program, public water and wastewater treatment facilities should be given the opportunity to sell small amounts of excess power to the IOU at incentivized rates and that such practice would encourage small-scale renewable distributed power.[51] Over the next five years, the Commission and the legislature made a series of changes to broaden this feed in tariff program to include traditional renewable energy sources like solar, wind, and baseload power such as hydro and geothermal.[52]

An interest in expanding the program to cover the conversion of waste products to energy began in 2011 and lead to the implementation of the provisions of Senate Bill (SB) 1122 (Rubio), stats. 2012, ch. 612. This legislation amends Public Utilities Code § 399.20 (the "feed-in tariff" provisions) of California's renewables portfolio standard (RPS) program to require that IOUs procure 250 MW of RPS-eligible generation from facilities using specified types of bioenergy, including urban waste, dairy and agricultural waste, and forest biomass. In particular, there was a 50 MW procurement requirement for the forest biomass sector, which is the focus of this analysis. The BioMAT program is a five-year program that will end January 31, 2021.[53]

Basic Project BioMAT Program Requirements

There are several basic requirements that a project must meet in order to be eligible for a BioMAT contract:

- A project must qualify under Federal Energy Regulatory Commission (FERC) as a "Qualified Facility" and be certified as RPS eligible[54] Both of these requirements are met if the project is going to use biomass waste conversion for electricity generation.[55]
- A project may not have commenced before June 1, 2013.
- The physical location of the projects must be within Investor Owned Utility (IOU) service territory.[56]

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[51] AB 1969 (Yee, Stats. 2006, ch. 731).

[52] Amendments to Pub. Util. Code § 399.20 enacted by Senate Bill (SB) 380 (Kehoe, Stats. 2008, ch. 544, § 1), SB 32 (Negrete McLeod, Stats. 2009, ch. 328, § 3.5), and by SB 2 of the 2011-2012 First Extraordinary Session (Simitian, Stats. 2011, ch. 1) (SB 2 1X).

[53] D.14-12-081 P.72.

[54] http://www.energy.ca.gov/2015publications/CEC-300-2015-001/CEC-300-2015-001-ED8-CMF.pdf.

[55] https://www.ferc.gov/industries/electric/gen-info/qual-fac/what-is.asp .

[56] Except that there are three MW available within SCE territory.

- The project applicants must demonstrate 100 percent site control through land ownership, a lease, or lease option contingent on execution of a Power Purchase Agreement (PPA).

Project Size

Recently, the size of projects allowed to participate in the program increased. AB 1923 (Wood) adds California Public Utilities Code Section 399.20(f)(2)(E) that allows for projects participating in the program to provide electricity to a project's on-site power demand in the amount up to 2 MW, and still export the previously allowable 3 MW to the grid, essentially expanding the size of biomass projects that can participate in the program to 5 MW. Projects can now operate co-located businesses onsite and utilize larger scale energy production facilities.

Interconnection

There is a statutory emphasis on the need to ensure that projects understand the needs for the interconnection of the facility to the grid. In support of that intent, the California Public Utilities Commission (CPUC) requires that before a project is eligible for the BioMAT queue,[57] it must have a System Impact Study or Phase 1 Distribution Group Study.[58] In 2016, this program requirement changes significantly with the passage of SB 840 (trailer). This lengthy bill included language that clarified the eligibility criteria requirements for the BioMAT program pertaining to interconnection study requirements.[59] Before this change, the BioMAT program required that a project obtain a "completed interconnection study", but it remained unclear whether that also meant that the project had to maintain a position within the interconnection queue.[60]

In a series of public proceedings in early 2016, the CPUC suggested that a project would need to maintain a place within the interconnection queue while the project was waiting to strike at a price within the BioMAT program queue. Due to many complexities and project challenges associated with this interpretation, the Governor's office sponsored clarifying language that now requires that projects be allowed to participate the BioMAT Program if a series of requirements are met. These requirements are:

i) The project is already interconnected, or

ii) The project has been found to be eligible for interconnection pursuant to the fast track process under the relevant tariff, or

iii) A system impact study or other interconnection study has been completed for the project under the relevant tariff, and there was no determination in the study that, with the identified interconnection upgrades, if any, a condition specified in paragraph (2),

[57] The BioMat queue is a reference to participation in the BioMat program. Application to the program will be discussed further on.

[58] These studies are produced under Rule 21, or WDT interconnection processes.

[59] See Section 9 of the Bill.

[60] The interconnection queue essentially means the continuation of the processing an interconnection request, including the placement of several expensive down payments.

(3), or (4) of subdivision (n) of 399.20 of the Public Utilities Code would exist. For a project meeting the eligibility requirements pursuant to clause (iii), projects are deemed to be able to interconnect within the required time limits for the purpose of determining eligibility for the tariff under the statute.

This new language is located at California Public Utilities Code Section 399.20(f)(4), and was implemented by the CPUC, and the IOU tariffs have been updated.[61] Now, projects can enter the BioMAT program with System Impact Studies that are no longer tied to live interconnection applications. The expectation is that this will facilitate project participation.

Developer Experience

The general requirement is that one member of team must have completed at least one project of similar capacity *and* technology, or begun construction on similar project. [62] This language has been expanded upon within the BioMAT tariff to mean that a project with a size less than 1 MW will be deemed to be a project with similar capacity to a Project up to 1 MW. A project between 1 MW to 3 MW will be deemed to be a project with similar capacity to a Project up to 3 MW. For example, for a 3 MW Project, a project of similar capacity cannot be smaller than 1 MW.

Daisy Chaining

Daisy chaining is the process of breaking up one larger project into a series of smaller projects that each meet size limitations, but cumulatively are larger than the size limitation. The applicant must provide to the IOU an attestation that either the Project is the only exporting project being developed or owned or controlled by the Applicant on any single or contiguous pieces of property or, if more than one exporting project is being developed or owned or controlled by the applicant on any single or contiguous pieces of property, the total aggregated installed capacity of the projects does not exceed 3 MW. The IOU may, in its sole discretion, determine that the applicant does not satisfy this Eligibility Criteria if the Project appears to be part of an installation in the same general location that has been or is being developed by the applicant or the applicant's affiliates and the total aggregated installed capacity of the installation is greater than 3 MW. Note, however, that energy facilities that are on site but are under contract through a different program, like Self Generation Incentive Program or Net Energy Metering, are not considered "daisy chaining".

Feedstock for Category 3 Projects

Another requirement to participate in the program goes beyond the earlier mentioned requirements of simply using woody biomass for RPS and Qualified Facility qualification; there is also a requirement that 80 percent of the wood come from sustainable sources. The other 20 percent of the wood may be other wood that qualifies for the program in other categories: such

[61] http://www.pge.com/includes/docs/pdfs/b2b/wholesaleelectricsuppliersolicitation/BioMAT/ELEC_SCHEDS_E-BioMAT.pdf

[62] D. 12-05-035 Page 69.

as agricultural or urban wood waste. Note that feedstock can come from anywhere, including across IOU territory boundaries.

Forest biomass must be "sustainable" as defined by the CPUC specifically for this program, as waster derived from (1) fire threat reduction activities (2) fire threat clearance activities, (3) Infrastructure clearance projects or (4) "other" waste wood that must be analyzed through a check list that generally assures it comes from projects associated with current forest practice act and other federal and state rules.

In terms of wood being used under category 4 "other" waste wood, below are interpretations of these checklist requirements from three registered professional foresters (RPF):

> "Most of the checklist are desired stand conditions or components and with the exception of a few (that seem to be focused on retaining larger trees) could be found post-harvest regardless of the prescription being even aged or uneven aged. For example, under "Habitat Elements" B4, you can retain snags per acre to meet some desired condition and still conduct an even aged harvest using shelterwood removal (even aged). You can also leave a certain desired amount of down logs (B5) to benefit wildlife regardless of the prescription. So, several of these conditions can easily be obtained and aren't dependent on the type of silviculture but are more specific to the desired future forest stand condition. This is consistent for all the items A-E, for example most of the air and water quality protection are covered under the standard Forest Practice Rule Watercourse and Lake Protection Zones, these protections apply regardless of prescription. So I don't see the checklist being restricted to any type of prescription, Landowner's have the option of retaining trees, habitat or providing protections above what is required in the Forest Practice Rule to meet their management objectives. An even aged prescription is simply a regeneration method and doesn't directly translate to specific habitat, water quality or wildlife impacts or protections. Future forest stand conditions aren't entirely depend on silvicultural prescriptions. Good foresters will identify these desired conditions, build then into the harvest plan and ensure they are retained post-harvest."

Statewide Pricing Pool

The CPUC has developed a Price Adjustment Mechanism, which will change over time under certain conditions, presumably based on market fluctuations that reflect a proper value of a PPA. "Price Offering Periods" (Periods) will occur every 30 days until there is full subscription of allocation available in one Period. Then, they will occur every 60 days. There are 6 MW available during each period.

The Price moves by an increment of $4/MWh, then $8/MWh, then $12/MWh thereafter if there are at least three projects in the queue. After the first bidder accepts the offered price, there must be at least five projects in the queue before the price will move again. If there are at least five projects, the price will rise until the next project accepts a PPA.[63] Whenever a project

[63] Except that if a project is less than 1.2 MW is size, its acceptance of a PPA will not freeze the price movement.

accepts a price, then the price that was accepted will be offered for the next Period, and then continue to rise the following Period as long as there are five projects in the queue. That will continue until the Period in which all 6 MW are allocated.[64] When that occurs, the price will go down by an increment of $4/MWh, as long as there are still five projects in the queue. If there are not five projects in the queue at that time, the price will freeze (rather than drop).

Note that some projects that are in the queue may be disqualified from triggering price adjustments if they are "affiliated". The definition of affiliated has been altered within the BioMAT program from the definition of that term used in common parlance, or even other associated programs like Rule 21.[65] Under the Tariff, even if a project shares a 1 percent ownership interest with another project, they will be considered 'affiliated' and only the project that was in the queue first will count towards the number of projects needed for a price adjustment. The CPUC did not choose to challenge this new use of the term when it was brought up by various parties.

Program Participation Request

To participate in the BioMAT program, an applicant must submit a program participation request (PPR). Within 20 business days of receiving a PPR, the IOU, in its sole discretion, will confirm whether the Applicant's PPR is deemed complete and satisfies the Eligibility Criteria. Applicants will be assigned a program position (BioMAT Queue Number) once the PPR is deemed complete. If the PPR is deemed complete, the BioMAT Queue Number assignment will be based on the date and time that the PPR was received by the IOU.

If an applicant's PPR is deemed incomplete, or the applicant is otherwise ineligible for a BioMAT PPA, the IOU will notify the Applicant that the PPR has been rejected (for example, the PPR is null and void). If rejected, the Applicant will be required to submit a new, correct and complete PPR demonstrating the Applicant's eligibility. The Applicant's BioMAT Queue Number will be based on the date and time of the re-submitted, correct and complete PPR. There are timelines that must be met to correct your submission which are outlined within the Tariff.[66] Once an Applicant has a BioMAT Queue Number for its proposed Project, the information provided in the PPR regarding the Project may not be modified, unless permitted or approved by the IOU, and shall be used for the completion of the BioMAT PPA. The IOU will indicate what information, if any, in the PPR can be modified in its BioMAT program materials and/or online platform.

From the opening of each auction, the applicant will have 10 days to accept the price offered for that Period. If the applicant accepts the price, but are rejected due to early-queued participants, the applicant will retain its place in the queue. Once an applicant has notified the

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[64] If the price rises to $197.00 dollars per MWh, the CPUC will pause the program to review if there if there are problems with the program. While this is not a hard "price cap", it could be a problem if the price reaches this level.

[65] The definition of affiliate project under Rule 21 is: "With respect to a corporation, partnership or other entity, each such other corporation, partnership or other entity that directly or indirectly, through one or more intermediaries, controls, is controlled by, or is under common control with, such corporation, partnership or other entity."

[66] See Sheet 15, Section 9(3)

IOU of price acceptance, the IOU will deliver a template PPA, which must then be executed and returned within 10 days from receiving it from utility.

Economic Analysis

Economic analysis was conducted across all four technology configurations using the BioMAT financial model developed by Black & Veatch for the California Public Utilities Commission[67] as part of the development of the BioMAT program. The model solves for levelized cost of electricity (LCOE). Unless otherwise described in this section, the default settings were used.

Capital Cost

Capital cost of equipment is estimated based on technology configurations. A standardized approach to additional infrastructure necessary to develop an entire project is considered equal across all technology configurations. Consistent with the Black & Veatch analysis, interconnection costs are based on "simple interconnections to circuits with available capacity that do not require system upgrades are assumed in the analysis."[68] Table 91 summarizes capital costs assumed for each technology configuration.

Table 91: Capital Cost Summary

	Unit Cost ($000)	Quantity Required				Total Costs (thousand $)			
		Sys. 1	Sys. 2	Sys. 3	Sys. 4	Sys. 1	Sys. 2	Sys. 3	Sys. 4
Truck unloading/fuel yard equip	200	1	1	1	1	200	200	200	200
Feedstock sizing equipment	350	1	1	1	1	350	350	350	350
Metering and conveyance	200	1	1	1	1	200	200	200	200
Feedstock dryer	600	1	1	1	1	600	600	600	600
Feedstock torrefier	1,800	0	1	1	0	-	1,800	1,800	-
Distribution conveyance	200	1	1	1	0	200	200	200	-
CircleDraft gasifier	750	6	6	6	0	4,500	4,500	4,500	-
Rotary gasifier	2,500	0	0	0	1	-	-	-	2,500
Gas cleanup system	800	1	1	0	0	800	800	-	-
1 MWe Engine Generator	1,200	3	3	0	0	3,600	3,600	-	-
Thermal Oil Heater	2,600	0	0	1	1	-	-	2,600	2,600
3 MWe ORC Generator	4,000	0	0	1	1	-	-	4,000	4,000

[67] http://www.cpuc.ca.gov/WorkArea/DownloadAsset.aspx?id=5732

[68] Appendix D, page D-2.

	Unit Cost ($000)	Quantity Required				Total Costs (thousand $)			
		Sys. 1	Sys. 2	Sys. 3	Sys. 4	Sys. 1	Sys. 2	Sys. 3	Sys. 4
Thermal oxidizer flare	250	1	1	0	0	250	250	-	-
Interconnection gear cost	300	1	1	1	1	300	300	300	300
Site improvement costs	500	1	1	1	1	500	500	500	500
TOTAL SYSTEM:						**11,500**	**13,300**	**15,250**	**11,250**
Construction/installation costs, 30%:						3,450	3,990	4,575	3,375
Contingency, 20%:						2,300	2,660	3,050	2,250
GRAND TOTAL CAPITAL COST:						**17,250**	**19,950**	**22,875**	**16,875**
Cost per kW ($/kW):						5,750	6,650	7,625	5,625

Source: West Biofuels, LLC

Fixed Operation and Maintenance (O&M)

Fixed O&M represents the costs associated with commercially-operating a system regardless of whether the unit is operating. Operations include labor, insurance, property taxes, and utilities, administration. Maintenance is based on systems installed. The 2 percent escalation rate proposed by Black & Veatch was not changed.

Table 92: Fixed Operations Cost Summary

	Unit Cost ($000)	Quantity Required				Total Costs ($000/yr)			
		Sys. 1	Sys. 2	Sys. 3	Sys. 4	Sys. 1	Sys. 2	Sys. 3	Sys. 4
Manager-Level Staff	140	2	2	2	2	280	280	280	280
Labor-Level Staff	70	9	9	9	6	630	630	630	420
Insurance	75	1	1	1	1	75	75	75	75
Property Taxes	50	1	1	1	1	50	50	50	50
Utilities	60	1	1	1	1	60	60	60	60
Administration	40	1	1	1	1	40	40	40	40
TOTAL SYSTEM:						**1,135**	**1,135**	**1,135**	**925**
Construction/installation costs, 30%:						340.50	341	341	278
Contingency, 20%:						227	227	227	185
GRAND TOTAL FIXED OPERATIONS:						**1,703**	**1,703**	**1,703**	**1,388**
Cost per kW ($/kW):						568	568	568	463

Source: West Biofuels, LLC

Similarly to Black & Veatch's assumptions, this model includes what are traditionally variable maintenance expenses in fixed costs. Feedstock costs are accounted for separately. Maintenance costs are based on a percentage of capital costs.

Table 93: Fixed Maintenance Cost Summary

	% of Cap. Cost	Capital Cost ($,000)				Total Costs ($,000/yr)			
		Sys. 1	Sys. 2	Sys. 3	Sys. 4	Sys. 1	Sys. 2	Sys. 3	Sys. 4
Feedstock Handling	5%	1550	3350	3350	1350	78	168	168	68
Conversion System	5%	5300	5300	7100	5100	265	265	355	255
Generator - ICE	10%	3600	3600	0	0	360	360	-	-
Generator - ORC	2%	0	0	4000	4000	-	-	80	80
Other	5%	1050	1050	800	800	53	53	40	40
TOTAL SYSTEM:						**755**	**845**	**643**	**443**
Construction/installation costs, 30%:						226	254	193	133
Contingency, 20%:						151	169	129	89
GRAND TOTAL FIXED MAINTENANCE:						**1,133**	**1,268**	**964**	**664**
Cost per kW ($/kW-year):						378	423	321	221

Source: West Biofuels, LLC

Table 94: Total Fixed O&M Summary

	Total Costs ($,000/yr)			
	System 1	System 2	System 3	System 4
Fixed Operations	1,703	1,703	1,703	1,388
Fixed Maintenance	1,133	1,268	964	664
TOTAL	**2,836**	**2,971**	**2,667**	**2,052**
Cost per kW ($/kW)	**945**	**990**	**889**	**684**

Source: West Biofuels, LLC

Fuel Costs

Feedstock cost in the forested region varies dramatically by source and location. To be consistent with the Black & Veatch assessment, feedstock costs as identified in the study are used for this analysis, although Task 2 of this report outline more realistic values for feedstock pricing which are included in the sensitivity analysis in Section 0.

Heat Rate and Capacity Factor

Heat rate and capacity factor are discussed in Section 0 and Section 0 and are summarized in Table 95.

Table 95: Summary of Heat Rate and Capacity Factor

	System 1	System 2	System 3	System 4
Heat Rate	15,232	15,232	28,672	26,656
Capacity Factor	50.9%	73.6%	78.0%	81.1%

Source: West Biofuels, LLC

Other Incentives and Incentive Escalation

Biochar production is an important differentiator of gasification technologies from conventional combustion systems. The Black & Veatch study explicitly excludes value from co-products in its analysis. For the sake of comparison, the base-case will be designed without

value attributed to biochar production. However, the impact of the biochar market will be assessed in Section 0.

Summary of Model Inputs

Table 96 summarizes the entries in the Black & Veatch LCOE model.

Table 96: BioMAT Model Inputs

Technical Entries	System 1	System 2	System 3	System 4
Project Capacity (MW)	3	3	3	3
Capital Cost ($/kW)	5,750	6,650	7,625	5,625
Fixed O&M ($/kW)	945	990	889	684
Fixed O&M Escalation	2%	2%	2%	2%
Variable O&M ($/MWh)	0	0	0	0
Variable O&M Escalation	0%	0%	0%	0%
Fuel Cost ($/MBtu)	1.67	1.67	1.67	1.67
Fuel Cost Escalation	2%	2%	2%	2%
Heat Rate (Btu/kWh)	15,232	15,232	28,672	26,656
Capacity Factor	50.9%	73.6%	78.0%	81.1%
Financial Entries				
Debt Percentage	60%	60%	60%	60%
Debt Rate	7%	7%	7%	7%
Debt Term (years)	15	15	15	15
Economic Life (years)	20	20	20	20
Depreciation Term (years)	7	7	7	7
Percent Depreciated	100%	100%	100%	100%
Cost of Generation Escalation	0%	0%	0%	0%
Tax Rate	40%	40%	40%	40%
Cost of Equity	10%	10%	10%	10%
Discount Rate	7%	7%	7%	7%
Incentives				
PTC ($/MWh)	0	0	0	0
PTC Escalation	0%	0%	0%	0%
PTC Term (years)	0	0	0	0
ITC	0%	0%	0%	0%
Other Incentives ($/year)	0	0	0	0
Incentive Escalation (%)	0%	0%	0%	0%

Source: West Biofuels, LLC

Model Result

The LCOE for each system was calculated with the results shown in Table 97.

Table 97: Financial Model Baseline Results

	System 1	System 2	System 3	System 4
LCOE ($/MWh)	$403	$310	$317	$242

Source: West Biofuels, LLC

Sensitivity Analysis

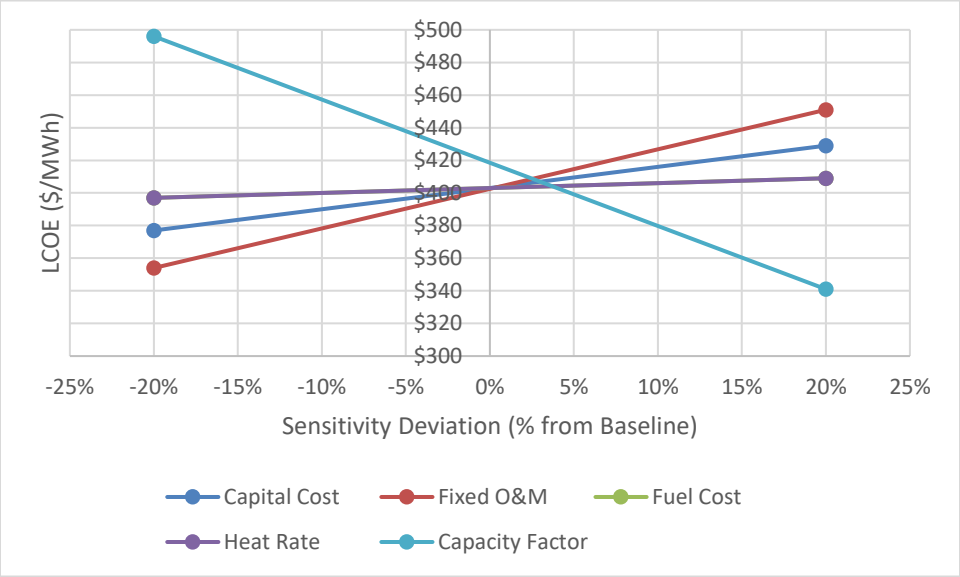
To understand the impact of each critical variable, each of the major inputs—capital cost, fixed O&M, fuel cost, heat rate, and capacity factor—were shifted by 20 percent. Note that changes to fuel cost and heat rate have the same impact on the financial model when biochar is not considered a value-added resource. The steeper the slope of the line, the more impactful the input. Results are shown in Table 98, Figure 96, Figure 97, Figure 98, and Figure 99.

Table 98: Sensitivity Analysis Results

	Sensitivity	System 1	System 2	System 3	System 4
Baseline	0%	$403	$310	$317	$242
Capital Cost	20%	$429	$331	$340	$258
Capital Cost	-20%	$377	$289	$294	$225
Fixed O&M	20%	$451	$345	$347	$264
Fixed O&M	-20%	$354	$275	$287	$220
Fuel Cost	20%	$409	$316	$328	$252
Fuel Cost	-20%	$397	$304	$306	$231
Heat Rate	20%	$409	$316	$328	$252
Heat Rate	-20%	$397	$304	$306	$231
Capacity Factor	20%	$341	$263	$273	$210
Capacity Factor	-20%	$496	$380	$383	$289

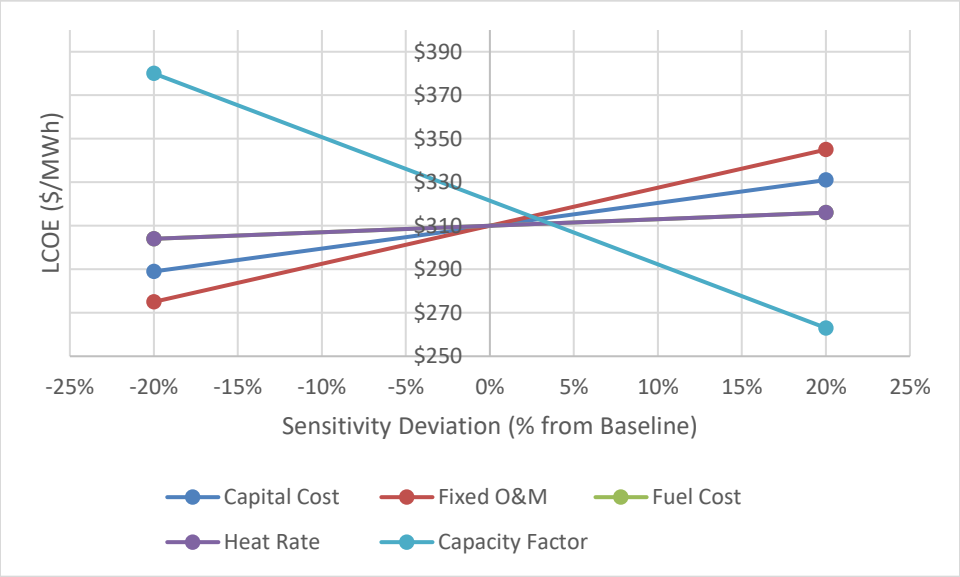
Source: West Biofuels, LLC

Figure 96: Sensitivity Analysis Results – System 1



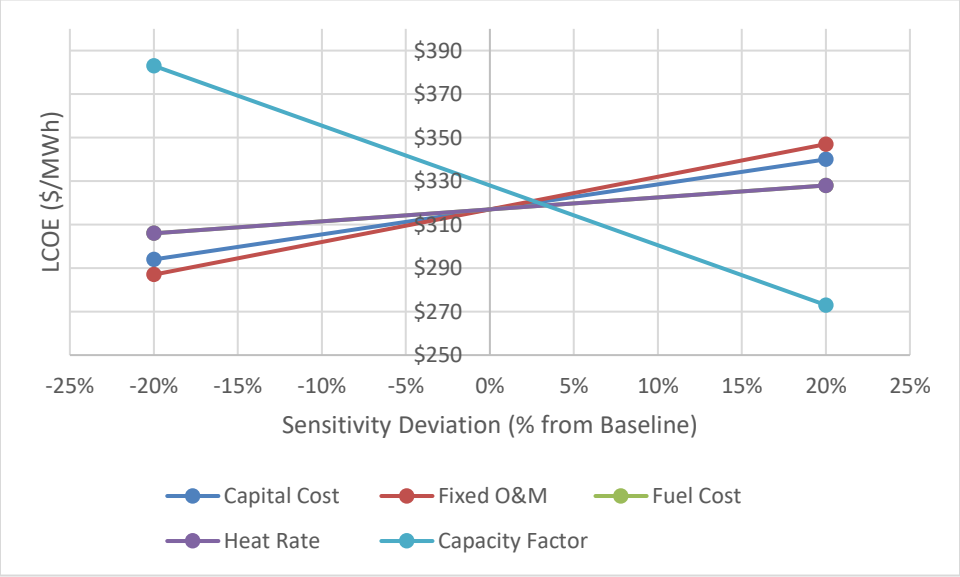
Source: West Biofuels, LLC

Figure 97: Sensitivity Analysis Results – System 2



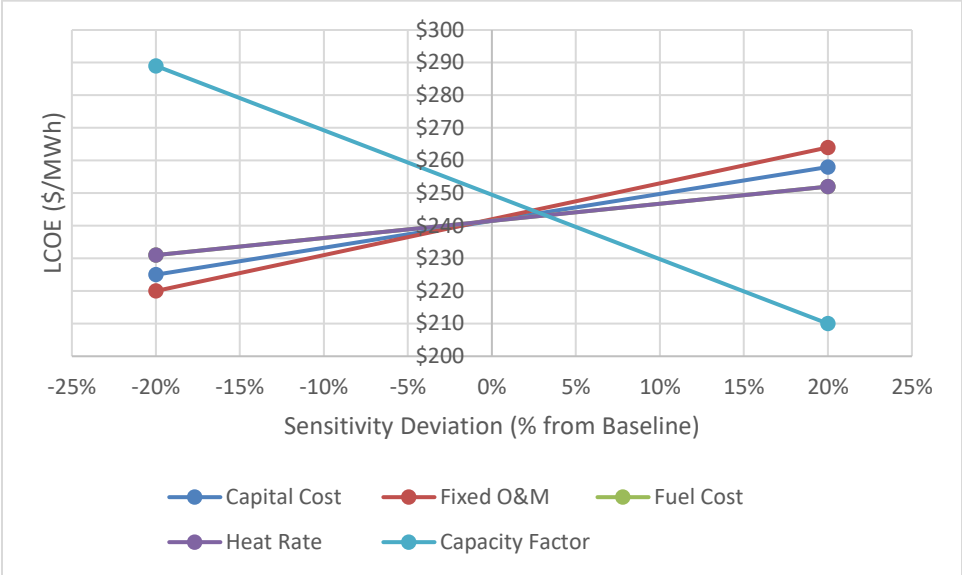
Source: West Biofuels, LLC

Figure 98: Sensitivity Analysis Results – System 3



Source: West Biofuels, LLC

Figure 99: Sensitivity Analysis Results – System 4



Source: West Biofuels, LLC

In all systems, capacity factor was the single largest important model input, followed by fixed O&M, capital cost, fuel cost, and heat rate. These results stress the importance of a highly reliable system that can maximize uptime and minimize cost of ongoing operations and maintenance. Capital cost, fuel cost, and heat rate (or efficiency) were of lower importance.

Biochar Sensitivity

Biochar has the potential to be a value co-product that can dramatically drive the price down. Biochar is a material with high levels of fixed carbon that can be used as a soil amendment or for filtration media. According to Grand View Research,[69] the global biochar market size was estimated at 283,200 tons in 2015. Globally increasing consumption of organic food and ability of biochar to enhance soil fertility & plant growth is expected to be a key factor driving the market growth. Biochar is an essential soil amendment as it removes toxic elements and sand pollutants from the soil. It prevents soil leeching, fertilizer runoff and maintains the moisture level of the soil. It also protects the crops during draughts and floods. Presently, synthetic and other bio-based fertilizers dominate the agricultural sector. But, led by several initiatives the awareness is spreading gradually amongst the farmers to include it into agricultural activities. Thus, creating important avenues for market growth in coming years.

North America was the dominant player in 2015 and accounted for 162,800 tons. It is expected to show significant growth on account of increasing need for organic food and high consumption of meat. As the farming community has more knowledge about its long terms benefits, the demand is expected to witness a significant increase over the forecast period. Low

[69] Grand View Research. "Biochar Market Analysis by Technology (Pyrolysis, Gasification, Others), By Application (Agriculture (Farming, Livestock, Others), Others), by Region, and Segment Forecasts, 2012-2015. Published May 2017. Report ID: 978-1-68038-681-3.

feed costs in the livestock sector are expected to result in expansion. Average wholesale and retail pricing is shown in Table 99.[70]

Table 99: Global Biochar Prices ($/kg)

Country	Pure Wholesale	Pure Retail	Number of Pure	Blend Wholesale	Blend Retail	Number of blends
Australia	$ 2.28	$ 6.72	10	$ 2.27	$ 12.83	5
Cambodia	$ 1.50	$ 4.00	2	-	-	0
Canada	$ 2.15	$ 6.49	3	$ 1.50	-	1
China	$ 0.49	-	1	$ 0.39	-	1
Germany	$ 0.56	$ 1.28	3	-	-	0
Ireland	$ 3.00	-	1	-	$ 4.00	1
Japan	$ 0.60	$ 1.00	2	$ 0.20	-	1
Kenya	-	-	0	$ 1.00	-	1
Mexico	$ 4.50	-	1	$ 4.50	-	1
Nigeria	$ 8.00	-	1	-	-	0
Pakistan	-	$ 1.00	1	-	$ 2.00	1
Philippines	$ 0.40	-	1	-	-	0
Russian Federation	$ 0.38	-	1	-	-	0
Sweden	-	-	0	$ 2.00	-	1
Switzerland	-	$ 0.78	1	-	$ 0.52	1
United Kingdom	$ 1.39	$ 2.20	3	$ 0.77	$ 2.60	3
United States	$ 1.50	$ 4.26	28	$ 1.29	$ 9.41	16
Global	$ 2.06	$ 3.08	59	$ 1.55	$ 5.23	33

Source: West Biofuels, LLC

Agriculture was the largest application segment in 2015 and accounted for over 70 percent of the share, in terms of volume. Biochar enhances soil's biological productivity, water holding and fertilizer holding capacity, which provides crop nutrition and improves plant growth. Farmers located in the North America and Europe regions in the present times are aware of its various benefits. However, a large part of the farming community still lacks knowledge about its advantages.

Using the wholesale price of $1.50/kg ($0.68/lb), additional revenue can be calculated as a function of the gasification configuration. Biochar production and associated revenue potential are shown in Table 100 and Figure 100.

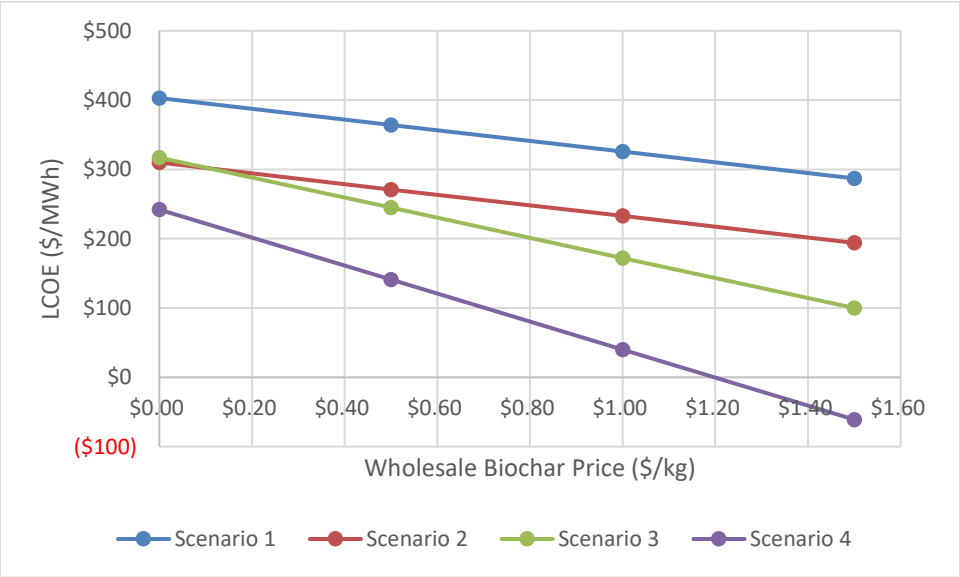
[70] Jirka, S., Tomlinson, T. "State of the Biochar Industry 2014: A Survey of Commercial Activity in the Biochar Sector." International Biochar Initiative. May 2015

Table 100: Biochar Production and Financial Impacts

	System 1	System 2	System 3	System 4
Biochar Production (% of feedstock)	10%	10%	10%	15%
Total Production (BDT/year)	1,131	1,637	3,265	4,734
LCOE at biochar prices				
$1.50/kg	$287	$194	$100	-$61
$1.00/kg	$326	$233	$172	$40
$0.50/kg	$364	$271	$245	$141
Baseline ($0/kg)	$403	$310	$317	$242

Source: West Biofuels, LLC

Figure 100: Biochar Sensitivity



Source: West Biofuels, LLC

Biochar is demonstrated to potentially have a dramatic impact on the business case for modular biomass energy products in the forest sector with the potential to reduce prices to become competitive with wind and solar. However, the biochar market is young and not well established, creating significant challenges finding long-term off-take agreements necessary to use this potential co-product stream to finance projects.

Environmental Compliance

Modular forest-based biomass gasification facilities, such as the West Biofuels model, will need to be permitted by a number of local, regional, and state agencies in California in order to be constructed and operate. The first step in the permitting process is for the facility to satisfy the requirements of the California Environmental Quality Act (CEQA)[71]. CEQA requires that "projects" in California satisfy the Act's requirements for protection of the environment unless

[71] Public Resources Code Sections 21000-21178.1, and CEQA Guidelines, Title 14 California Code of Regulations, Section 15000 *et. seq.* See also: CEQA Deskbook by Ronald E. Bass, Albert I. Herson, and Terry Rivesplata.

they are exempt under a provision in the Act. Under CEQA, all activities carried out or approved by California public agencies are projects. Since a modular forest-based biomass power facility will require discretionary approval by one or more California agencies, for example receive permits, it must comply with CEQA. The CEQA process requires preparation of an environmental impact report (EIR) for the project or a Negative Declaration if there is no significant impact on the environment, or a Mitigated Negative Declaration if there are potential significant environmental impacts that can be sufficiently reduced or eliminated.

CEQA has a number of Categorical and Statutory Exemptions. Categorical Exemptions are those classes of projects that generally will not have a significant impact on the environment. There are 29 classes of exemptions and examples are, 'Operation, Repair, or Maintenance of Existing Structures or Facilities', 'Replacement for Reconstruction of Existing Structures and Facilities', and "Construction or Conversion of Small New Facilities'. Statutory exemptions are those specifically established by the State legislature and are generally entitled to a blanket exemption from CEQA. None of the classes, actions, or projects included in Categorical Exemptions or Statutory Exemptions apply to modular forest-based biomass gasification facilities.

There are also a number of Program (a.k.a. Programmatic) Environmental Impact Reports (PEIRs) that have been prepared to cover other types of bioenergy projects that could be characterized as one large project and that are expected to have basically the same impact on the environment. For example, a PEIR has been prepared for anaerobic digester facilities for the treatment of food and organic waste[72], and one for dairy manure digester and co-digester facilities[73]. These have been suggested by some people as models for preparation of a Program EIR for modular forest-based biomass gasification facilities using forest waste for fuel. However, as of now, a Program EIR does not exist for these facilities. Therefore, a modular forest-based biomass gasification facility must go through the project and location specific CEQA process.

A modular forest-based biomass gasification facility could also be subject to the National Environmental Policy Act (NEPA)[74]. If a federal agency would have to issue a permit(s) or provide entitlements for the facility, it would be subject to and have to comply with NEPA in addition to complying with CEQA. For example, this could occur if the facility was to be located on federal land, if the facility's transmission connection to the electric grid crossed federal land, or if federal funding was instrumental in the construction of the bioenergy project even if on non-federal land. The process to comply with NEPA is similar to the CEQA process, requiring preparation of an Environmental Impact Statement (EIS), which is similar to an EIR or a Finding of No Significant Impact (FONSI), which is similar to a Negative Declaration. If compliance with NEPA is also required, California agencies are encouraged to prepare a joint CEQA/NEPA

[72] Program Environmental Impact Report (EIR) for Anaerobic Digestion Facilities http://www.calrecycle.ca.gov/SWFacilities/Compostables/AnaerobicDig/

[73] Program Environmental Impact (PIER) for Dairy Manure Digester and Co-Digester Facilities http://www.calrecycle.ca.gov/SWFacilities/Compostables/AnaerobicDig/DairyDigDEIR.pdf

[74] Pub L. 91-190, 42 USC 4321 *et. seq.*, and NEPA Regulations, 40 CFR Sections 1500 *et. seq.*

document, which could be a joint EIR/EIS or Negative Declaration/FONSI for both CEQA and NEPA.

As preparation of an EIR or a joint EIR/EIS is a relatively expensive and time-consuming process and for a 1-3 MW modular forest-based gasification facility either one could be a project killer. Preparation of a Negative Declaration or even a typical Mitigated Negative Declaration is usually feasible as to expense and time. A joint Negative Declaration/FONSI while adding some expense and time is also likely feasible.

For modular forest-based biomass gasification facilities the CEQA process will begin with a consultation with the government agency expected to take the lead implementing the CEQA process. The lead agency is the agency that has the principal responsibility for approving the project. In many cases, for modular forest-based biomass facilities using forest biomass, this will be the local jurisdiction of city or county where the project facility will be located in. Following the consultation, the facility's proponent will submit an application to the lead agency describing the project. Information required for the application varies from lead agency to lead agency but usually required is a complete description of the project and its operation including a site plan. Nearly all California cities and counties use a Conditional Use Permit form for the application form, which includes a checklist for the information required. Once the application is deemed to be complete, the lead agency determines if the project is subject to CEQA. If so, it then determines if any exemptions would remove the project from CEQA compliance. If no exemptions apply, the lead agency consults with other agencies with regulatory duties applicable to the project such as air emissions, water, biology, etc. The lead agency then decides whether a Negative Declaration, Mitigated Negative Declaration, or an EIR must be prepared. Once the lead agency completes and adopts the required document, it makes a decision to allow or disallow the project. Obtaining a Negative Declaration is estimated to take from 6-12 months, and an EIR approval from 12-24 months.

Figure 101 displays the general CEQA process used in California.

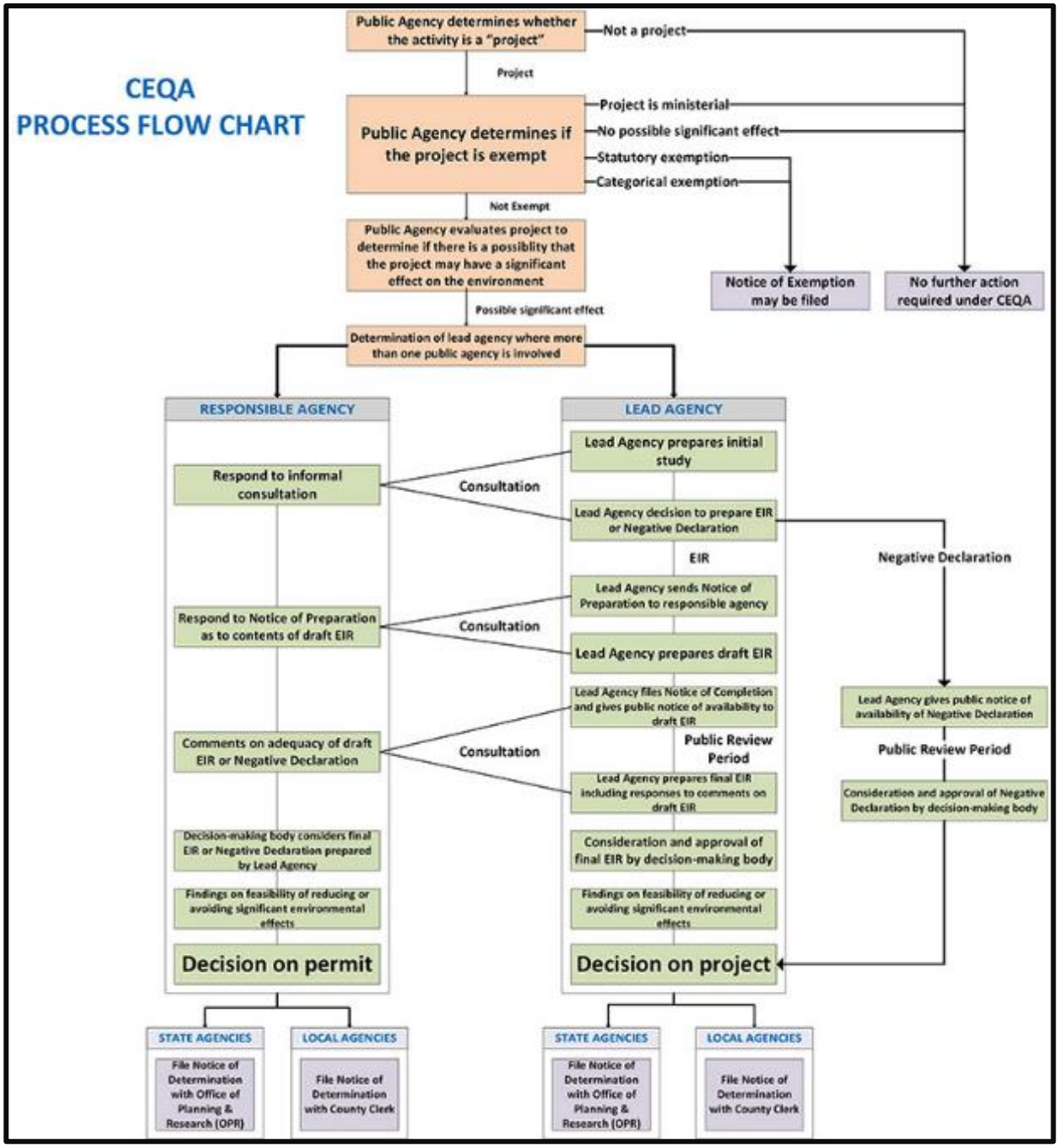
If the lead agency is a federal agency such as the United States Forest Service of the Bureau of Land Management (a possibility if the facility is located on federal land), the process would be similar but following the specific federal agency procedures based on NEPA rather than the State of California CEQA process. Again a joint process with CEQA resulting in a joint EIR/EIS or Negative Declaration/FONSI might be required.

Assuming the project is allowed to proceed, permits must be obtained and the following permits and approvals are deemed to be the most critical for a modular forest-based biomass gasification facility.

Major Permits and Approvals

Table 101 summarizes major and minor permits and approvals that will be required or may be required to construct and operate a modular forest-based biomass gasification facility. The table shows each permit/approval that might be required during construction and operation.

Figure 101: CEQA Process Flow Chart



Source: West Biofuels, LLC

Table 101: Permits and Approvals

Agency	Permit, Plan or Other Approval	Statutory Regulatory Source	Activity Regulated	When Required	Estimated Time Required	Comments
California						
CEQA*	Negative Declaration or Mit Neg/Dec Or EIR	PRC Sec. 21000-21178.1	Project Development	Prior to Construction	9-24 Months	Required prior to permitting
APCD/AQMD	Authority to Construct Permit	42 U.S.C. Sec. 7401 *et. seq*	Construction of Gasification Plt	Prior to Construction	10-12 Months	Will be required
APCD/AQMD	PTO	42 U.S.C. Sec. 7401 *et. seq*	Operation of Gasification Plant	Prior to Operating	1-4 Months	Will be required
RWQCB	Storm Water Construction	General Permit No. 2009-0009-DWG	Storm water runoff during construction	Prior to Construction	2-3 Months	Permitted under general permit by providing PRDs, SWPPP & other
RWQCB	Storm Water Operating	General Permit No. 2014-0057-DWG	Storm water runoff during operation	Prior to Operation	2-3 Months	Permitted under general permit by providing PRDs, SWPPP & other
RWQCB	WDR Permit	CWC Sec. 13260	Discharge of waste water to CA land & GW	Prior to discharging water	4-8 Months	Required if water discharge from plant must be impounded
RWQCB	NPDES Permit	40 CFR Sec. 122	Discharge to surface water	Prior to discharging water	4-8 Months	Required if water discharge from plant is to surface water
RWQCB	Sec. 401 Water Quality Certification	CWA Section 401	Discharges to navigable waters	Prior to discharging	4-8 Months	Applies to discharges to waters of the U.S.
CDFG	Biological opinion and consultation	CEQA	Insure no impacts to threatened & endangered species	Prior to construction	3-4 Months	Part of CEQA. Estimated time is included in CEQA time.
COHP	Sec. 106 Historical & Cultural	NHPA Section 106	Inspect site for historical	Prior to construction	3-4 Months	Part of CEQA. Estimated

Agency	Permit, Plan or Other Approval	Statutory Regulatory Source	Activity Regulated	When Required	Estimated Time Required	Comments
	Resources Review	36 CFR 800	& cultural features.			time is included in CEQA time
			Federal			
NEPA	EIS or FONSI	42 USC 4321 40 CFR 1500	Federal actions affecting environment	Prior to construction	FONSI-10-12 months; EIS-12-48 months	Use of federal land, a federal permit or federal funding trigger NEPA
COE	Sec. 10 Permit	Sec. 10 Rivers & Harbors Act; 33 CFR 322	Work affecting the navigable waters of US	Prior to work		Triggered by any permanent or semi-permanent impact including transmission lines
COE	Sec. 404 Permit	CWA Sec. 404	Discharge of dredge or fill material into US waters	Prior to discharge or fill		US Waters includes wetlands
EPA	SPCC Plan	40 CFR 112	Oil storage greater than 1,320 gals.	Prior to construction		Storage amount is sum of all oils on site
USFWS	Endangered Species Act Compliance Sec. 7 Consultation	16 USC 1531 50 CFR 17	Impacts to threatened and endangered species	Prior to construction	4-6 months	Required for NEPA, & CEQA
USFS or other federal agency	Easement/Lease		Use of federal land	Prior to use	Variable	Requires NEPA review
			Local			
County, City, State	Land Use Review Conditional Use Permit, Variance, Etc.	County and city ordinances	Site Plan Approval	Prior to Construction	6-9 Months	Will take longer to be approved if EIR is required
County, City, State	Building Permit	County and city ordinances	Construction of Facility	Prior to Construction	1-3 Months	
County, City, State	Certificate of Occupancy	County and city ordinances	Operation of Facility	Completion of Construction	1 Month	
County, City, State	Sewer/Water Hookup	County and city ordinances	Connection to Sewer & Water Lines	Construction	2-3 Months	

Agency	Permit, Plan or Other Approval	Statutory Regulatory Source	Activity Regulated	When Required	Estimated Time Required	Comments
County, City, State	Installation of Septic System &/or H_2O Well	County and city ordinances	Location & Construction of Septic Sys. & Well	Prior to or During Construction	2-3 Months	
County, City, State	Fire Safety Approval	CA Fire Code	Fire Protection Systems	Prior to and During Construction	2 Months	
Solid Waste	None required	County and city ordinances	Disposed of in a landfill	During construction & operation		If not hazardous can be sent to local sanitary landfill
Hazardous Materials	Hazardous Material Business Plan	CA Health & Safety Code Sec. 25507	Hazardous Materials stored & used on site	During Construction & Operation	2-3 Months	Required if: =>500 lbs. solid =>55 gallons liq. =>200 ft^3 comp. gas
Hazardous Waste	EPA Identification No.	Title 22 Div. 4.5 Chapter 12 CA Code of Regulations	Hazardous Waste Generators	Prior to generation of Hazardous Waste		

***CEQA-California Environmental Quality Act; APCD/AQMD-Air Pollution Control District/Air Quality Management District; RWQCB-Regional Water Quality Control Board; CDFG-California Department of Fish & Game; COHP-California Office of Historic Preservation; COE-U.S. Army Corps of Engineers; EPA-Environmental Protection Agency; USFWS-United States Fish & Wildlife Service; USFS-United States Forest Service.**

Source: West Biofuels, LLC

Air Quality

The Federal Clean Air Act[75] controls air pollution in the United States setting emissions standards from sources and permitting requirements. The California Air Resources Board (CARB) together with 35 air districts oversees and controls air pollution within the state[76]. Of these 35 air districts, about half have jurisdiction over bioenergy projects that might occur within the California forests. Although CARB does not issue permits to construct and operate stationary sources of pollution such as modular forest-based biomass gasification facilities, the responsibility for permitting has been allocated to the local air districts known as Air Pollution Control Districts (APCD) or Air Quality Managements Districts (AQMD)[77]. For stationary sources proposing to construct and operate a facility, a permitting process called New Source Review or NSR is followed. The APCD or AQMD requires that they first obtain an Authority to Construct

[75] 42 U.S.C. Sec. 7401 *et. seq,* and regulations at 40 C.F.R pts. 50-99.

[76] https://www.arb.ca.gov/.

[77] https://www.arb.ca.gov/permits/airdisac.htm.

(ATC) permit to construct the facility and then a Permit to Operate (PTO) once the district determines that the facility can meet the air emissions limits as determined in the ATC process.

Large biomass projects in past have required a Prevention of Significant Deterioration (PSD) permit from the U.S. Environmental Agency (U.S. EPA). This permit is required when certain pollutants (such as, CO, NO_x, SO_x, PM, PM-10, VOC) exceed an annual level of emissions of 100 tons for certain industrial activities and 250 tons for other industrial activities, and the project will be in an area where the ambient air quality is not being exceeded for the pollutant emitted. The permit is required on a pollutant-by-pollutant basis, so if any one of the pollutants is above 100 tons and the ambient air for that pollutant is not exceeded, the PSD permit would be required. The permit requires a New Source Review and a Best Available Control Technology analysis.

Fortunately, modular forest-based biomass gasification facilities in the 1-3 MW size using state of the art internal combustion engine generator sets emit a level of criteria pollutants well under 100 tons per year. However, air districts can have lower thresholds of significant emission rates for the above named pollutants, particularly NOx, VOC, and PM, and any planned biomass gasification project will require New Source Review process and Best Available Control Technology analysis is generally required in all California air districts for biomass gasification projects, even in the 1-3 MW range.

All air districts also have thresholds for what constitutes a Major Source of air pollutants, and when Emission Offsets are required. For the very stringent air districts such as San Joaquin Valley APCD (which includes the forest portions of Madera and Fresno County), the Major Source and Emissions Offset thresholds are 10 tons per year (TPY) of NOx and VOC, 15 TPY for PM10, 100 TPY for CO, and 27 TPY for SOx. With the possible exception of NOx from a 3 MW gasification engine genset, the emissions from 1 – 3 MW biomass gasification systems is well under the Major Source and Emission Offset threshold. This distinction is very important as being a Major Source requires a Title V air permit, which is definitely more complex, and costly, to comply with than a standard air district PTO. And, Emission Offset Credit is generally expensive and in many air districts, particularly the forested air district, may not be available or in very low supply (thus increasing their costs).

The procedure for obtaining an Authority to Construct Permit begins with making an application to the APCD or AQMD in which the biomass facility will be located. While each air district has its own procedures for evaluating permit applications, in general, the application will be reviewed for completeness, and if not complete, will be returned to the applicant requesting additional information. Once deemed complete, it is evaluated for conformance with New Source Review rules, district, state, and national emission limitation and national and state ambient air quality standards. The air district calculates emissions (or reviews applicant submitted emissions calculations) for the principal emissions of concern (CO, NO_x, VOC PM, SO_2) expected from the facility based on facility size and expected operating conditions.

In addition to evaluating criteria pollutants, the air district will evaluate the potential for the facility emitting non-criteria pollutants known as “toxic air pollutants”. Toxic air pollutants are

those that cause cancer or could cause other adverse health effects. After completing its evaluation, the air district's air pollution control officer (APCO) approves, conditionally approves, or disproves the ATC. The written decision by the APCO is published and provides 30 days for CARB, the U.S. EPA and the public to submit comments. An air district may take four to six months to review an application for an Authority to Construct. Most district rules require that an ATC be issued within 180 days of declaring the ATC application complete. However, the district may ask for clarifying or additional data and information during the review period if deemed necessary. The applicant should be ready to supply this data and information in order to keep the permit issuance schedule on track.

Once an Authority to Construct permit has been obtained and the facility has been constructed, the facility developer must apply for a PTO from the district that issued the Authority to Construct. Each air district uses its own application form, but generally the applicant must certify that the facility was constructed according to the terms and conditions of the Authority to Construct. The air district determines if the facility was constructed correctly and will likely require a compliance test of the facility (this emissions test is outlined in the ATC). If the facility meets the required criteria, the district APCO issues the PTO. The process usually takes from one to four months. The PTO is valid for one year, and is renewable with payment of an annual fee based primarily on the emissions rate of the bioenergy facility.

Water Quality

Relevant water related permits for construction and operation of a 1-3 MW modular forest-based biomass power facility consist of a Construction Storm Water Permit, an Operating Storm Water Permit and a Waste Water Discharge Permit.

Storm Water Construction Permit

A Storm Water Construction Permit is required for construction activities that result in one acre or more of land disturbance. Construction activity consists of clearing, grading, excavation, stockpiling, and removal and replacement of existing facilities. California has adopted a General Permit that applies to most storm water discharges from construction activities[78].

To obtain coverage under the General Permit, the facility developer must prepare and file Permit Registration Documents (PRDs) prior to commencement of construction. The PRDs include a Notice of Intent (NOI), a Storm Water Pollution Prevention Plan (SWPPP), and other documents required by the General Permit. The documents are electronically submitted via the Storm Water Multi-Application Report Tracking System (SMARTS)[79]. When construction has been completed, a Notice of Termination must be filed with the appropriate Regional Water Quality Control Board (RWQCB).

78 Permit No. 2009-009-DWG (as amended by 2010-0014-DWG, and 2012-006-DWG); NPDES No. CAS 000002; www.waterboards.ca.gov/water-issues/programs/stormwater/constpermits.shtml.

79 https://smarts.waterboards.ca.gov/smarts/faces/SwSmartsLogin.xhtml

Storm Water Industrial Permit

The storm water permit for operating industrial facilities is required for biomass gasification plants, due primarily to the non-power portions of the facility, such as the fuel storage yard where storm water may discharge off the site. Similar to the Storm Water Construction Permit, California has also adopted a General Industrial Permit[80] that is applied for by the applicant in a similar manner as the Construction Storm Water Permit as discussed above

Discharge of Waste Water

Section 13260 of the California Water Code controls discharges of wastewater to the waters of California that could affect water quality. For discharges to land and groundwater, per the Code, a Report of Waste Discharge must be made to the appropriate RWQCB. This report is in the form of an application to obtain a Waste Discharge Requirements (WDRs) permit. For discharges to surface waters, an application for a National Pollutant Discharge Elimination System (NPDES) permit must be made, also to the appropriate RWQCB.

Application for either a WDR or an NPDES permit is made using the same form[81]. However if the application is for an NPDES permit, additional forms must be submitted[82]. Information required consists of such items as facility owner, type of discharge, location of the facility, reason for filing, CEQA compliance, etc.

Report of Waste Discharge or NPDES permit needs can apply to modular forest-based biomass direct burn steam cycle turbine generator of 1-3 MW size could require from 5,000 to 15,000 gallons of water per day primarily for its cooling tower. Of this, about 25 percent may need to be discharged, so this technology would require a WDR or NPDES permit for discharge to a surface impoundment or to adjacent surface water unless the discharge was to a community sewer system (which could accept the discharge per its own permit). Modular forest-based biomass gasification generator systems require little or no water. Some use water for producer gas cleanup and utilize a small cooling tower that cools and recycles the cleanup water. There is some water lost through evaporation but there is no discharge. Others use a non-water cleanup system. Neither of these would require a wastewater discharge permit.

Land Use

It is possible, but unlikely that a county or city in California will have existing zoning for a modular forest-based biomass electric generating facility where the use as such is an outright permitted use. Therefore, a facility will have to obtain a Use Permit or Conditional Use Permit (CUP) from the land use agency in which the facility is to be located. This will be the Planning Department (or Division) within the city or county of proposed facility location.

The common process for obtaining a CUP is to begin with contact of the city or county Planning Department and discuss the planned facility. This pre-application meeting is highly

80 CA Storm Water Industrial Permit No. 2014-0057-DWQ http://www.swrcb.ca.gov/water_issues/programs/stormwater/igp_20140057dwq.shtml.

81 Form 200. http://www.waterboards.ca.gov/centralvalley/helpbusiness_help/permit3.shtml.

82 Form 200 plus either Form 2E or Form 2F.

recommended with the department. Then the application for a CUP is made using the department's application form. The process and application form will differ from county to county but much of the same basic information will be required, however some Planning Department may require considerably more. At minimum, the following is generally required:

- Use Permit application form(s) with original signature by applicant and landowner (if not the same), along with associated application fees.
- Development Plan – Drawings of project site plans to scale with dimensions and generally including:
  - Property dimensions and acreage
  - Existing and proposed buildings, structures, and such things as biomass feedstock storage area, feedstock receiving area, ancillary and outside power generation related equipment.
  - Off street parking per local planning requirements
  - Access points for vehicular for ingress, egress, and internal circulation, along with type of surfacing of roads, driveways, and areas where buildings and structures are not located
  - Names of all adjoining streets
  - Location and nature of all on-site utilities, which may include septic tanks, community sewage systems, potable water sources (wells and water supply pipes)
  - A location/vicinity map identifying the project site within an identifiable geographic area.
- Project description and a detailed facility operation plan that includes but not limited to: Hours of operation, estimated number of employees, types of equipment used (and how used), and chemicals used. Some planning departments have an Operations Statement form or a Project Information Questionnaire that can be filled out that has these and other project related questions.

In addition to this information requested by the Planning Department, some require more information, data, and plans, such as:

- A biological inventory
- Preliminary Drainage Analysis
- Building elevations and floor plans
- Landscaping plan
- Signage plan
- Lighting plan

COE Section 10

Section 10 of the Rivers and Harbors Act of 1899 requires authorization from the COE for construction of any structure in or over any navigable water of the United States. A Section 10 permit is required if the work affects the course, location or condition of the water body. Included are such actions as dredging, filling, alteration of stream course, construction of transmission lines, and intake or outfall pipes. There are a number of permits such as a Regional General Permit, Programmatic General Permit, Nationwide Permit, Standard Permit, and Letter of Permission. According to the COE, the Standard Permit is the most stringent and time consuming permit process. A decision under the Standard Permit usually required a minimum of 120 days. To determine which process would be required, the local COE office (Sacramento) should be contacted to arrange a pre-application meeting.

COE Section 404

Section 404 of the Clean Water Act (CWA) regulates the discharge of dredged or fill material into the waters of the United States. Section 10 (previously described) pertains to "navigable waters of the United States" which are included in "waters of the United States". However, Section 404 includes waters in addition to navigable waters. Those most likely to be encountered by a modular forest-based biomass electric generating facility are "wetlands". What is a wetland and what are the waters of the United States has been debated since the inception of the CWA. What constitutes waters of the United States has been contested often in the courts including a number of times all the way to the United States Supreme Court. Recently, the U.S. EPA expanded the existing definition through a rule that included almost all waters on federal, state, and private land that could be considered a wetland. The COE and the U.S. EPA have defined a wetland as "those areas that are inundated or saturated by surface or ground water at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions". The COE, which is responsible for issuing Section 404 permits, uses three characteristics of wetlands when making wetland determinations. These are vegetation, soil, and hydrology. A discussion of these characteristics can be found on the COE's website. Note that water does not have to be continuously present to constitute a wetland. The seasonal presence of wetlands vegetation and animals can constitute wetlands to be protected.

If a wetland is to be impacted, a Section 404 permit must be obtained from the COE. To obtain a permit one must show that steps have been made to avoid impact to the wetland and that potential impacts have been minimized. If impacts cannot be minimized, offsets (purchase or creation of comparable wetlands) must be purchased for the remaining unavoidable impacts. Wetland property "banks" in California offer offsets.

Minor Permits and Approvals

The following are considered minor since much of the permitting or approval is ministerial by the agencies, for example, the applicant or project developer prepares the necessary applications and notifications according to prescribed requirements or protocols and the permits are granted.

Solid Waste

Solid waste from a small biomass gasification facility consists almost completely domestic waste from the facility. As gasification produces biochar, not ash as from a direct combustion system, the biochar is a byproduct, with market value and not a waste.

Hazardous Materials

Hazardous materials are those that pose a significant present or potential hazard to human health and safety or to the environment if released into the workplace or environment. Hazardous materials are regulated by the federal government, states, and locally by counties and cities or a consortium of counties and cities through a Certified Unified Program Agency (CUPA) which is certified by CalEPA to enforce hazardous materials laws and regulations. If a facility handles quantities of hazardous materials equal to or above a certain quantity they are required to prepare a Hazardous Material Business Plan (HMBP). The State of California quantities are 55 gallons of liquids, 500 pounds of solids and 200 cubic feet of compressed gas. There also federal requirements that apply to much greater quantities and require a separate (Tier II Form) report. The business plan provides information for first responders and satisfies state right-to-know laws. The HMBP is submitted electronically and the facility is subject to periodic inspection by the regulating county, city, or CUPA.

The U.S. EPA has a Spill Prevention, Control and Countermeasure rule which is to help facilities prevent a discharge of oil into navigable waters. The rule is part of the EPA's oil spill prevention program and can be found at Title 40, Code of Federal Regulations, Part 112. A facility comes under the rule if has a total aboveground oil or petroleum fuel storage capacity greater than 1,320 gallons, or a buried storage capacity greater than 42,000 gallons and there is a reasonable expectation of an oil discharge into navigable waters of the United States. The shell volume of the container is used to determine the quantity of oil stored. Only containers with storage capacity equal to or greater than 55 gallons are counted. Facilities covered by the rule must take steps to prevent oil spills such as using suitable containers for storage, providing overfill prevention and secondary containment, and prepare and implement an SPCC plan. The SPCC plan must include operating procedures to prevent oil spills, control measures (such as secondary containment) to prevent release to navigable waters, and countermeasures to contain, cleanup, and mitigate the effects of a spill. The plan can be self-certified if storage meets certain criteria, or if does not certification must be by a licensed Professional Engineer. The plan should be maintained at the facility and submitted to the EPA only if requested.[83]

Hazardous Waste

Hazardous wastes are those that are toxic, reactive, ignitable, or corrosive. They are controlled in California by the California Environmental Protection Agency (Cal/EPA) and the California Department of Toxic Substances Control (DTSC). Hazardous waste generators are divided into those that generate less than 1,000 kilograms/month of hazardous waste and 1 kilogram of extremely hazardous waste and those that generate 1,000 kg or more of hazardous waste and more than 1 kg/month of extremely hazardous waste. Requirements for generators include

83 See https://www.epa.gov/sites/production/files/documents/spccbluebroch.pdf for additional information.

obtaining an identification number, storage methods, labeling of storage containers, time that wastes can be kept on site, disposal methods, etc. These can be found at the DTSC website.

Building Permit/Certificate of Occupancy

If a woody biomass gasification facility were to be located within a city or county, these would usually be obtained from the city/county building department by following their permit application procedure.

Sewer & Water/Septic System & Well/Fire Safety

Permits or approvals for these items would be obtained from the city/county utilities department, health department, and local or regional fire marshal. For state or federal owned land their specific procedure for approval would be followed.

Permitting Challenges

Challenges to permitting modular forest-based biomass gasification facility in California forested regions will arise initially in meeting CEQA requirements. And the level of challenges will be highly dependent upon the site selected on which to locate the generating facility. There are a large number of areas of issue under CEQA that must be addressed and be shown to have no significant environmental impact from implementation of the project to result in a negative declaration.[84] It goes without saying that requiring preparation of an EIR for a project of this size could, due to the time and expense involved, stop any proposed project from moving forward.

Almost if not all of the CEQA areas of issue could be shown to have no significant impact from the project through careful site selection. This also includes the potential requirement to prepare an Environmental Impact Statement if a federal permit is required, or federal funding is involved.

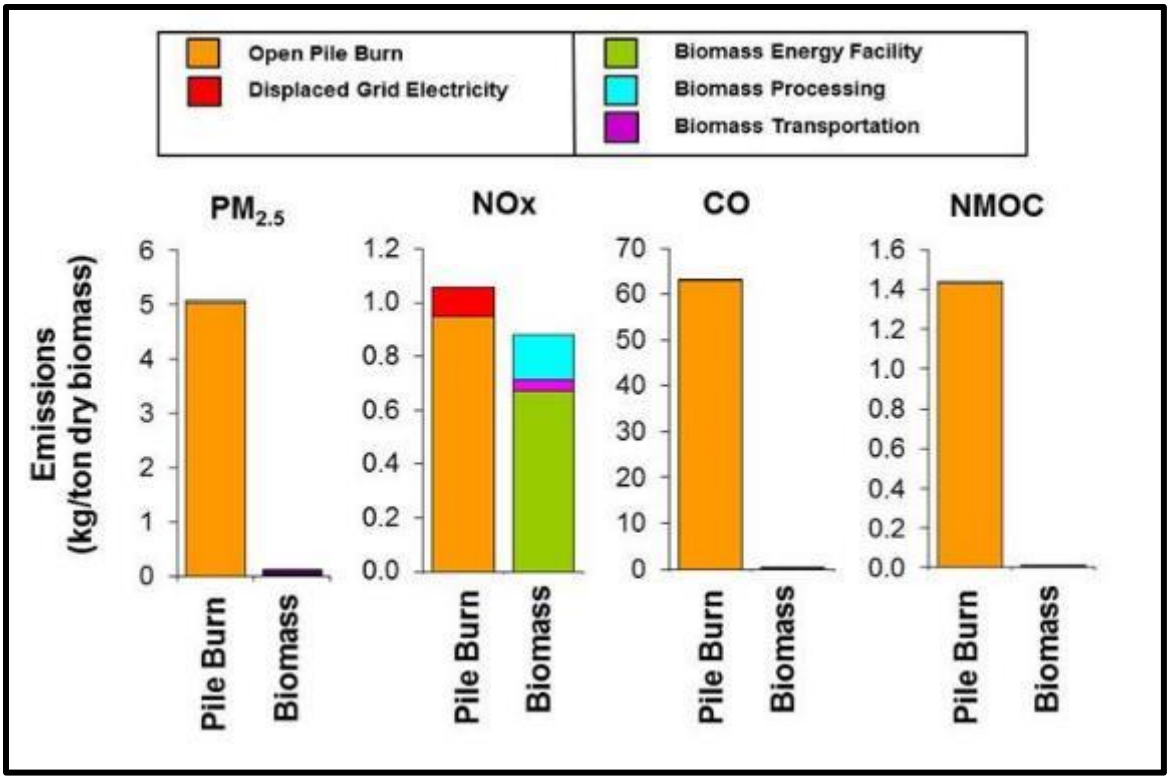
Although it has been seen that most of the forested community view community-scale biomass to electricity facilities as a positive way of assisting in forest health and reduction of wildfire threat, the CEQA and CUP processes do allow for opposition to enter into the picture. Opposition can be local or from outside the community as there are environmental groups that do not believe that the removal of biomass from the forest for use in power production is necessary. Past projects have had non-local environmental groups weigh in on the CEQA and CUP processes, which have led to significant increases in environmental impact assessment work.

Another permitting challenge is generally considered to be the acquisition of air quality permits. Although the ATC process can be a time consuming, which translates to additional costs, it has been noted that many of the California air districts appear to be favorable to operation of forest biomass power plants as these systems represent an air emissions controlled process as opposed

[84] Included are: Aesthetics, Agriculture Resources, Air Quality, Biological Resources, Geology and soils, Hazardous Materials, Hazardous Waste, Hydrology and Water Quality, Land Use Planning, Mineral Resources, Noise, Population and Housing, Public Services, Recreation, Transportation/Traffic, Utilities, Energy and Service Systems, and Cumulative Impacts.

to pile and burn (of forest biomass waste) practices. The reduction of criteria pollutants by a power plant is very significant as can be seen in Figure 102.[85]

Figure 102: Pile and Burn v. Controlled Emissions



Source: Chart courtesy of the Placer County Air Pollution Control District

Siting Assessment

Potential Candidate Forest BioMAT Sites

TSS Consultants identified 20 candidate sites for community-scale forest biomass development. Sites are shown in Table 102, Figure 103, and Figure 104.

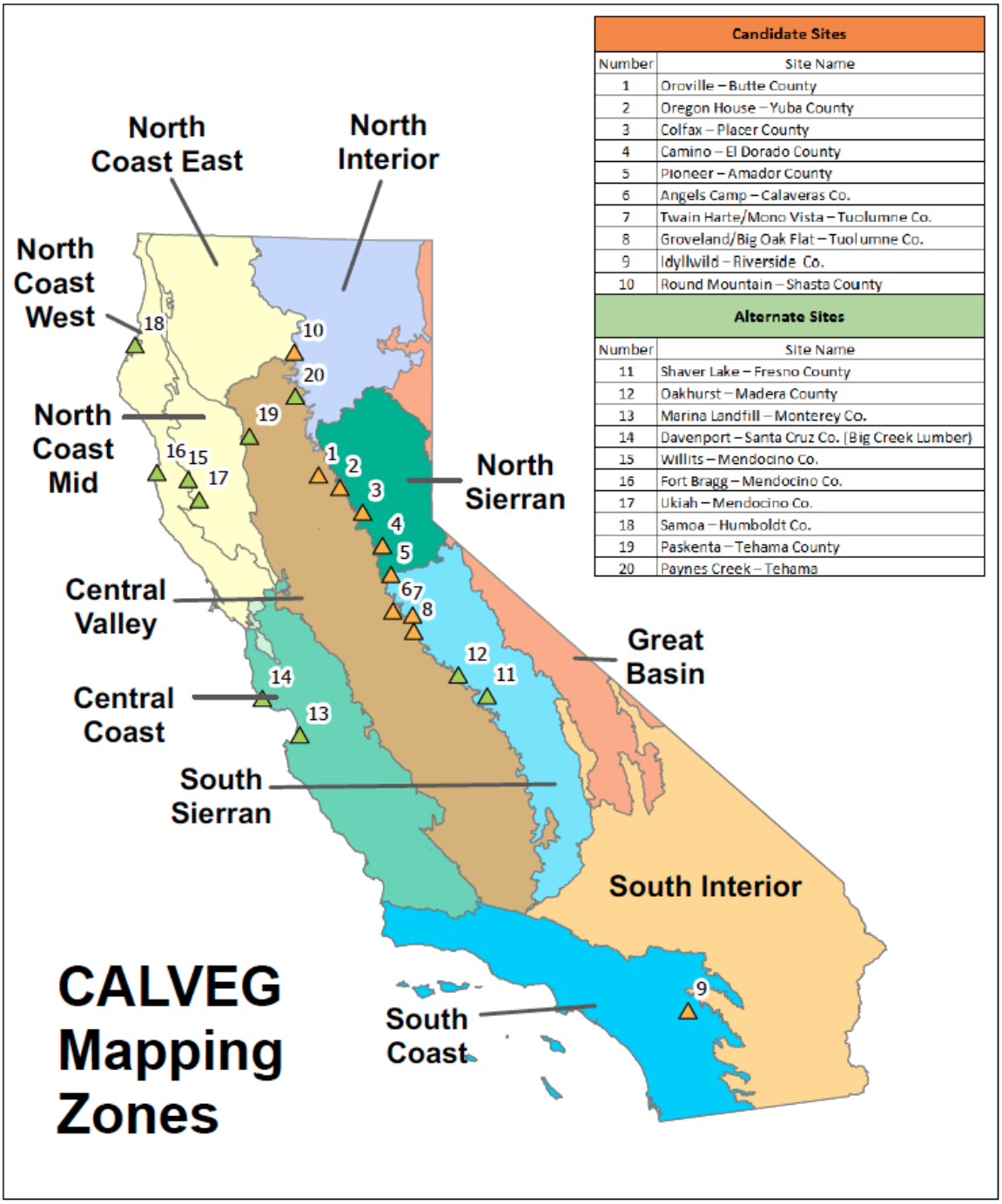
[85] The biomass emissions in this chart are based on a direct combustion power plant. In a gasification system using an internal combustion engine genset the NOx emissions would be lower by an approximate order of magnitude

Table 102: Candidate and Alternate Sites

	Candidate Site	Region	Location Coordinates	BioMAT Electric Utility
1	Oroville – Butte County	North Sierran	39.487425 -121.569300	PG&E
2	Oregon House – Yuba County	North Sierran	39.357252 -121.271207	PG&E
3	Colfax – Placer County	North Sierran	39.096568 -120.953597	PG&E
4	Camino – El Dorado County	North Sierran	38.742782 -120.677504	PG&E
5	Pioneer – Amador County	North Sierran	38.433329 -120.559454	PG&E
6	Angels Camp – Calaveras County	South Sierran	38.045495 -120.528571	PG&E
7	Twain Harte/Mono Vista – Tuolumne County	South Sierran	38.001156 -120.262307	PG&E
8	Groveland/Big Oak Flat – Tuolumne County	South Sierran	37.829064 -120.246062	PG&E
9	Idyllwild – Riverside County	South Coast	33.725019 -116.717143	SCE
10	Round Mountain – Shasta County	North Interior	40.795778 -121.938338	PG&E
Alternate Sites				
11	Shaver Lake – Fresno County	South Sierran	37.136383 -119.260697	SCE
12	Oakhurst – Madera County	South Sierran	37.361862 -119.646501	PG&E
13	Marina Landfill – Monterey County	Central Coast	36.708238 -121.761352	PG&E
14	Davenport – Santa Cruz County (Big Creek Lumber)	Central Coast	37.089363 -122.271808	PG&E
15	Willits – Mendocino County	North Coast West (and Mid)	39.401936 -123.366809	PG&E
16	Fort Bragg – Mendocino County	North Coast West	39.465391 -123.803640	PG&E
17	Ukiah – Mendocino County	North Coast Mid	39.189448 -123.205833	PG&E
18	Samoa – Humboldt County	North Coast West	40.817930 -124.183644	PG&E
19	Paskenta – Tehama County	North Coast East	39.885620 -122.537725	PG&E
20	Paynes Creek – Tehama County	North Interior	40.326633 -121.91262	PG&E

Source: West Biofuels, LLC

Figure 103: Candidate and Alternate Sites in the Forest Regions of California

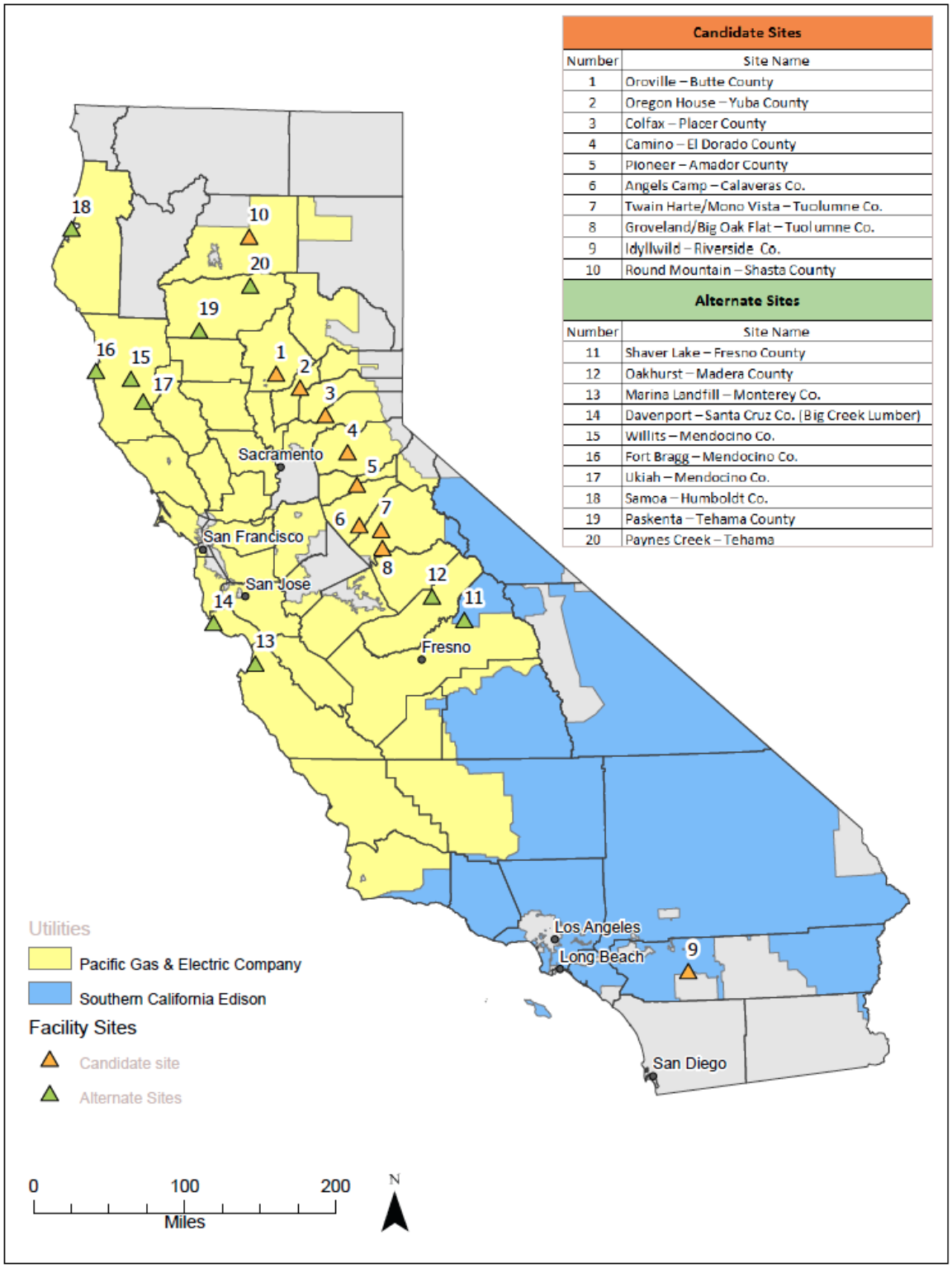


Candidate Sites	
Number	Site Name
1	Oroville – Butte County
2	Oregon House – Yuba County
3	Colfax – Placer County
4	Camino – El Dorado County
5	Pioneer – Amador County
6	Angels Camp – Calaveras Co.
7	Twain Harte/Mono Vista – Tuolumne Co.
8	Groveland/Big Oak Flat – Tuolumne Co.
9	Idyllwild – Riverside Co.
10	Round Mountain – Shasta County

Alternate Sites	
Number	Site Name
11	Shaver Lake – Fresno County
12	Oakhurst – Madera County
13	Marina Landfill – Monterey Co.
14	Davenport – Santa Cruz Co. (Big Creek Lumber)
15	Willits – Mendocino Co.
16	Fort Bragg – Mendocino Co.
17	Ukiah – Mendocino Co.
18	Samoa – Humboldt Co.
19	Paskenta – Tehama County
20	Paynes Creek – Tehama

Source: West Biofuels, LLC

Figure 104: Candidate and Alternate Sites per PG&E and SCE Territory



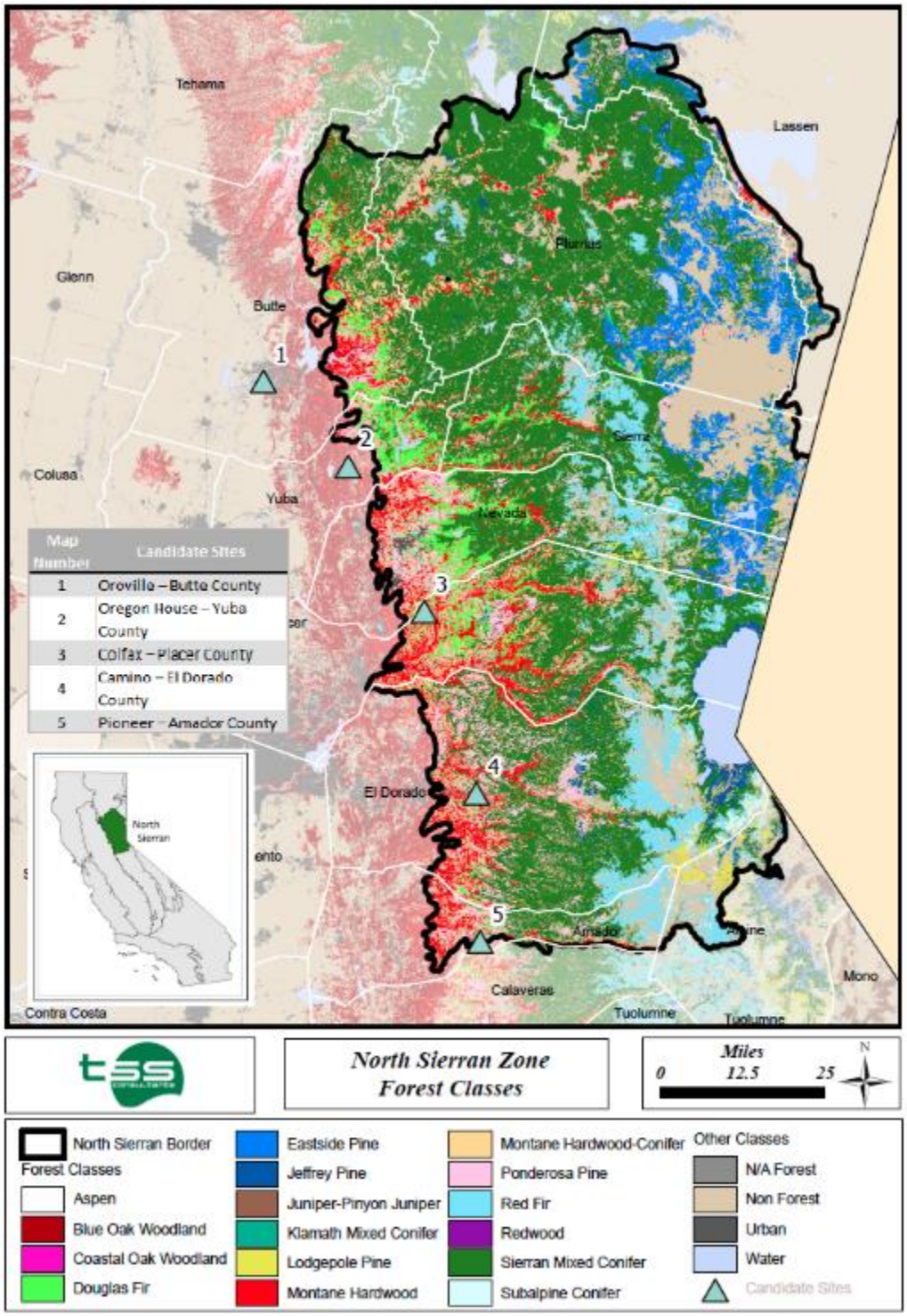
Candidate Sites	
Number	Site Name
1	Oroville – Butte County
2	Oregon House – Yuba County
3	Colfax – Placer County
4	Camino – El Dorado County
5	Pioneer – Amador County
6	Angels Camp – Calaveras Co.
7	Twain Harte/Mono Vista – Tuolumne Co.
8	Groveland/Big Oak Flat – Tuolumne Co.
9	Idyllwild – Riverside Co.
10	Round Mountain – Shasta County

Alternate Sites	
Number	Site Name
11	Shaver Lake – Fresno County
12	Oakhurst – Madera County
13	Marina Landfill – Monterey Co.
14	Davenport – Santa Cruz Co. (Big Creek Lumber)
15	Willits – Mendocino Co.
16	Fort Bragg – Mendocino Co.
17	Ukiah – Mendocino Co.
18	Samoa – Humboldt Co.
19	Paskenta – Tehama County
20	Paynes Creek – Tehama

Source: West Biofuels, LLC

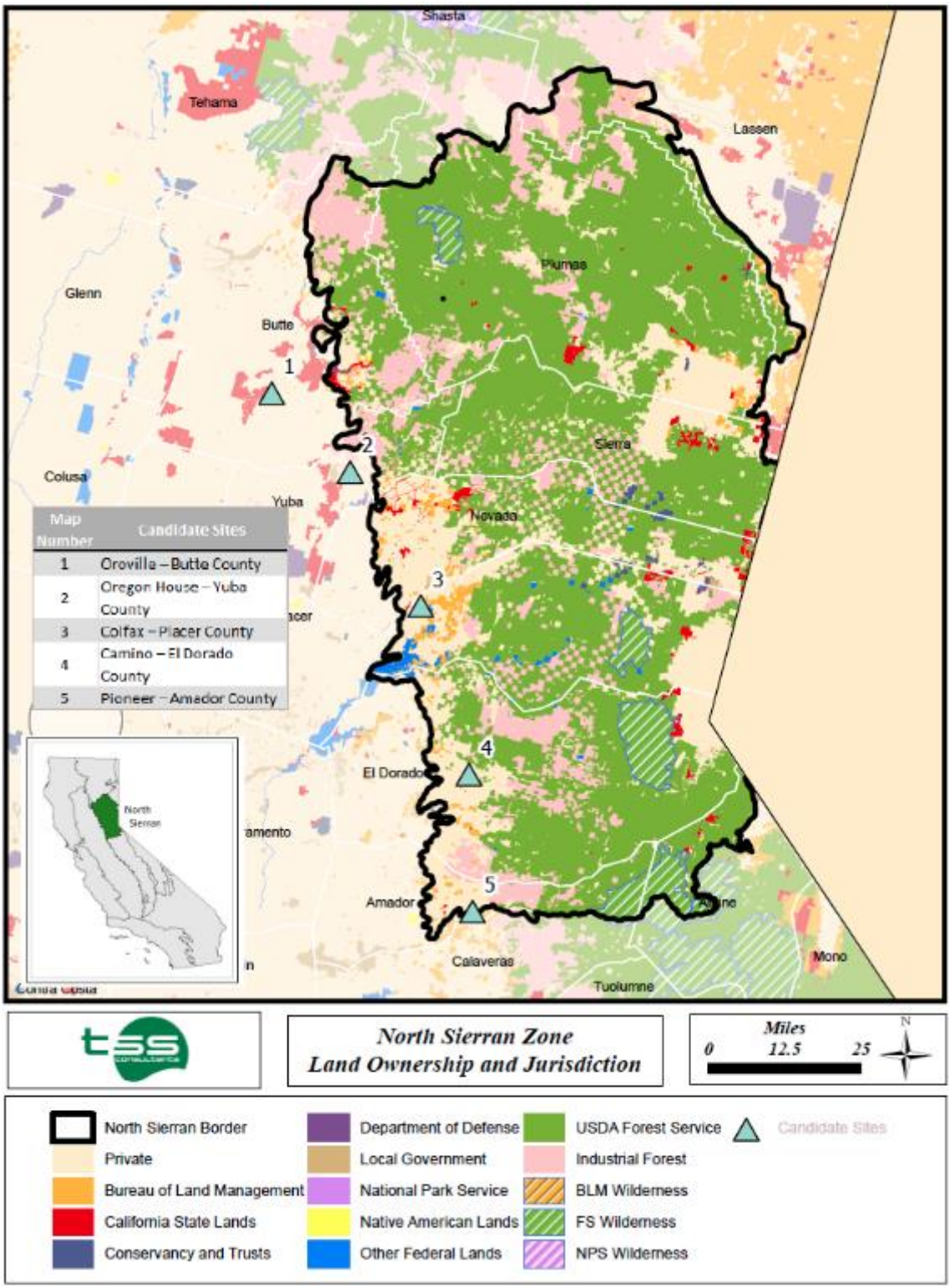
Location of Ten Candidate Sites

Figure 105: Candidate Sites and North Sierran Forest Classes



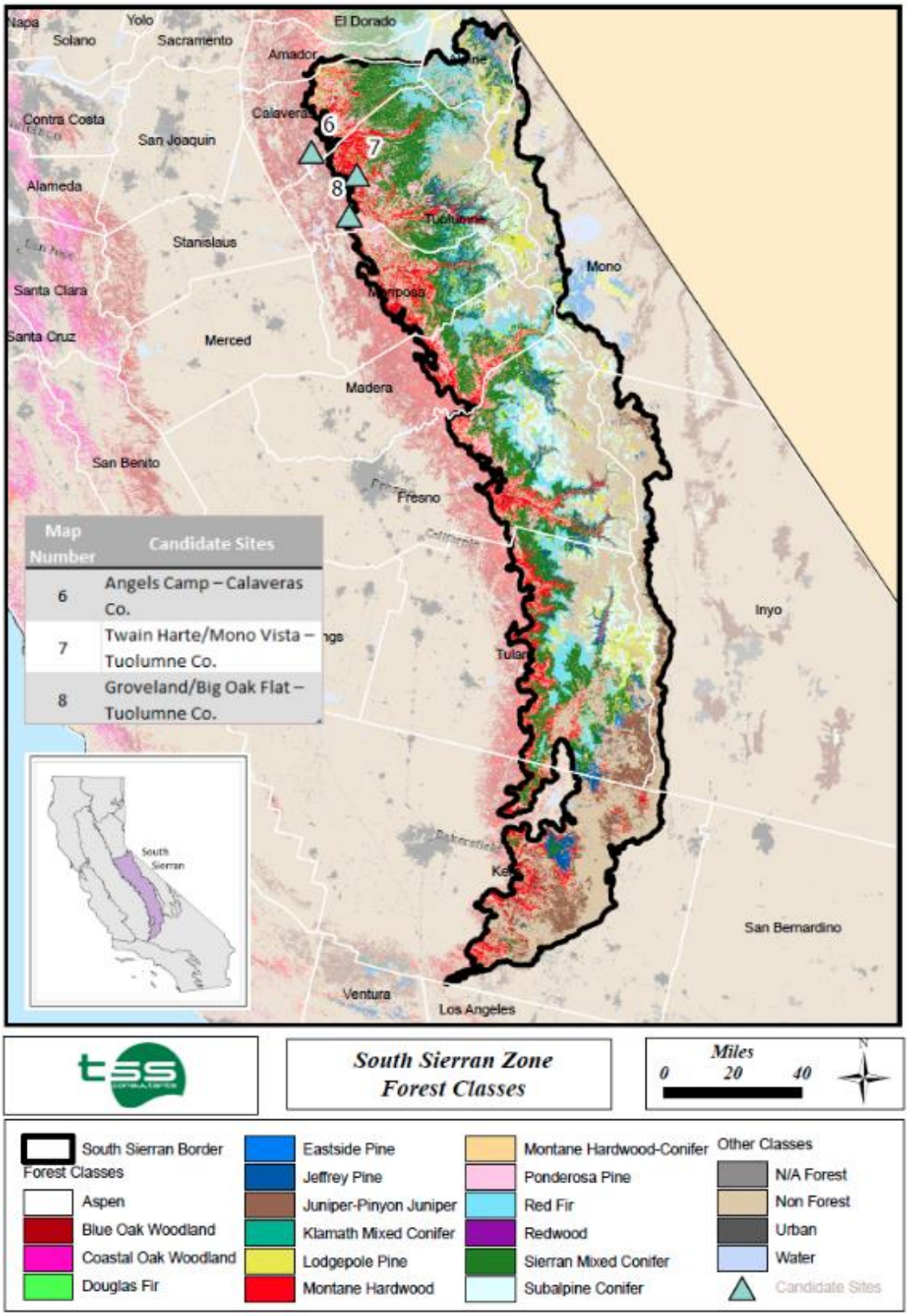
Source: West Biofuels, LLC

Figure 106: Candidate Sites and North Sierran Forest Ownership



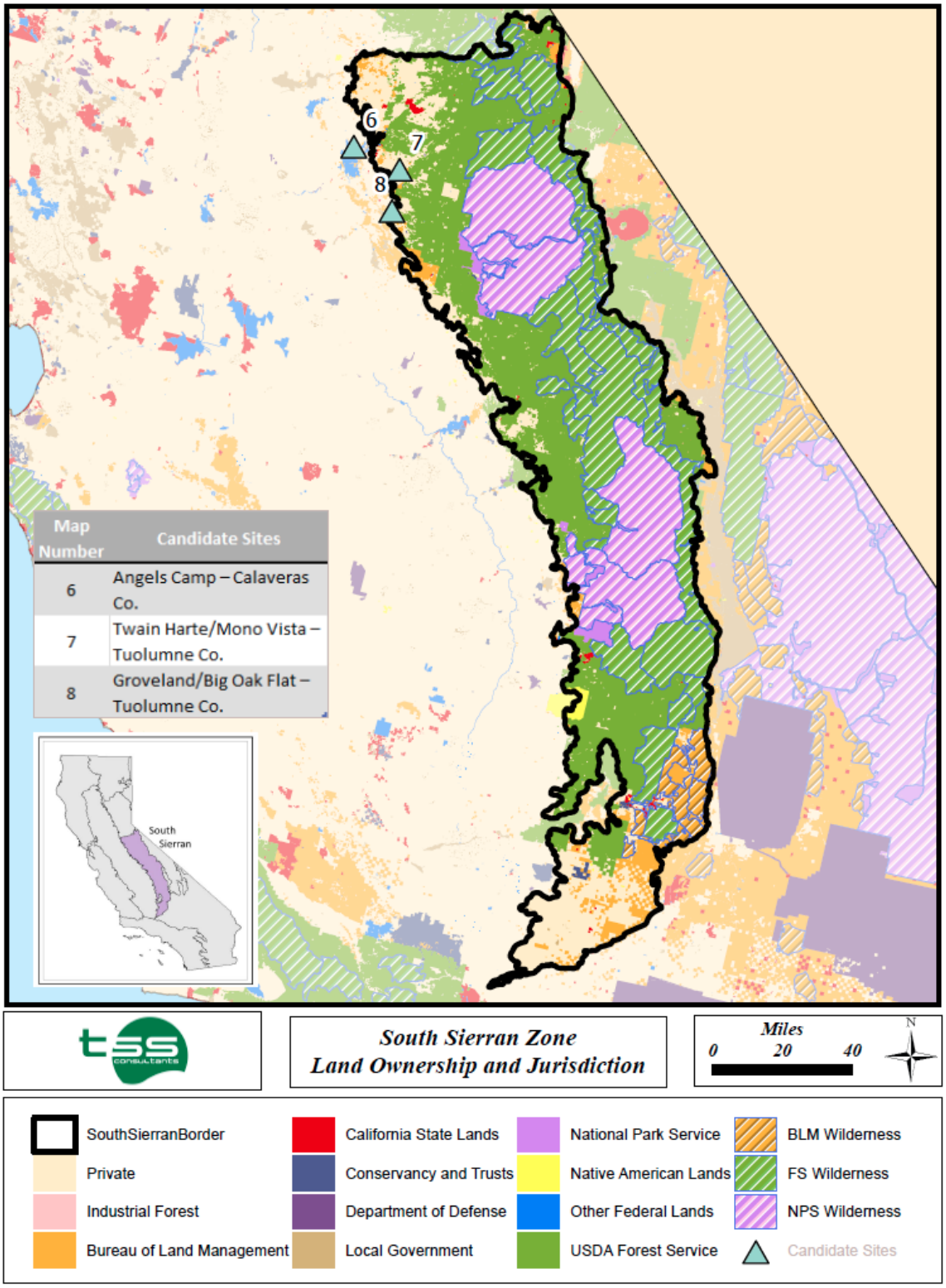
Source: West Biofuels, LLC

Figure 107: Candidate Sites and South Sierran Forest Classes



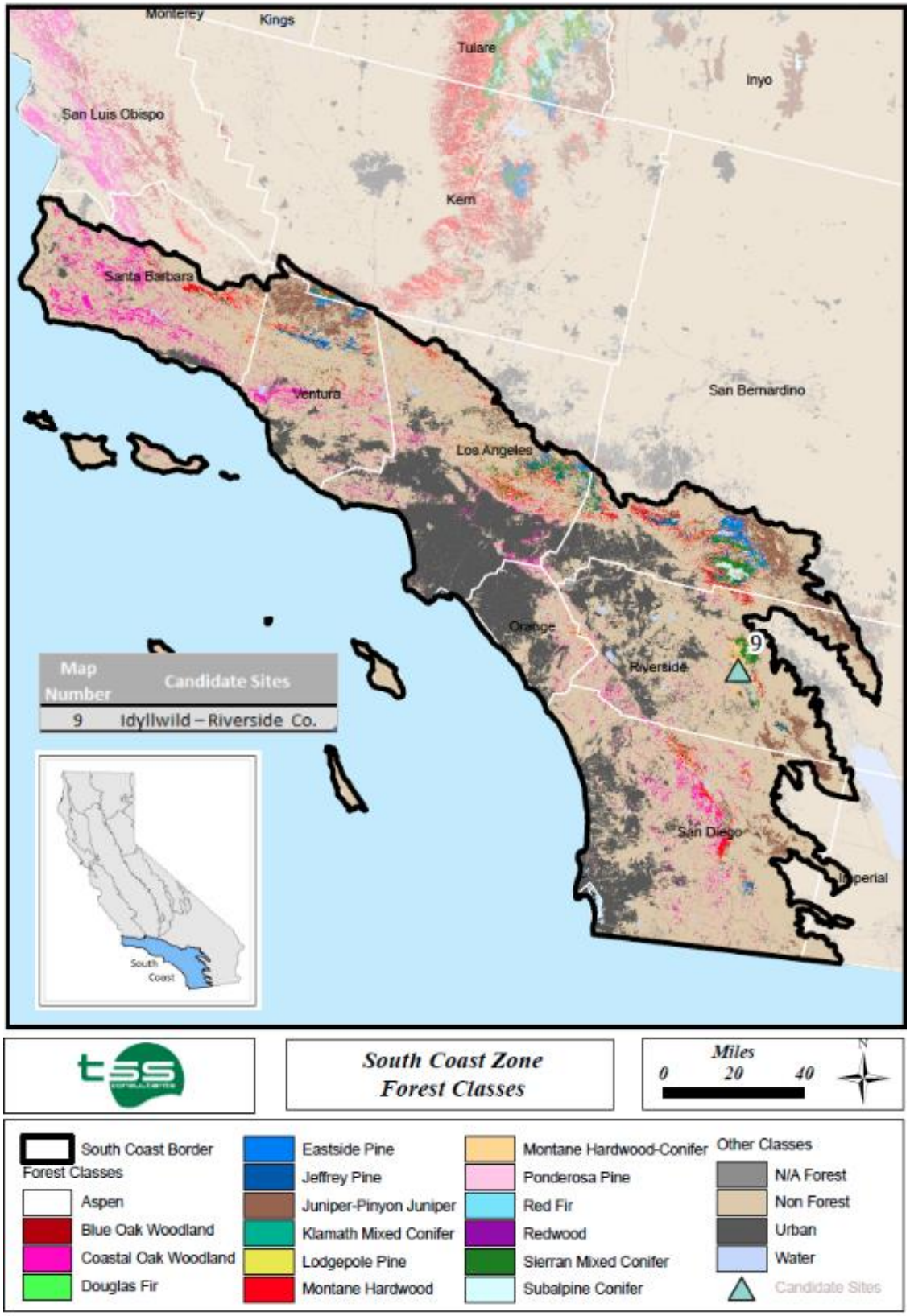
Source: West Biofuels, LLC

Figure 108: Candidate Sites and North Sierran Forest Ownership



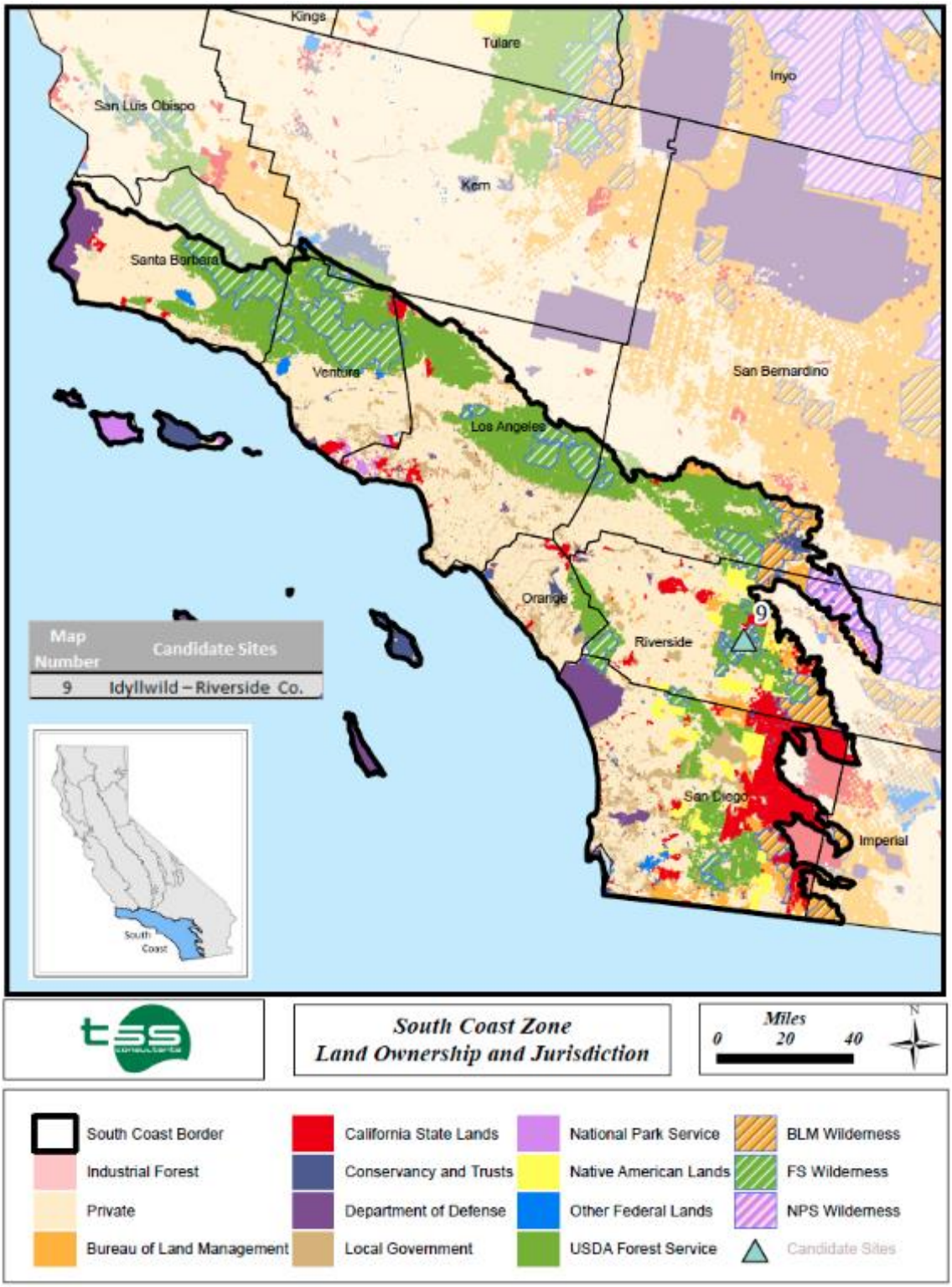
Source: West Biofuels, LLC

Figure 109: Candidate Sites and South Coast Forest Classes



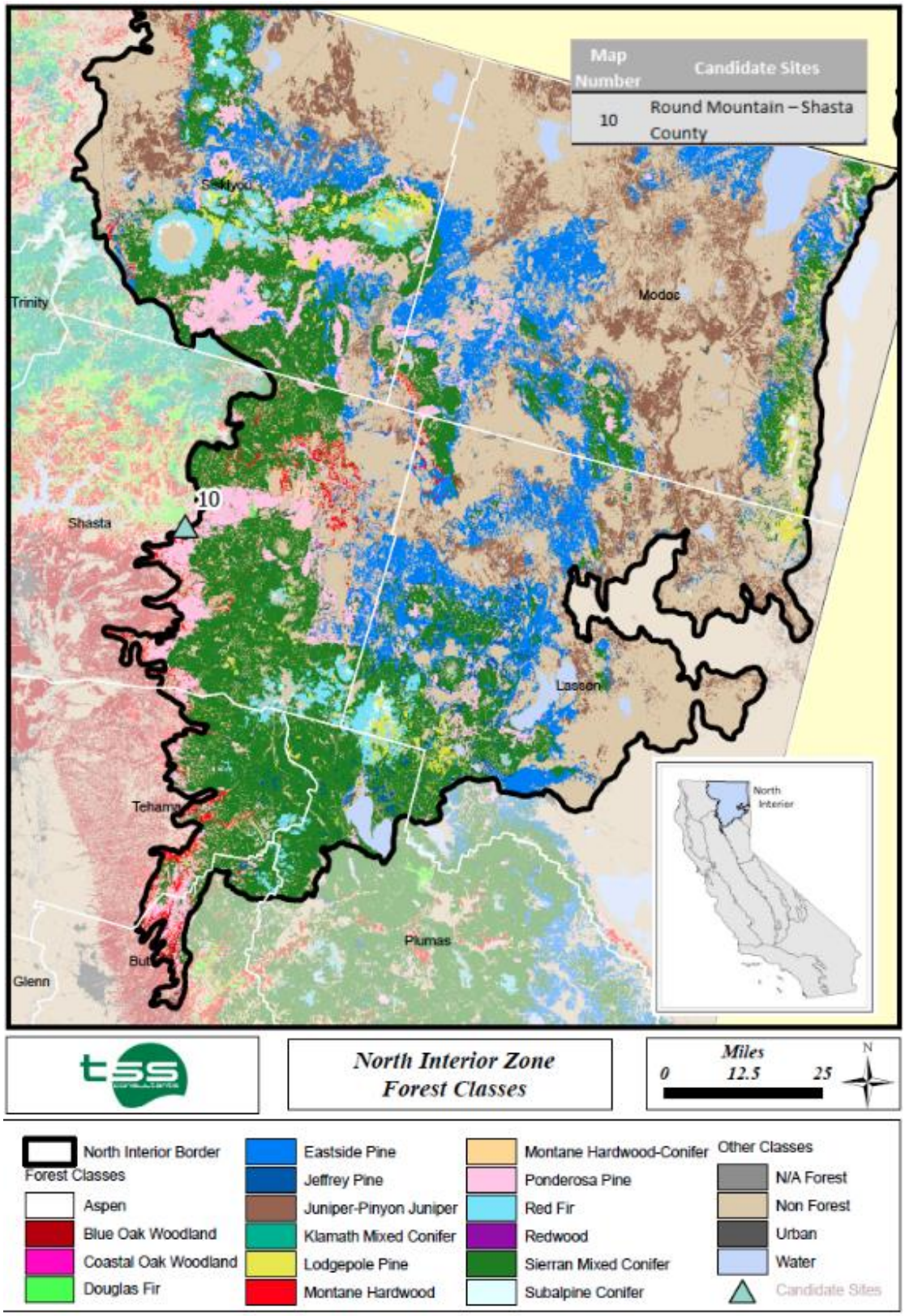
Source: West Biofuels, LLC

Figure 110: Candidate Sites and South Coast Land Ownership



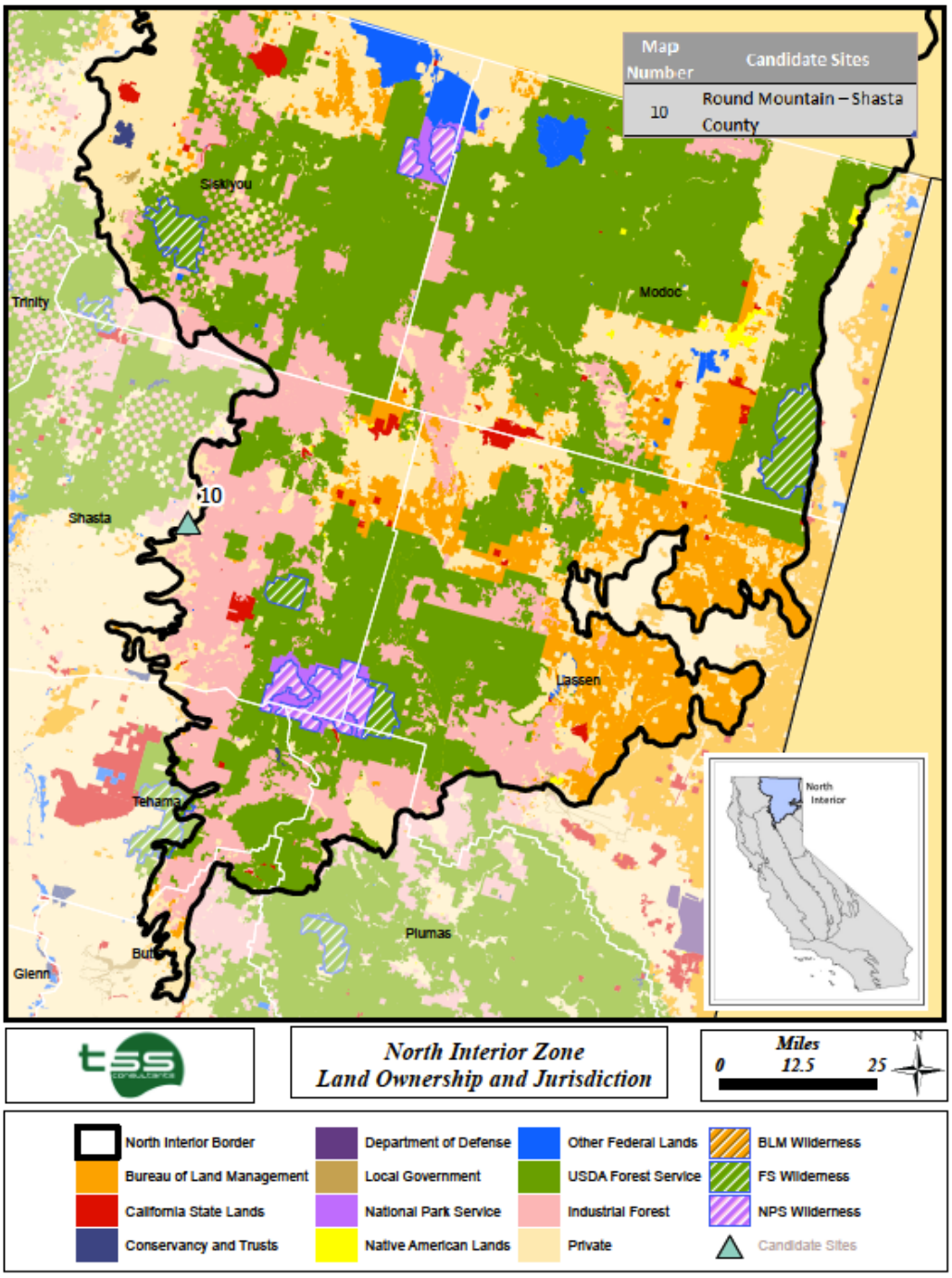
Source: West Biofuels, LLC

Figure 111: Candidate Sites and North Interior Forest Classes



Source: West Biofuels, LLC

Figure 112: Candidate Sites and North Interior Land Ownership



Source: West Biofuels, LLC

Table 103: Priority Locations Parameters

	Environmental Permitting	Feedstock Availability	Other Bioenergy Projects	Electrical Grid Access (Relative Line Capacity)
Oroville – Butte County	- Industrial zoning, CUP required. - MND probable - Air permit achievable, no offsets needed	Site is actually located outside of North Sierran region, but near an area of the region where there is considerable industrial forests. Feedstock should be adequate for a 1 to 3 MW forest biomass facility. A biomass availability study conducted for a nearby proposed BioMAT 3 MW facility indicated that nearly 15 MW of economic feedstock supply is available in the area[86]	Large biomass power plant nearby but shutdown, and likely not to restart. Feasibility study conducted for potential BioMAT facility nearby (Feather Falls Casino)	Medium to low
Oregon House – Yuba County	- Commercial zoning, CUP required - MND probable - Air permit achievable; no offsets needed	Site is located just outside of the western border of the North Sierran region. Previous feedstock assessment study indicates somewhat limited economic feedstock to support more than 1 or 2 - 3MW BioMAT facilities in the candidate site area[87].	Camptonville Community Partnership potential BioMAT facility 20 miles northeast. Closest operating large biomass plant (Rio Bravo Rocklin) 55 miles south.	Low
Colfax – Placer County	- Industrial zoning, CUP required - MND possible, potential opposition - Air permit achievable; no offsets needed	Most of the available biomass for this candidate site would likely come from timber harvest residuals. Previous estimates[88] from a large 5 county area in which the site is located indicated sustainable forest sourced feedstock at between 63,428 and 199,444 BDT annually. Focusing this down to a source area in the Colfax site area there should be enough economic feedstock for a 3 MW facility.	Closest large biomass plant is Rio Bravo Rocklin approximately 40 miles southwest. A BioMAT facility is proposed in Grass Valley, 15 miles north	Medium
Camino – El Dorado County	- Industrial zoning, CUP required - MND probable	Most of the available biomass for this candidate site would likely come from timber harvest	Closest large operating biomass plant is Rio Bravo Rocklin approximately 50	High

[86] "Feasibility Study: Energy Generation from Forest Biomass, Mooretown Rancheria, Oroville, CA", prepared by The Beck Group, July 2015

[87] Table 2-6 of the Yuba Foothills Biomass Feasibility Study, prepared by TSS Consultants, December 2010, http://tssconsultants.com/reports/2010-12-Yuba-Foothills-Biomass-Feasibility-Study.pdf

[88] "Siting and Feasibility Study for Pilot and Commercial Scale Biomethane Facilities in California", prepared by TSS Consultants, April 2015.

	Environmental Permitting	Feedstock Availability	Other Bioenergy Projects	Electrical Grid Access (Relative Line Capacity)
	- Air permit achievable; no offsets needed	residuals. Previous estimates[89] from a large 5 county area in which the site is located indicated sustainable forest sourced feedstock at between 63,428 and 199,444 BDT annually. Focusing this down to a source area in the Camino site area there should be enough economic feedstock for a 3 MW facility.	miles west. No other forest biomass BioMAT facilities currently planned within 50 miles of Camino	
Pioneer – Amador County	- Manufacturing zoning, CUP required - MND probable - Air permit achievable; no offsets needed	Site is located in the far southwestern corner of the North Sierran region. Previous feedstock assessment study indicates somewhat limited economic feedstock to support more than 2 BioMAT 3 MW facilities in the candidate site area[90].	Closest large biomass plant is 25 miles southwest but no longer operating (Buena Vista Biomass Power). Potential BioMAT facility being planned at Wilseyville, 14 miles south	High
Angels Camp – Calaveras County	- Public Service zoning, CUP required - MND probable - Air permit achievable; no offsets needed	This site is located just outside of the South Sierran zone. A recent high level biomass feedstock review in the area indicates that economic forest-sourced biomass could allow for a 3 MW facility at Angels Camp	Closest large biomass plant is 20 miles south (Chinese Station). Nearest proposed BioMAT facility is Wilseyville, 36 miles north	Low
Twain Harte/Mono Vista – Tuolumne County	- Industrial Zoning, CUP required - MND possible, potential opposition - Air permit achievable; no offsets needed	This site is located just inside of the South Sierran zone. A recent high level biomass feedstock review in the area[91] indicates that economic forest-sourced biomass could allow for a 3 MW facility at Mono Vista. However, it could compete for feedstock if a facility was located at Angels Camp.	Closest large biomass plant is 18 miles southwest (Chinese Station). Nearest proposed BioMAT facility is Wilseyville,60 miles north.	Low
Groveland/Big Oak Flat –	- Commercial zoning, CUP required	This site is located on the western border of the South Sierran zone. A recent high level	Closest large biomass plant is 16 miles northwest	Medium to low

[89] "Siting and Feasibility Study for Pilot and Commercial Scale Biomethane Facilities in California", prepared by TSS Consultants, April 2015.

[90] Table 14 of the Updated Wilseyville Woody Biomass Value-Added Product Yard Feasibility Study, prepared by TSS Consultants, April 2013 http://tssconsultants.com/reports/2013-4-5-Updated-Wilseyville-Woody-Biomass-Value-Added-Product-Yard-Feasibility-Study.pdf

[91] "High-Level Review of Forest Feedstock Availability and Site Options for a Community-Scale Bioenergy Facility with Calaveras County", prepared by TSS Consultants, September 2016

	Environmental Permitting	Feedstock Availability	Other Bioenergy Projects	Electrical Grid Access (Relative Line Capacity)
Tuolumne County	- MND probable - Air permit achievable; no offsets needed	biomass feedstock review in the area indicates that economic forest-sourced biomass could allow for a 3 MW facility at Big Oak Flat. However, it could compete for feedstock if a facility was located at Angels Camp and a 2 MW facility previously proposed for Mariposa.	(Chinese Station). Nearest proposed BioMAT facility is in Mariposa, 40 miles south.	
Idyllwild – Riverside County	- Natural Resources zoning, CUP required - MND possible, potential public opposition - Air permit achievable; no offsets needed	Economic biomass feedstock in the Idyllwild area of the South Coast zone is likely limited as the forested area around the candidate site is relatively limited. It would be expected that a 1 MW or less facility is all that is feasible in the Idyllwild area.	Closest large biomass plant is 80 miles west (Desert View). Nearest proposed BioMAT facility (currently under construction) is in North Fork, 350 miles north.	Low
Round Mountain – Shasta County	- Multiple Use zoning, CUP required - MND possible - Air permit achievable; no offsets needed	Although there are large biomass plants in the site region (North Interior), which will continue to operate for the next several years on forest-sourced biomass feedstock, there is also considerable industrial forest land in the zone which will continue to produce economically available biomass waste. A 3 MW facility at Round Mountain could be sustainable.	Closest large biomass plant is 20 miles west (SPI Burney) and the Wheelabrator in Anderson 40 miles southwest. Nearest proposed BioMAT facility is Hat Creek Construction Company near Burney, 30 miles northeast.	High

Source: West Biofuels, LLC

Additional Site Details

The information presented below was compiled to supplement the siting assessment and priority location parameters in Table 3 above. A significant portion of this information was obtained during the interviews and discussions with the location's respective Planning Department.

City of Oroville – Butte County

Site Name: Sites in South Oroville east of Highway 70 zoned M-2	CEQA Lead Agency: City of Oroville Community Development Department Planning Division
Site APN No.: TBD – several parcels	Sewer Availability: Yes-City of Oroville
Latitude: N 39.357252	Water Source: South Feather Water and Power serves the City
Longitude: W -120.954787	Air District: Butte County Air Quality Management District
Zoning: M-2, Intensive Industrial	Water Quality Control: Central Valley Regional Water Quality Control Board
Contacts: Luis Topete – Senior Planner; (530) 538-2401	County: Butte

Figure 113: Oroville Site Aerial

Source: West Biofuels, LLC

Site Location Approval

The City of Oroville Planning Department is the lead agency for CEQA and a CUP at this site. The potential site area is zoned M-2 and there are numerous medium and large-sized parcels in the area. The zoning code for the City is found in Title 17 of the Oroville Municipal Code[92]. Chapter 17.36-Industrial Districts describes the industrial districts of the City and their zoning, and Section 17.36.010 lists the allowed uses in the Industrial Districts. Zoning M-2, Intensive Industrial, is the most likely zoning area for a power plant, however power plants are not specifically listed as an allowable use under Zoning M-2.

Discussion with Planning Department representative[93] indicated that even though power plants are not listed as an allowed use, that it is possible to locate a power plant in the M-2 District. The process would begin with a pre-application meeting and assuming that no big problems became evident, the CEQA process would begin with the City as Lead Agency. The department representative stated they would be amenable to a Negative Declaration or Mitigated Negative Declaration. Given the zoning and department procedures Zoning Administrator could issue an administrative use permit. If the Zoning Administrator finds any potential issues, the department would require a CUP (which requires approval by the Oroville Planning Commission). If a CUP is required, it could be processed in parallel with the CEQA process.

Preliminary CEQA Review

The site location area in South Oroville east of Highway 70 is away from the downtown area of Oroville and residential and commercial areas. It is already light and heavy industrial facilities, along with public facilities such as the City's wastewater treatment plant. At this time there are none of the areas addressed in the CEQA analysis that appear to pose a significant problem with the possible exception of air emissions. Obtaining a Negative Declaration or a minimal Mitigated Negative Declaration should be possible in a reasonable amount of time and at a reasonable expense.

Air Emissions Permit

The site is under the jurisdiction of the Butte County Air Quality Management District. The principal district rules for a project that employs a gasification to electricity system using a internal combustion genset are:

- Rule 430, New Source Review:
  - Major Source threshold – 100 TPY for NOx, VOC, PM10, PM2.5 (Section 4.24)
  - Best Available Control Technology – NOx – 25 pounds/day; VOC – 25 pounds/day; PM10 – 80 pounds/day; SOx – 80 pounds/day; CO – 500 pounds/day (Section 5.1)
  - Emission Offsets Need Thresholds – NOx, VOC, PM10, SOx – 25 TPY (each), no threshold for CO (Section 5.2).
- Rule 252, Section 5.1, Stationary Internal Combustion Engine Emissions Limitations

[92] City of Oroville Municipal Code, http://www.qcode.us/codes/oroville/.

[93] Personal communications with Luis Topete, Senior Planner, City of Oroville Planning Department, March 2017.

- Rich Burn engine – NOx – 640 ppmv; CO – 4500 ppmv
- Lean Burn engine – NOx – 740 ppmv; CO – 4500 ppmv
- Rule is for engines 50 brake horsepower (bhp) to 300 bhp. No specific rule for engines exceeding 300 bhp

Grid Connection

Figure 114: Oroville Area Electric Grid

Source: West Biofuels, LLC

Oregon House - Yuba County

Site Name: Oregon House – Former Siller Sawmill site	CEQA Lead Agency: Yuba County Planning Department
Site APN No.: 048-080-018	Sewer Availability: None Septic tank
Latitude: N 39.357252	Water Source: Individual well
Longitude: W 121.954787	Air District: Feather River Air Quality Management District
Zoning: RC – Rural Commercial	Water District: Central Valley Regional Water Quality Control Board
Contacts: Kevin Perkins-Senior Planner; (530) 749-5674	

Figure 115: Oregon House Site Aerial

Source: West Biofuels, LLC

Site Location Approval

The Yuba County Planning Department[94] confirmed that the site is zoned Rural Commercial (RC) and not Agriculture/Rural Residential (A/RR05), as it was rezoned in 2015. With the RC zone, as described in the Yuba County zoning ordinance[95] a power plant could be located there with a CUP approved by the Yuba County Planning Commission. The Department representative described that there would probably be some areas that would need additional analysis (potential field surveys) such as cultural and biological resource, but based on the Department's knowledge of the site the analysis should be relatively. It would be likely that a Mitigated Negative Declaration could be issued. The application for the CUP could be done simultaneously with the CEQA process and the process would take 4-6 months assuming any required studies had been completed. One advantage is the site has already been used for an industrial use, for example a sawmill. There is a height limitation of 35 feet but a variance could probably be obtained since the county has a number of cell towers as high as 150 feet being allowed.

Preliminary CEQA Review

The Oregon House site was previously the site of an operating sawmill (the Siller Sawmill), which has reportedly been gone since the 1970's. The only remaining remnant of the sawmill is the old mill office building (now abandoned), and a large maintenance building located near Highway 20. Currently, a portion of the site is being used as a firewood production yard. At a 115 acres, the site is large enough where the plant could be sited so as to avoid any significant impacts to neighboring properties. As mentioned above, cultural resource investigation (not

[94] Personal communications with Kevin Perkins, Senior Planner, Yuba County Planning Department, March 2017

[95] Chapter 12.43 - http://www.co.yuba.ca.us/departments/bos/documents/ordinance/titlexii.pdf

necessarily a field survey) and biological field surveys may be necessary. However, with residences within 1,000 feet of a bioenergy facility and the relatively stringent noise impact thresholds in Yuba County[96], a noise survey and impact mitigation study is likely warranted as well.

Air Emissions Permit

The site is under the jurisdiction of the Feather River Air Quality Management District. The principal district rules for a project that employs a gasification to electricity system using a internal combustion genset are:

- Rule 10.1, New Source Review:
  - Major Source threshold – 100 TPY for NOx, VOC, PM10, PM2.5 (Section D.25)
  - Best Available Control Technology – 25 pounds/ day for NOx and VOC; 80 pounds/day for PM10 and SOx, 500 pounds/day for CO (Section E.1)
  - Emission Offsets Need Thresholds – NOx, VOC, PM10 – 25 TPY (each), no threshold for CO (Section 5.2).
- Rule 3-22, Section D, Stationary Internal Combustion Engine Emissions Limitations
  - Rich Burn engine – NOx – 90 ppmv; VOC – 250 ppmv; CO – 4000 ppmv
  - Lean Burn engine – NOx – 150 ppmv; VOC – 750 ppmv; CO – 4000 ppmv

Grid Connection

Figure 116: Oregon House Area Electric Grid

Source: West Biofuels, LLC

[96] Yuba County General Plan Update, Section 9, Public Health and Safety Element, Table-2 (Yuba County Maximum Allowable Noise Exposure form Non-Transportation Noise Sources at Noise Sensitive Land Uses)

City of Colfax – Placer County

Site Name: Sites zoned Industrial (I)	CEQA Lead Agency: City of Colfax Planning Department
Site APN No.: TBD	Sewer Availability: Yes. City of Colfax
Latitude: N 39.095313	Water Source: Placer County Water Agency
Longitude: W 120.954787	Air District: Placer County Air Pollution Control District
Zoning: I - Industrial	Water District: Central Valley Regional Water Quality Control Board
Contacts: Amy Feagans-Director of Planning (530) 346-2313	

Figure 117: Colfax Site Aerial

Source: West Biofuels, LLC

Site Location Approval

Zoning for the City of Colfax is found in Title 17 of the Colfax Municipal Code. Section 17.80.020 describes the industrial zone (I), and one of the permitted uses for this zone is General Generating Facilities[97]. This use requires a permit, most likely a Conditional Use Permit.

[97] http://www.colfax-ca.gov/municipal_code/2015/128.pdf

The City of Colfax Director of Planning stated that the sites zoned I at the southwest end of the City limits would be a possibility[98]. Problems might be the height of a gasifier unit and the availability of 3-5 acres although several parcels could probably be combined together.

The site approval process would begin with an initial meeting with the Colfax Planning Department to describe the project and if the Planning Department decides that the project is acceptable, the CEQA process would begin with the City of Colfax as Lead Agency. Upon satisfactory completion of the CEQA process, the City could issue a Negative Declaration or Mitigated Negative Declaration. Upon completion of the CEQA process, Conditional Use Permit could be approved by the Colfax Planning Commission.

Preliminary CEQA Review

The proposed site is located 1,400-1,500 feet north of the Mink Creek Homeowners' Association, a 100+ house residential development. Also most of the development near the site is commercial. This could result in opposition by the Homeowners Association and possibly some of the nearby commercial businesses. However, the site is already being used for an industrial purpose and this would eliminate many of the items in CEQA which must be addressed. A pre-application meeting with City Planning would provide an estimate of the probability of successfully locating a power plant there.

Air Emissions Permit

The site is under the jurisdiction of the Placer County Air Pollution Control District. The principal district rules for a project that employs a gasification to electricity system using an internal combustion genset are:

- Rule 502, New Source Review:
  - Major Source threshold – 25 TPY for NOx, VOC; 100 TPY for PM2.5, SOx (Section 230)
  - Best Available Control Technology – 10 pounds/ day for NOx and VOC; 80 pounds/day for PM10, PM2.5, SOx, 550 pounds/day for CO (Section 302)
  - Emission Offsets Need Thresholds – NOx, VOC – 10 TPY; PM10 and PM2.5 – 15 TPY; SOx – 27.5 TPY; CO – 99 TPY (Section 303).
- Rule 301, Stationary Internal Combustion Engine Emissions Limitations
  - Rich Burn engine – NOx – 90 ppmv; CO – 2000 ppmv
  - Lean Burn engine – NOx – 150 ppmv; CO – 2000 ppmv

[98] Personal communications with Amy Feagans, Planning Director, City of Colfax, March 2017.

Grid Connection

Figure 118: Colfax Area Electric Grid

Source: West Biofuels, LLC

Camino - El Dorado County

Site Name: Camino-SPI Sawmill	CEQA Lead Agency: El Dorado County Community Development Agency, Planning Services Division
Site APN No.: Potentially 04317026, 04317015, 04318015 or 04318011	Sewer Availability: Yes. Placerville Sewer System
Latitude: N 38.742782	Water Source: El Dorado Irrigation System
Longitude: W 120.677504	Air District: El Dorado Air Pollution Control District
Zoning: IL – Light Industrial	Water District: Central Valley Regional Water Quality Control Board
Contacts: Aaron Mount-Planner; (530) 621-5345	

Figure 119: Camino Site Aerial

Source: West Biofuels, LLC

Site Location Approval

The now-closed Sierra Pacific Industries sawmill and log storage yard currently occupy the site. The site is zoned Light Industrial (IL) as described in Section 130.23.010 B.1. of the El Dorado zoning code[99]. Power plants are not listed as an allowed use, but some uses appear to be allowed even though they are not listed by obtaining a Conditional Use Permit.

An El Dorado County Planning Department representative[100] states that a power plant would be allowed but would require a Conditional Use Permit. There is a large empty area adjacent to the sawmill which may have been used to store logs. Zoning shows it to be zoned R-20, but Aaron said that that area is now zoned IL like the rest of the sawmill. He said that the county would be the lead agency for CEQA.

Preliminary CEQA Review

The south side of the Site is about one quarter mile from Highway 50. There is a commercial/residential development just east of the southeast edge of the site. However, the large empty and cleared area (former log yard) attached to the north side of the sawmill development is largely surrounded by vacant land. The site was an occupied industrial site so many of the items in CEQA would not be a factor. However it is unknown whether there would be public opposition to a power plant at the Site. The Planning Department has a Pre-Application Review process that should identify any serious problems or opposition to the project.

[99]https://www.municode.com/library/ca/el_dorado_county/codes/code_of_ordinances?nodeId=TIT130ZO_ART2ZOALUSZOST_CH130.24REZO_S130.24.020MAALUS

[100] Personal communications with Aaron Mount, Planner, El Dorado County Planning Department, March 2016

The Pre-Application Review process takes 1-2.5 months. With the submittal of a CUP application and it being deemed complete by the Department, the Initial Study for CEQA is estimated to take 30 days and a Mitigatred Negative Declaration 105 days.

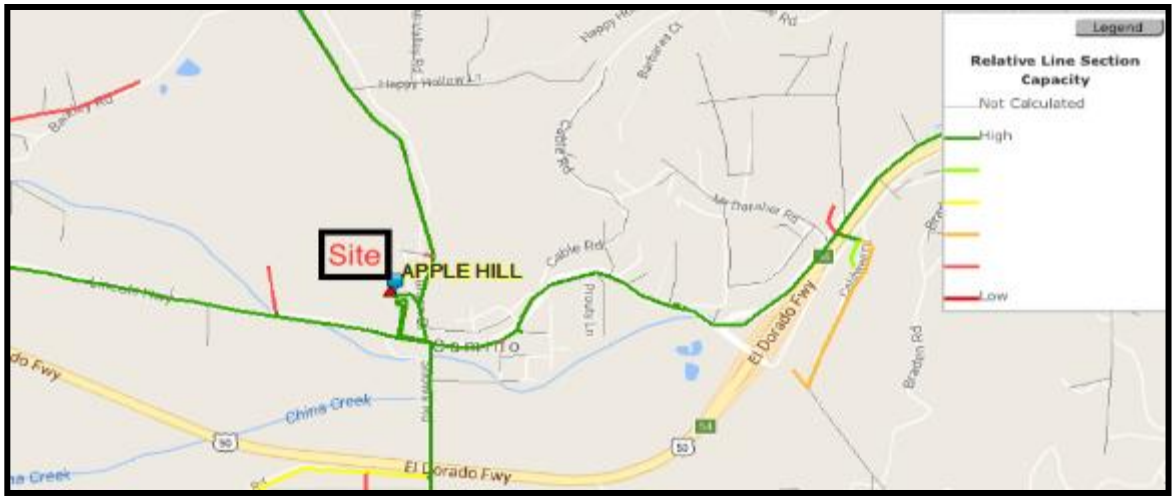
Air Emissions Permit

The site is under the jurisdiction of the El Dorado Air Quality Management District. The principal district rules for a project that employs a gasification to electricity system using a internal combustion genset are:

- Rule 523, New Source Review:
  - Major Source threshold – 25 TPY for NOx, VOC; 100 TPY for PM2.5, SOx (Section 523.2)
  - Best Available Control Technology – 10 pounds/ day for NOx and VOC; 80 pounds/day for PM10, SOx, 550 pounds/day for CO (Section 523.3)
  - Emission Offsets Need Thresholds – NOx, VOC – 5,000 pound/quarter; PM10 – 7,500 pound/quarter; SOx – 12,500 pounds/quarter (Section 523.3).
- Rule 233.3, Stationary Internal Combustion Engine Emissions Limitations
  - Rich Burn engine – NOx – 25 ppmv; CO – 2000 ppmv
  - Lean Burn engine – NOx – 65 ppmv; CO – 2000 ppmv

Grid Connection

Figure 120: Camino Area Electric Grid



Source: West Biofuels, LLC

Pioneer - Amador County

Site Name: Pioneer Greenhouses, 25270 State Highway 88, Pioneer CA	CEQA Lead Agency: Amador County Planning Department
Site APN No.: 031060015000	Sewer Availability: Unknown - unlikely
Latitude: N 38.433329	Water Source: Unknown – likely water well
Longitude: W 120.559454	Air District: Amador County Air Pollution Control District
Zoning: M - Manufacturing	Water District: Central Valley Regional Water Quality Control Board
Contacts: Chuck Beatty-Planner; Susan Grijalva-Director of Planning; (209) 223-6380	

Figure 121: Pioneer Site Aerial

Source: West Biofuels, LLC

Site Location Approval

The Amador County Planning Department representative was familiar with the site[101]. The site is currently occupied by a large complex of biomass heated greenhouses, which are no longer being operated. The land is zoned Manufacturing (M) and would be suitable for a power plant. A power plant facility would require a Conditional Use Permit and that the county would be the

[101] Personal communications with Chuck Beatty, Planner, Amador County Planning Department, March 2017

Lead Agency for CEQA. M zoning has a height limitation of 35 feet, but a variance can be obtained

Preliminary CEQA Review

This site should be able to obtain a Negative Declaration or a Mitigated Negative Declaration under the CEQA. It has been previously used for a manufacturing purpose (greenhouse) and is more than large enough (23.5 acres). Cultural and biological studies should not be required since it has already been developed. The height of a tower for gasification may be a CEQA issue (visual impact) since it will be visible from Highway 88. However, the Planning Department agreed there are ways to mitigate the visual impact if it becomes an issue.

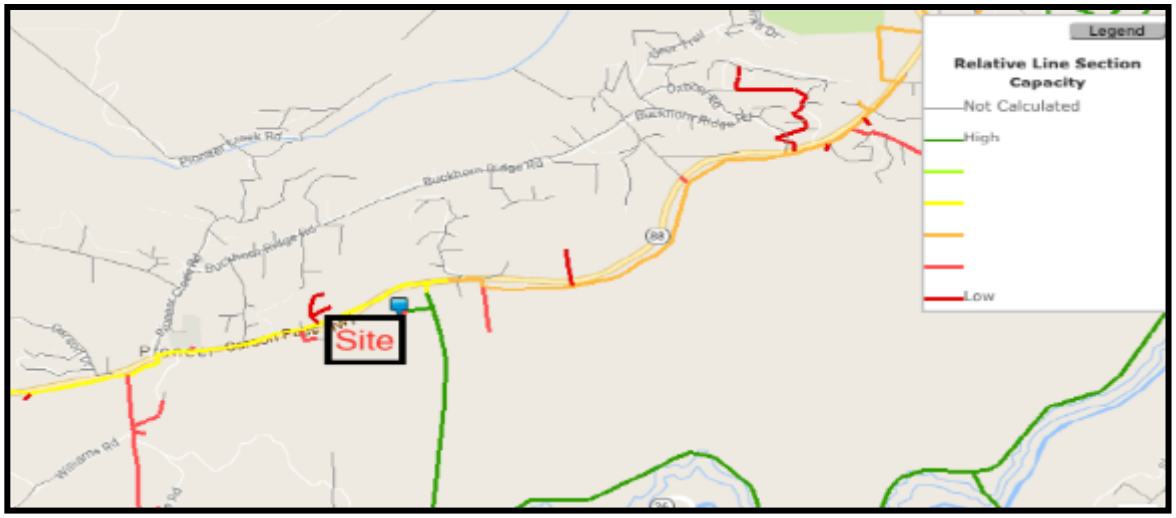
Air Emissions Permit:

The site is under the jurisdiction of the Amador County Air Pollution Control District. The principal district rules for a project that employs a gasification to electricity system using a internal combustion genset are:

- New Source Review:
  - Major Source threshold – 100 TPY of any one pollutant (Rule 102)
  - Best Available Control Technology – No specific thresholds, case-by-case basis with district (Rule 102)
  - Emission Offsets Need Thresholds – No thresholds listed – assumes 100 TPY (Rule 411).
- Stationary Internal Combustion Engine Emissions Limitations – no specific rule

Grid Connection

Figure 122: Pioneer Area Electric Grid



Source: West Biofuels, LLC

Angels Camp - Calaveras County

Site Name: Angels Camp	CEQA Lead Agency: City of Angels Camp
Site APN No.: 64007003	Sewer Availability: Angels Camp Water and Sewer Department
Latitude: N 38.045495	Water Source: Angels Camp Water and Sewer Department
Longitude: W 120.528571	Air District: Calaveras County Air Pollution Control District
Zoning: PS – Public Service	Water District: Central Valley Regional Water Quality Control Board
Contacts: Dan Hanham-Director of Planning, City of Angels Camp; 209-736-1346	

Figure 123: Angels Camp Site Aerial

Source: West Biofuels, LLC

Site Location Approval

The site property is owned by the City of Angels Camp and is adjacent to the City wastewater treatment facility. Zoning for the site is Public Service District (PS) and is found in the City of Angels Camp Municipal Code at Title 17. Chapter 17.36 contains the description of the PS zoning. The purpose of the zoning is "to provide areas for local, state and federal use of the land, and public utility uses of land to meet a public need". In a PS district, the following uses are acceptable with a CUP issued by the City of Angels Camp Planning Department:

- All government agency uses and structures, and public utility uses and structures.

Regarding is a private party or non-governmental entity could also apply for a CUP on the site, the City Planning Department stated that was possible.[102] The City would be the Lead Agency for CEQA.

Preliminary CEQA Review

The Site is primarily grassland with scattered oaks and is currently being used as a spray field for the wastewater treatment facility. There are no nearby residences. There is industrial/commercial development across Highway 49. The site is owned by the City of Angels Camp which seems amenable to location of power plant there.[103] Also supportive of a biomass power plant at the site is Utica Water and Power Authority, which owns and operates hydroelectric facilities in the area.

Air Emissions Permit

The site is under the jurisdiction of the Calaveras County Air Pollution Control District. The principal district rules for a project that employs a gasification to electricity system using an internal combustion genset are:

- New Source Review:
  - Major Source threshold – 100 TPY of any one pollutant (Rule 102)
  - Best Available Control Technology – No specific thresholds, case-by-case basis with district (Rule 102)
  - Emission Offsets Need Thresholds – No thresholds listed – assume 100 TPY (Rule 411).
- Stationary Internal Combustion Engine Emissions Limitations – no specific rule

Grid Connection

Figure 124: Angels Camp Area Electric Grid

Source: West Biofuels, LLC

[102] Personal communication with Dan Hanham, Director of Planning, City of Angels Camp, March 2017

[103] Ibid

Twain Harte/Mono Vista

Site Name: Mono Vista	CEQA Lead Agency: Tuolumne County Planning Department
Site APN No. 08906007 and adjacent parcels	Sewer Availability: Tuolumne Utilities District
Latitude: N 38.001156	Water Source: Tuolumne Utilities District
Longitude: W -120.262307	Air District: Tuolumne County Air Pollution Control District
Zoning: M-1 – Light Industrial	Water District: Central Valley Regional Water Quality Control Board
Contacts: Dan Essen-Planner; (209) 533-6920	

Figure 125: Twain Harte/Mono Vista Aerial

Source: West Biofuels, LLC

Site Location Approval

The site is located in the community of Mono Vista, between Twain Harte and Sonora. Zoning for the site is found in Title 17 of the Tuolumne County Ordinance Code[104]. The site is zoned Light Industrial District (M-1). This zoning (Chapter 17.38 of the Code) does not specifically list power plants as an allowable use or as being allowed to be used with a Use Permit.

The Tuolumne County Planning Department confirmed that it is zoned Manufacturing (M-1) and could be used for a power plant if a CUP was obtained[105]. Regarding CEQA the Department

[104] http://www.tuolumnecounty.ca.gov/index.aspx?NID=165#

[105] Personal communications with Dan Essen, Tuolumne County Planning Department, March 2017

stated that there could be some opposition by residential neighbors. The Department suggest that any power plant applicant request a Pre-Application Review which could give a much better idea whether a power plant facility CUP for the site could be approved.

Preliminary CEQA Review

The site is currently in use as a lumber yard (Deutschman Lumber) and may have been the site of sawmill in the past. The subject parcel is 4 acres in size, but adjoining parcels to the south and bordering the Highway 108 freeway are another 11 acres. Potential impacts from issues such as traffic, noise, and visual are unknown but are possible due to surrounding businesses and the public. There are some residences to the north of the site across Longeway Road. Visual impact from a relatively high profile of the gasification system might be an issue to these residences. The county's Pre-Application Review option is considered a necessity in addressing CEQA requirements and potential opposition to the project.

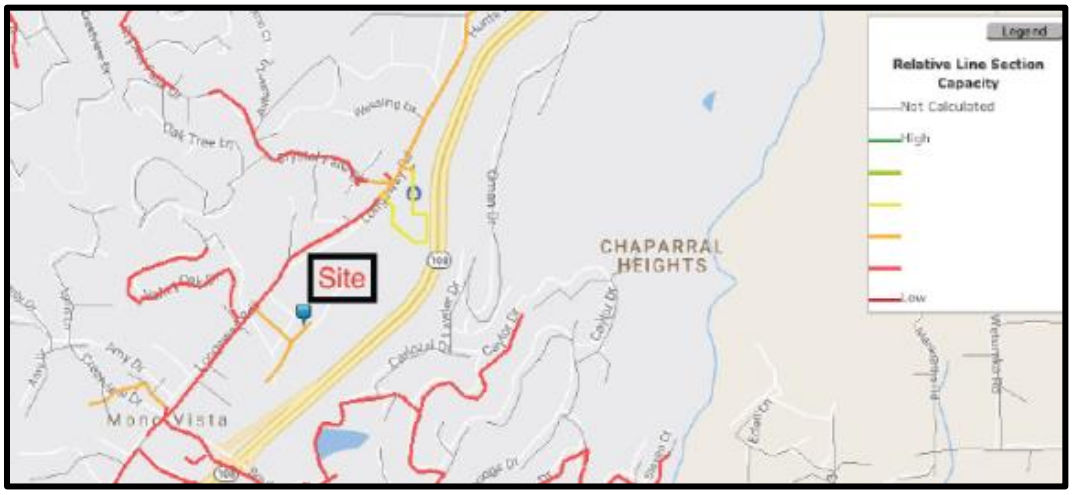
Air Emissions Permit

The site is under the jurisdiction of the Tuolumne County Air Pollution Control District. The principal district rules for a project that employs a gasification to electricity system using an internal combustion genset are:

- New Source Review:
  - Major Source threshold – 100 TPY of any one pollutant (Rule 102)
  - Best Available Control Technology – No specific thresholds, case-by-case basis with district (Rule 102)
  - Emission Offsets Need Thresholds – No thresholds listed – assume 100 TPY (Rule 411).
- Stationary Internal Combustion Engine Emissions Limitations – no specific rule

Grid Connection

Figure 126: Mono Vista Area Electric Grid



Source: West Biofuels, LLC

Groveland/Big Oak Flat – Tuolumne County

Site Name: Big Oak Flat-2 Sites	CEQA Lead Agency: Tuolumne County
Site APN No.: 06614031 and adjacent parcels	Sewer Availability: Groveland Community Services District
Latitude: Parcel 06614031- N37.8256; Parcel 06650035-N37.8291	Water Source: Groveland Community Services District
Longitude: Parcel 06614031-W120.2510; Parcel 06650035-W120.2465	Air District: Tuolumne County Air Pollution Control District
Zoning: C-1 – General Commercial	Water District: Central Valley Regional Water Quality Control Board
Contacts: Dan Essen-Planner; (209) 533-6920	

Figure 127: Groveland/Big Oak Flat Aerial

Source: West Biofuels, LLC

Site Location Approval

The site is located between Big Oak Flat and Groveland on Highway, Zoning is found in Title 17 of the Tuolumne County Ordinance Code[106]. The 6 acre parcel is zoned commercial as well as the adjacent parcels to the north and east. Per the Planning Department all of these parcels are zoned General Commercial District or C-1 (Chapter 17.34). This zone does not specifically list power plants as an allowable use or are listed as being allowed to be used with a Use Permit.

[106] http://www.tuolumnecounty.ca.gov/index.aspx?NID=165#

The Tuolumne County Planning Department representatives determined that the sites could be used for a power plant upon obtaining a Site Development Permit (similar to a CUP), although not listed in the current version of the zoning code[107]. As mentioned previously Tuolumne County Planning Department encourages the use of its Pre-Application Review process, which would provide information to better assess the probability of achieving success in siting a power plant facility at the location.

Preliminary CEQA Review

The site parcel is slightly over 6 acres. The site and adjoining area was cleared several years ago when the land was subdivided into a commercial business park (which subsequently was never developed. The site's biological and cultural resources (if any) were likely significantly impacted during the clearing activity. However, the site appears to have recovering habitat so a biological field survey is probably warranted. Nearby residences are very limited and the location being on Highway 120 indicates that potential significant impacts are unlikely, and a Mitigated Negative Declaration is likely to be achieved.

Air Emissions Permit

The site is under the jurisdiction of the Tuolumne County Air Pollution Control District. The principal district rules for a project that employs a gasification to electricity system using an internal combustion genset are:

- New Source Review:
  - Major Source threshold – 100 TPY of any one pollutant (Rule 102)
  - Best Available Control Technology – No specific thresholds, case-by-case basis with district (Rule 102)
  - Emission Offsets Need Thresholds – No thresholds listed – assume 100 TPY (Rule 411).
- Stationary Internal Combustion Engine Emissions Limitations – no specific rule

[107] Personal communications with Dan Essen, Planner, and David Gonzalves, Director, Tuolumne County Planning Department, March 2017

Grid Connection

Figure 128: Big Oak Flat Area Electric Grid

Source: West Biofuels, LLC

Idyllwild - Riverside County

Site Name: Idyllwild Transfer Station	CEQA Lead Agency: Riverside County
Site APN No.: County Property	Sewer Availability: Unlikely
Latitude: N 33.7238	Water Source: Idyllwild Water District or well
Longitude: W 116.7169	Air District: South Coast Air Quality Management District
Zoning: N-A – Natural Resources	Water District: Colorado Regional Water Quality Control Board
Contacts: Office Administrator (Rosalee) - Planning; (951) 955-3200	

Figure 129: Idyllwild Aerial

Source: West Biofuels, LLC

Site Location Approval

The Riverside County Planning Department is the agency for site approval. The Site is currently occupied by the Idyllwild Solid Waste Transfer Station and a closes landfill which is zoned Natural Resources (N-A). Article XV, Section 15.200 of the Riverside County zoning code listes permitted used for N-A and power plants are not included. The Riverside County Planning Department, however, stated that power plants may be approved even though the zoning code does not specifically provide for them. Siing of a power plant would require a Public Use Permit which would take 9-12 months to receive and cost $15,000-30,000. Rosalee said that there could be public opposition to a power plant but they have a Pre-Application Review to assist in determining potential. The review should provide the probability of obtaining a CEQA Negative Declaration and the Public Use Permit.

It is also noted that there is currently a bark beetle affected woody biomass grinding facility located nearby, but it is located on federal property.

Preliminary CEQA Analysis

The Idyllwild Transfer Station is a large site which appears to have sufficient room for a small power plant. It is remote from residences and is well disturbed from waste haul trucks and waste transfer and landfill activities. It seems that most of the items addressed by CEQA would not be sufficiently impacted and that a Negative Declaration and Public Use Permit could be obtained within reasonable time and cost. The operator of the transfer station is CR&R Environmental Services and its agreement with Riverside County was not known to the Planning Department.

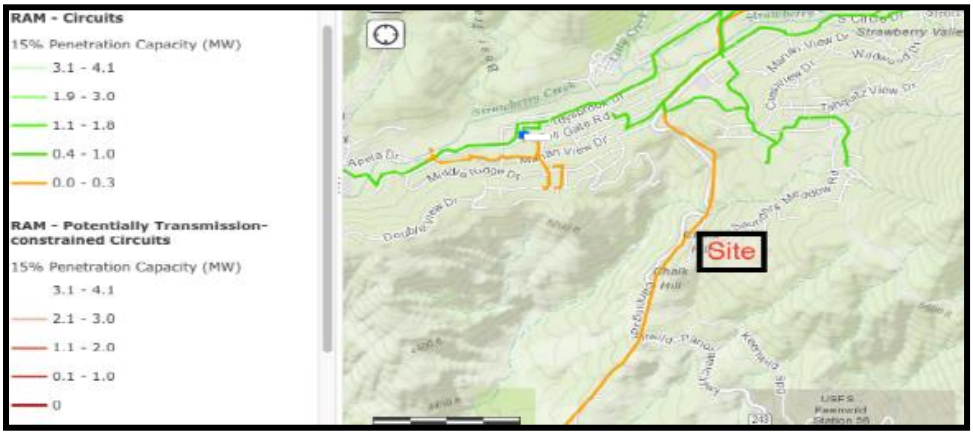
Air Emissions Permit

The site is under the jurisdiction of the South Coast Air Quality Management District and within the South Coast Air Basin portion of Riverside County. The principal district rules for a project that employs a gasification to electricity system using an internal combustion genset are:

- Rule 1302, Definitions:
  - Major Source threshold – 10 TPY - NOx and VOC; 70 TPY - PM10 and SOx; 50 TPY – CO
- SCAQMD BACT Guidelines
  - Best Available Control Technology –10 TPY - NOx and VOC; 70 TPY - PM10 and SOx; 50 TPY – CO
- Rule 1303, Requirements
  - Emission Offsets Need Thresholds – 10 TPY - NOx and VOC; 70 TPY - PM10 and SOx; 50 TPY – CO
- Rule 1110.2, Emissions from Gaseous- and Liquid-Fueled Engines, Table III-B (effective January 1, 2017)
  - NOx – 11 ppmvd; VOC – 30 ppmvd; CO - ppmvd

Grid Connection

Figure 130: Idyllwild Area Electric Grid



Source: West Biofuels, LLC

Round Mountain - Shasta County

Site Name: Round Mountain-2 parcels	CEQA Lead Agency: Shasta County
Site APN No.: 029080012000 and 029080024000	Sewer Availability: Unknown
Latitude: N 40.7960	Water Source: Unknown
Longitude: W 121.9395	Air District: Shasta County Air Quality Management District
Zoning: MU – Multiple Use and R-R – Rural Residential	Water District: Central Valley Regional Water Quality Control Board
Contacts: Lio Salazar-Senior Planner; 530-245-6496	

Figure 131: Round Mountain Aerial

Source: West Biofuels, LLC

Site Location Approval

This site is located along Highway 299 near the intersection of Terry Mill Road and was a former sawmill site. The site zoning code is Title 17 of the Shasta County Ordinance[108]. The site is zoned Multiple Use (MU) in the southern portion of the site and Rural Residential (R-R) for the remainder. The purpose of MU zoning is to allow a variety of residential, commercial, and light industrial uses (Chapter 17.54). The purpose of R-R is to provide for a rural residential living environment (Chapter 17.26). Power Plants are not shown under either of the zonings either as an allowed use, or under any of the uses that require a Zoning Permit, Administrative Permit or a Use Permit. However, Shasta County Planning Department indicated that a power plant could theoretically be permitted in any zoning including MU and R-R by obtaining a Use Permit[109]. A Use Permit usually takes 3 to 6 months to obtain once a Use Permit application is deemed complete and accepted by Shasta County. The Shasta County Planning Department also said that there is usually not a lot of opposition to allowing projects in Shasta County. The County would be the lead agency for CEQA and that they are receptive to projects in Shasta County.

Preliminary CEQA Review

The Site is in a rural area and consists of about 16 acres. There is sufficient room on the Site to keep the power plant away from the school across Terry Mill Road and a few houses west of Highway 299. It appears that the Site has been previously used and should not pose a problem for cultural and biological impacts. According to the Planning Department, there is usually little

[108] https://www.municode.com/library/ca/shasta_county/codes/code_of_ordinances?nodeId=CD_ORD_TIT17ZO

[109] Personal communication with Lio Salazar, Senior Planner, Shasta County Planning Department, March 2017

opposition to similar projects in Shasta County. However, there are numerous nearby residences, but there is also a very large electrical substation immediately to the north.

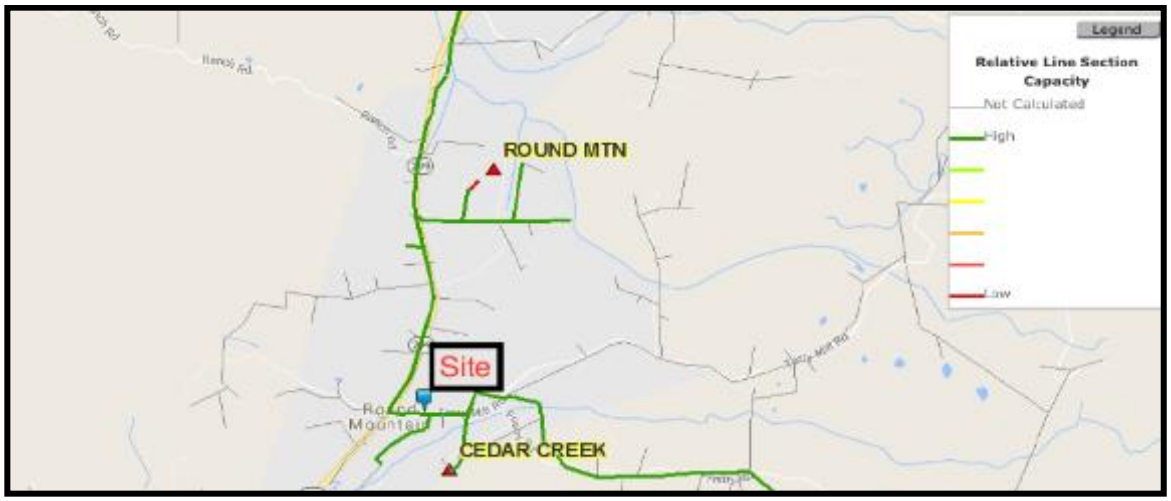
Air Emissions Permit

The site is under the jurisdiction of the Shasta County Air Quality Management District. The principal district rules for a project that employs a gasification to electricity system using a internal combustion genset are:

- Rule 2:1, New Source Review:
  - Major Source threshold – 100 TPY for NOx, VOC; 100 TPY for PM2.5, SOx
  - Best Available Control Technology – 25 pounds/ day for NOx and VOC; 80 pounds/day for PM10, SOx, 5o0 pounds/day for CO (Section 301)
  - Emission Offsets Need Thresholds – No specific thresholds
- Rule 3:28, Stationary Internal Combustion Engine Emissions Limitations (>300 bhp)
  - Rich Burn engine – NOx – 640 ppmv; CO – 4500 ppmv
  - Lean Burn engine – NOx – 740 ppmv; CO – 4500 ppmv

Grid Connection

Figure 132: Round Mountain Area Electric Grid



Source: West Biofuels, LLC

CHAPTER 6: Project Benefits

Questionnaires, as provided by the Energy Commission were completed for Task 6. These questionnaires are located in Appendix B.

Greenhouse Gas Lifecycle

Greenhouse gases lifecycle emissions were calculated in a manner consistent with the Placer County Cabin Creek EIR,[110] using emission factors for the proposed technologies. Greenhouse gas lifecycle includes emissions associated with facility construction, facility operations, and mobile operations. When evaluating the lifecycle, it is critical to understand the potential business-as-usual disposal method of forest feedstock. For this analysis, West Biofuels considered a 50 percent disposal through open pile burning and 50 percent through chip and scatter (mastication). Emission factors were derived by Stockholm Environmental Institute independently of this analysis. [111]

Table 104: GHG Emissions from Business-As-Usual Practices

	System 1	System 2	System 3	System 4
Feedstock Consumption (BDT/yr)	11,310	16,370	32,650	31,560
Avoided Pile & Burn (BDT/yr)	5,655	8,185	16,325	15,780
Pile & Burn Avoided Emissions (MT CO2e/BDT)	1.84			
Avoided Emissions from Pile & Burn (MT CO2e/yr)	**10,405**	**15,060**	**30,038**	**29,035**
Avoided Mastication (BDT/yr)	5,655	8,185	16,325	15,780
Pile & Burn Avoided Emissions (MT CO2e/BDT)	1.58			
Avoided Emissions from Mastication (MT CO2e/yr)	**8,935**	**12,932**	**25,794**	**24,932**

Source: West Biofuels, LLC

Construction emissions and mobile emissions for a 3 MW facility are based on the Placer County Biomass Environmental Impact Report.[112] The Placer County Biomass EIR used CalEEMod, ARB's OFFROAD2007, ARB's EMFAC2011, ARB's Mandatory Reporting Guidance, and EPA AP-42 for greenhouse gas modeling and calculations. Construction emissions and mobile

[110] Cabin Creek Biomass Facility Project DEIR, July 2012, State Clearinghouse #2011122032, Placer County Community Development Resources Agency.

[111] Greenhouse Gas and Air Pollutant Emissions of Alternatives for Woody Biomass Residues. Lee, C., Lazarus, M., Smith, G. November 2010, Stockholm Environment Institute.

[112] Cabin Creek Biomass Facility Project DEIR, July 2012, State Clearinghouse #2011122032, Placer County Community Development Resources Agency.

emissions (not including biomass trucking) were scaled by a factor of 1.5 from a 2MW assessment to a 3MW assessment. GHG estimates for construction and mobile emissions are summarized in Table 105.

Table 105: GHG Emission Estimates for Construction and Mobile Sources

	System 1	System 2	System 3	System 4
Construction Emissions*	247.5 MT CO_2e 8.25 MT CO_2e /yr	247.5 MT CO_2e 8.25 MT CO_2e /yr	247.5 MT CO_2e 8.25 MT CO_2e /yr	247.5 MT CO_2e 8.25 MT CO_2e /yr
Mobile Emissions	926 MT CO_2e /yr	926 MT CO_2e /yr	926 MT CO_2e /yr	1,389 MT CO_2e /yr
* Construction emissions are amortized over 30 years.				

Source: West Biofuels, LLC

Project emissions are based on the total feedstock consumed annually; therefore, the project emissions were scaled consistent with feedstock consumption. The Placer County EIR evaluated 17,000 BDT per year consumed. The Placer County numbers are adjusted for each system and shown in Table 106.

Table 106: GHG Emissions Estimates for Operations

	System 1	System 2	System 3	System 4
Feedstock Consumption (BDT/yr)	11,310	16,370	32,650	31,560
Project Emissions (MT CO_2e /yr)	19,623	28,402	56,648	54,757

Source: West Biofuels, LLC

Lastly, biochar sequestration potential should be evaluated. The fixed carbon within the biochar has a half-life of over 1,000 years.[113] Based on the data from Task 3 and Task 4, fixed carbon in the CircleDraft system averages 79.7 percent while the rotary gasification system is only 69.4 percent. To estimate carbon dioxide equivalent sequestration, fixed carbon is converted to carbon dioxide equivalent based on atom mass of carbon and carbon dioxide.[114]

Table 107: Biochar Sequestration

	System 1	System 2	System 3	System 4
Biochar Production (% of feedstock)	10%	10%	10%	15%
Total Biochar Production (BDT/year)	1,131	1,637	3,265	4,734
Fixed Carbon (% of biochar)	79.7%	79.7%	79.7%	69.4%
Carbon Sequestration* (MT CO2e/yr)	**3,005**	**4,349**	**8,674**	**10,951**
*Biochar*1MT/1.1BDT*Fixed Carbon %*44amu CO2/12amu C				

Source: West Biofuels, LLC

113 Spokas, K. "Review of the stability of biochar in soils: predictability of O:C molar ratios." Carbon Management (2010) 1(2), 289-303. Future Science Group.

114 The atomic mass of carbon is approximately 12 amu while the atomic mass of carbon dioxide is approximately 44 amu. To convert from carbon to carbon dioxide, the carbon value is multiplied by 44/12.

Net GHG lifecycle emissions are summarized in Table 108. The net GHG impacts of community-scale biomass gasification systems are negative based on avoided business-as-usual disposal methods for biomass and sequestered biochar. Note that this analysis did not include displaced fossil power generation. Based on consistent load growth and significant renewable and non-fossil electricity sources, it is challenging to identify the impact of additional 3 MW renewable electricity generators.

Table 108: Net GHG Lifecycle Emissions

	System 1	System 2	System 3	System 4
Construction Emissions (MT CO2e/yr)	8.25	8.25	8.25	8.25
Project Emissions (MT CO2e/yr)	19,623	28,402	56,648	54,757
Mobile Emissions (MT CO2e/yr)	926	926	926	1,389
Gross Emissions (MT CO2e/yr)	**20,557**	**29,336**	**57,582**	**56,154**
Avoided Pile & Burn (MT CO2e/yr)	10,405	14,591	30,038	29,035
Avoided Mastication (MT CO2e/yr)	8,935	12,529	25,794	24,932
Sequestered Carbon (MT CO2e/yr)	3,005	4,213	8,674	10,951
Gross Savings (MT CO2e/yr)	**22,345**	**31,333**	**64,506**	**64,918**
Net Lifecycle (MT/CO2e/yr)	**-1,788**	**-3,005**	**-6,924**	**-8,764**

Source: West Biofuels, LLC

CHAPTER 7: Technology/Knowledge Transfer Activities

The purpose of this technology/knowledge transfer plan is to share findings from the research and development project, *Modular Biomass Power Systems to Facilitate Forest Fuel Reduction Treatments*. The technology and knowledge developed through the implementation of this project will be shared with other technology experts, other researchers, and the larger community of engaged forest communities, forest-focused agencies and non-profits, and the wood products industry. The project team conducted outreach by three primary mean: 1. Conference Presentations; 2. Annual Project Review Meetings; and 3. Technology Presentations to Community and Industry.

Conference Presentations

The project team attended technical conferences and presented the status and results of the project with other subject matter technical experts in the area of thermochemical conversion of biomass for energy. These are national and international gatherings of experts in this field where there is an opportunity to transfer knowledge to others and help spread the technology and efforts of California to improve technology. These meetings are also a chance for the project team to keep informed on other efforts that may be beneficial and complementary to this project. The team gave more than two technical conference presentations per year during the course of the project.

Annual Project Review Meetings

The project team gathered the entire project team, including remote and related project researchers, to review the project related results from each part of the technology development effort. The Energy Commission project manager and the TAC were invited to participate in these annual meetings. This is an opportunity to share results, transfer knowledge between the project participants and advisors, and improve the technology results.

Technology Presentations to Community and Industry

The Project Team gave technology presentations to industry, government, and community members interested in the CircleDraft technology and addressing forest-source residue management. These presentations took place at the project site and at other locations on an invited basis. These presentations are opportunities to transfer information about the project and CircleDraft technology to a wider audience. The team gave at least five of these presentations per year during the course of the project.

Conference Presentations

2015

- TC Biomass: November 2-5, 2015: tcbiomass2015 brings together the world's experts in biomass gasification, pretreatment, pyrolysis, and upgrading to explore progress in the bioeconomy. Developments in the conversion of renewable resources into a variety of fuels, chemicals and energy products is driving the emergence of an increasingly diverse and significant bioeconomy. Thermochemical processes extract maximum product yields from biomass resources. Taking Technology for the Bioeconomy as the overall theme, tcbiomass2015 participants heard the latest research, development, and deployment results for thermal biomass conversion and upgrading technologies and systems to help grow the bioeconomy and achieve a clean and sustainable energy future. West Biofuels provided a poster board for the conference.

WEST BIOFUELS

ON-SITE BIOMASS GASIFICATION AS A NATURAL GAS SUBSTITUTE

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Dr. Reinhard Seiser, Dr. Robert Cattolica, University of California at San Diego, La Jolla, CA 92093 USA

Abstract

A large share of the agricultural biomass resources remain underutilized while local and national policies continue to mandate increasing levels of renewable energy. Only a small fraction of the available agricultural residues are currently utilized for energy, even where sustainability would support it. This virtually untapped resource for energy has struggled because it is low in energy density, diffusely located, and costly to transport to large, centralized energy facilities. The use of smaller on-site gasification systems to produce bio-syngas from agricultural biomass residues shows promise for increasing resource utilization for displacement of fossil fuels. Bio-syngas generated in on site systems can provide a direct energy substitution for natural gas in gas devices like boilers, dryers, heaters, engines, etc. Proliferation of these systems would help industrial and agricultural processing facilities trying to decrease their carbon emissions footprint, a large part of which comes from on-site natural gas usage. This project shows the technical, economic, and environmental feasibilities associated with on site conversion of residue biomass to bio-syngas for fuel in industrial and agricultural applications. The project samples and characterizes the physical, chemical, and thermal properties of the biomass residues and resulting bio-syngas from the CircleDraft® gasifier system being deployed for commercial operation by West Biofuels, LLC, and its development partner, INSER Energia, S.P.A. The project develops the optimal feedstock and operational conditions required to deliver bio syngas that is compatible with common natural-gas devices used in industry. In addition, the market potential of the bio-char produced as a byproduct of the gasification process is reviewed. The optimized results are used to evaluate the overall costs of using bio syngas in comparison with current and forecast industrial natural gas prices, to determine the economic feasibility for commercial projects. The net environmental benefits including potential greenhouse gas emission reductions and carbon sequestration will be reviewed.

Project Goal: The goal of this project is to determine the feasibility of using currently underutilized agricultural biomass residues for conversion to synthetic gas to replace or blend with natural gas for direct, on-site industrial and agricultural use

Project Tasks	Performance / Cost Objectives
1) Experimental design and selection and characterization of available biomass residues from agricultural sector	At least 3 specific biomass residues will be selected for potential suitability for gasification via the CircleDraft® gasifier system that meet criteria for high quality gasification. The experimental design will be developed to determine the performance and the gas quality from each feedstock at various operating conditions. *Performance targets:* Statewide Availability: 1 million tons/year aggregate; Cost: < $30 per ton; Moisture Content: < 25%; Ash Content: < 5%; Higher Heating Value: > 7,000 BTU/lb; Ash Melting Temperature: >1100°C; Particle Size: < 3 in.
2) Setup measurement systems to characterize performance and gas quality on a commercial CircleDraft® gasifier system	A CircleDraft® gasifier system will be provided by West Biofuels that nominally produces 6.75 MMBTU/hr of synthetic gas from 1000 pounds per hour of dry wood chips and will be outfitted with sensors and sampling ports so that the performance and gas quality can be analyzed for the selected residue feedstock. *Performance targets:* Feedstock: mass flow measurement to ± 5% and composition to ± 3%; Gas: flow measurement to ± 10% and characterize 99% of major and trace gases; Energy: heating value to ± 3% for feedstock and synthetic gas.
3) Conduct testing of biomass feedstock for performance and gas quality with CircleDraft® gasifier system	Tests with each feedstock will be conducted with the CircleDraft® gasifier system over a range of selected operating conditions from the experimental design and the performance of the gasifier will be measured and the gas quality characterized. *Performance targets:* Gasifier efficiency: >70%; Gas heating value: 150-300 BTU/SCF; Gas inert content: <60%; Gas impurities: Less than air quality and manufacturer requirements;
4) Analysis of technical and economic feasibility of natural gas replacement	Based on the optimal results from Task 3, the technical and economic feasibility of industrial or agricultural on-site gasifier projects for the replacement of natural gas will be developed. *Performance targets:* Compatibility with natural gas devices (boilers/engines); Gasifier system capital cost: <$100,000 per MMBTU/hr capacity; Operating hours: 7000/year; Synthetic gas cost: $6-$12/MMBTU; Project simple payback: 3-6 years;

Conclusion

An 2 MW thermal biomass gas production facility has been constructed and is being operated in California for demonstration on both forest and agricultural biomass feedstock. The produced gas is intended to be used as a replacement for Natural Gas in typical gas appliances used by the processing industries. While the project is ongoing, early results indicate that the performance targets listed above are within the capabilities of the technology.

References

The CircleDraft® Gasification Process

Biomass Feeding
Airlock Valve
Drying Zone
Pyrolysis & Gas Cleaning Zone 350-450°C
Gas Outlet Coolers/ Air & Steam Preheaters
Char Stabilizing Zone
Internal Gas Circulation
Cleaned, Cooled Syngas To Polishing & Usage
Char Gasification Zone 900-1050°C
Ash or Biochar
Preheated Air & Steam

Process Unit Specifications

Description	Value
Fuel Type	Chips, Sticks, Residues, Pellets & Cubes
Oxidant	Humidified Air
Fuel Heating Value	8,500 BTU/dry lb
Moisture	25%
Specific Consumption	150 lbs/MMBTU
Gas Production Rate	45 SCF/dry lb
Gas Heating Value	150 BTU/SCF
Fuel Consumption	~1000 lbs/hr
Total Gas Output	6.75 MMBTU/hr
Electrical Consumption	90 kW
Working Temperatures	350 °C-1050 °C
Pressure	Max: 20 in H2O
Thermal Efficiency	75%

Product Syngas Composition

Synthetic Gas Characteristic	CircleDraft® Range
H_2	10 - 35%
CO	15 - 48%
CH_4	1 - 4%
C_2H_4	0.1 - 0.5%
C_2H_6	0.1 - 0.3%
CO_2	0.1 – 15%
N_2	15 - 49%
H_2/CO Ratio	0.5 – 1.5
HHV (MJ/Nm^3) [BTU/scf]	5.6 – 10.3 [150 - 300]
Wobbe Index (MJ/Nm^3)	22 – 38
Tars (mg/Nm^3)	5 - 25
Particulate (mg/Nm^3)	1 – 20
H_2S (ppm)	5 – 50

Control Panel for Gas Production Plant

Agricultural Biomass Potential

California Biomass Feedstock Potential

Almond Shell — Almond Pruning

California Almond Industry Energy Potential vs. Current Usage

Type	Current Industry Energy Usage	BCHP Energy Production Potential*	Net Energy Potential
Power (GwH)	744	1,368	622
Power Value ($)	-$120 M @ $0.16/kWh	$188 M	$68M @ $0.11/kWh
Natural Gas (BCF)	14.9	49	35.1
Nat Gas Value ($)	-$119 M @ $8/1000 ft^3	$255 M	$136 M @ $4/1000 ft^3

* From Estimated 825,000 BDT of almond shell and 550,000 BDT of prunings.

Plant Construction

Erection of Gasifier Structure — Fabrication of Lower Grate Housing

Upper Reactor with Feeder — Lower Cone Hot Face Refractory

Lower Cone Prior to Grate Installation — Modular Control Room Fabrication

3D CAD and Actual Photo of Gas Production Plant

Acknowledgement: Funds for this project were provided by West Biofuels and the California Energy Commission under Grant Agreement Number: #14-01-11G

Source: West Biofuels, LLC

2016

- European Biomass Conference and Exhibition (EUBCE): June 6-9, 2016. The EUBCE represents one of the key events on both a European and global scale for companies and professionals operating at the top end of the biomass and bioenergy sector. Held in a different city each year for over 30 years, the EUBCE has successfully combined a highly renowned international scientific conference with an ever-growing industry exhibition, thus rightfully earning its place as one of the world's most influential biomass sector events. West Biofuels provided a poster board for the conference.

WESTBIOFUELS

MODULAR BIOMASS POWER SYSTEMS TO FACILITATE FOREST FUEL REDUCTION EFFORTS

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Abstract

Community-scale bioenergy infrastructure is critical to support sustainable management of the forested landscape to protect communities, watersheds, and energy infrastructure from the threat of catastrophic wildfire in the western United States and other parts of the world with similar dry, overstocked, and threatened forests. The project team has developed a modular biomass gasification system integrated with a high-efficiency lean-burn engine in order to convert forest residues into renewable grid power to reduce the cost and increase the benefits of forest fuel reduction projects in high fire risk regions. West Biofuels has constructed the patented CircleDraft© gasification with Italian partner INSER, S.P.A. at their facility in Woodland, CA, USA. The purpose of this project is to identify the appropriate supporting equipment for the thermochemical conversion of wood feedstock to syngas and syngas to electricity. Unlike biomass gasification in other settings, forest residue feedstock is more costly to recover and is comprised of tops, limbs, branches, and sub-merchantable timber.

Project Goal: To determine the feasibility of using modular biomass gasification technology to convert forest-sourced feedstock into renewable grid power to reduce the cost and increase the benefits of forest fuel reduction projects in California's high fire risk regions

Project Objectives	Performance / Cost Targets
1) Design, build, and install a system to process incoming forest-sourced feedstock to create a uniform feedstock without fines, overs, an inorganic material (e.g., rock and dirt).	Targets, after processing, include: • Total Inert Content <5%; • Ash Characteristics: Melting point greater than 900°C; • Particle Size: <1% 3-inch and over, <5% fines (Less than ¼ inch); • Moisture Content: Less than 25%; and • Higher Heating Value (HHV): Greater than 7,500 Btu/dry pound.
2) Test the CircleDraft®gasifier that is already installed at the West Biofuels facility to determine operating conditions for optimized efficiency and syngas quality;	Targets for efficiency and syngas quality include: • Thermal Efficiency: >70%; • Throughput Rate: > 900 dry pounds per hour; • Syngas Energy Content: > 150 Btu per ft3; • Tar Content: < 20 mg per Nm3; • Tar Dew Point: < 15°C; • Particulates: < 5 mg per Nm3 and less than 1 micron; • Hydrogen Sulfide: < 50 ppm; • Biochar Production: > 72 dry pounds per hour; and • Biochar Quality: Meets or exceeds IBI Biochar Standards
3) Install and test a lean-burn internal combustion engine generator under various operational settings to identify the optimal configuration for syngas fuel. Targets for performance include:	Targets for performance include: • Electrical Efficiency: > 35%; • CHP Efficiency: > 75%; • Oil Change Frequency: >750 hours; • Generator Faults: <1 fault per 250 hours; • Operating Speed: 1,000 to 2,000 PRM; • Equivalence Ratio: < 0.56; and • Compression Ratio: > 11:1.
4) Demonstrate emission controls that meet California Air Resources Board (CARB) and Regional Air District standards.	Targets for emissions include: • Nitrogen Oxide (NOx): < 0.07 pounds per MWh; • Carbon Monoxide (CO): < 0.1 pounds per MWh; • Volatile Organic Compounds (VOC): < 0.02 pounds per MWh; and • Particulate Matter (PM): < 0.31 pounds per MWh.
5) Research the potential to site modular community-scale biomass gasification projects in the forest/urban interface factoring grid infrastructure and high fire risk areas.	Research includes: • Identify 10 high-priority locations in the forest/urban interface; • Cost/Benefit analysis of feedstock transportation and plant replication; • Assess environmental impacts of modular power system; • GHG life cycle analysis utilizing forestry waste to generate electricity; and • Identify opportunities and challenges for community-scale deployment.
6) Assess production readiness and perform economic analysis to evaluate feasibility for deployment of modular bioenergy technology.	Targets include: • Deployment capacity ramping from 3 MW to 20 MW per year; • SB 1122 competitive LCOE of $124.66 per MWh; • Support 4.9 local renewable energy jobs per MW; and • Support 700 acres/yr. of forest treatment/thinning projects per MW.

Conclusion

An 2-MW modular bio-syngas production facility has been constructed and is being operated in California for demonstration on forest residual biomass feedstock. The produced gas is intended to be used with a gas engine generator to produce heat and electrical power with very low emissions. While the project is ongoing, early results indicate that the performance targets listed above are within the capabilities of the technology.

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The CircleDraft® Gasification Process

Process Unit Specifications

Description	Value
Fuel Type	Chips, Shells, Residue Pellets & Cubes
Oxidant	Humidified Air
Fuel Heating Value	8,500 BTU/dry lb
Moisture	25%
Specific Consumption	150 lbs/MMBTU
Gas Production Rate	45 SCF/dry lb
Gas Heating Value	150 BTU/SCF
Fuel Consumption	~1000 lbs/hr
Total Gas Output	6.75 MMBTU/hr
Electrical Consumption	90 kW
Working Temperatures	350 °C-1050 °C
Pressure	Max 20 in H2O
Thermal Efficiency	75%

Product Syngas Composition

Syngas Data	Units	Design Target	Range Low	– High
LHV Gas Production	kW	1950	1500	2100
Gas LHV	MJ/Nm³	4.9	4.7	5.2
Gas LHV	KWh/Nm³	1.36	1.31	1.44
Gas Flowrate	Nm³/h	1433	1149	1454
Gas Temperature	°C	25	25	40
Gas Pressure	(kPA)	20	15	35
Gas Composition				
H2	%	18	17	22
CO	%	18	15	20
H2 + CO	%	36	35	40
CH4	%	7	1	8
C2H4	%	0.4	0.2	0.5
C3+	%	0.3	0.1	0.4
CO2	%	13	10	15
N2	%	48	45	50
Gas Cont. After Cleanup				
Tars	mg/Nm³	20	5	40
Tar Dew Point	°C	15	10	20
Particulate	mg/Nm³	0.8	0.1	1.5
Particulate Size	micron	<1	na	na
H_2S	ppm	25	10	50

Forest Residue Biomass

Typical Pile of Forest Thinning Material

Field Equipment for Size Reduction and Hauling

Screening Equipment

Project Team

Plant Construction

Erection of Gasifier Structure

Fabrication of Lower Grate Housing

Upper Reactor with Feeder

Lower Cone Hot Face Refractory

Lower Cone Prior to Grate Installation

Modular Control Room Fabrication

Control Panel for Gas Production Plant

3D CAD and Actual Photo of Gas Production Plant

Acknowledgement: Funds for this project were provided by West Biofuels and the California Energy Commission under Grant Agreement Number: EPC-14-024

Source: West Biofuels, LLC

2017

- TC Biomass: September 19-21, 2017. The fifth annual tcbiomass event, tcbiomass2017, reflected the conference theme, “The Global Future of Bioenergy,” in every aspect of its three-day program. Attendees hailed from 16 different countries spanning four continents: Asia, Europe, North America, and South America. Oral and poster presenters echoed the diversity of the delegates, including the winners of the 2017 Student Poster Challenge, who represented universities in South Korea, the United States, and Italy. West Biofuels provided a poster board for the conference.

WESTBIOFUELS

OPERATION A 1-MWth FICFB BIOMASS GASIFIER IN CALIFORNIA

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Background and Introduction Community-scale bioenergy infrastructure can enhance the sustainable management of forested lands at high-risk of wild fire in regions of California and other parts of the world. Only a small fraction of the available forest residues in the state are currently used for energy even where sustainability could support it. In addition, the by-product biochar provides additional economic value for horticultural, agricultural, and other environmental applications. The use of smaller on-site gasification systems offers benefits by generating synthetic gas for substitution of natural gas in natural-gas devices like boilers, dryers, heaters, engine generators, etc. The project team has developed a feedstock processing and modular biomass gasification system at their facility in Norther California in attempt to convert forest residues into energy rich syngas and biochar. The system is based on the patented CircleDraft© gasification reactor (Fig.1) developed by Italian partner INSER, S.P.A. with process improvement by the West Biofuels team required for conversion of this feedstock. To address the challenges with this feedstock source and with deploying these systems in forest communities, the team:

- Evaluates processing techniques to prepare feedstock and feedstock mixtures for optimal feedstock uniformity and system performance;
- Tests the modified CircleDraft© gasification system with both hardwood and softwood forest residues to identify optimal feedstock characteristics and operating conditions;
- Determines the thermal efficiency, throughput rate, syngas energy content, tar content, tar dew point, particulates, hydrogen sulfide for the conversion system;
- Determines the biochar production rate and biochar characteristics and quality from the system;
- Assesses the results to determine the economic and environmental viability of deploying this type of system in communities looking to manage forest residues to reduce wild-fire risk.

Figure 1: The CircleDraft® Gasification System in cross-section showing gas flows and zones.

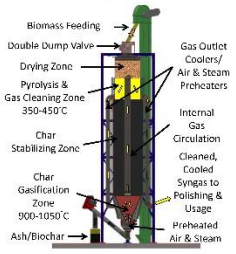

Table 1: Process unit specification

Description	Value
Fuel Type	Forest Residual Chips (hardwood/softwood)
Oxidant	Humidified Air
Fuel HHV	8,500 BTU/dry lb, (18-19 MJ/kg)
Moisture	< 25%
Ash	Max: 5%
Production Rate	40 SCF/dry lb
Syngas Heating Value	150 BTU/SCF (5588.8 KJ/SCM)
Fuel Consumption	~1000 lbs/h (454 kg/h)
Biochar Production	~125 lbs/h (56.8 kg/h) @ 10% Ash
Electric Power Output	500 kW

Figure 2: Conceptual layout of CircleDraft System

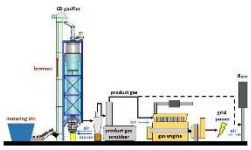

Figure 3: CircleDraft gasifier system integrated with IC-engine generator

Table 2: Test matrix for the completed gasifier testing on forest biomass

Parameter	Test #3	Test #4	Test #5	Test #6
Biomass Type	Forest, Hardwood	Forest, Hardwood	Forest, Hardwood	Forest, Hardwood
Biomass Feed Rate* [kg/h]	105	105	132	132
Air Flowrate [kg/h]	132	132	171	171
Steam Input [kg/h]	20	65	50	50
Biochar Removal Rate [kg/h]	20	30	25	25
Gasification Zone Temp. [°C]	820-1030	650-1000	>1000	>1000
Pyrolysis Zone Temp. [°C]	150-350	100-350	100-350	100-350

*Estimated from mass balance.

Table 3: Measured operating characteristics of the CircleDraft gasifier system

Gas Composition	Min	Max	Average
H_2 (vol %)	12.49%	20.28%	15.47%
CO (vol %)	23.52%	29.41%	26.59%
CH_4 (vol %)	1.47%	7.13%	3.55%
C_2H_4 (vol %)	0.00%	1.80%	0.35%
C_3+ (vol %)	0.06%	0.15%	0.10%
CO_2 (vol %)	7.39%	16.44%	10.68%
N_2 (vol %)	35.94%	46.06%	42.51%
HHV(MJ/kg)	5.31	7.78	6.29
Cold Gas Eff. (%)	57.20%	78.50%	65.20%
Biochar Production (kg/dry kg)	0.09	0.21	0.15

Figure 4. Gas composition during operation for Test #2, Loc 4 and Loc 7

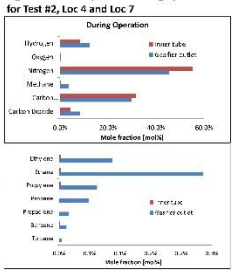

Figure 5: Syngas composition during stable testing periods, major gasses (vol%)

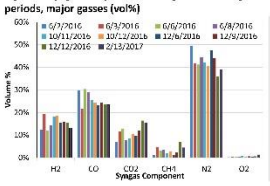

Figure 6: Syngas composition during stable testing periods, minor HC gasses (vol%)

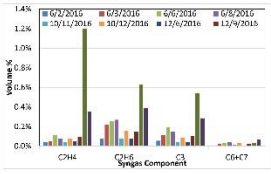

Figure 7: Raw forest feedstock tends to cause bridge inside the reactor

Figure 8: Ash melting within the gasification zone above the air nozzles

Results and Conclusion

A 2-MW thermal CircleDraft® gasifier with nominal specifications (Table 1) was constructed and tested in California for system performance evaluation on forest residue feedstock. In various test conditions (Table 2) the gasifier showed suitable major gas composition, heating value, efficiency, and biochar production (Table 3, Fig. 5) but too many higher molecular weight condensable hydrocarbons and tars (Fig. 6) for gas engine applications. The most revealing result (Fig. 4) was that the char gasification zone gas was much lower in higher hydrocarbons and tars than the final gas produced by the system. This indicated that the upper pyrolysis zone greatly increased the amount of gas contaminants instead of having a gas filtration effect, making the gas unsuitable for engine applications in spite of suitable energy quality. Since the char gasification accounts for nearly 80% of the energetic gas production, opportunities to change gas circulation within the system or the overall design changes to eliminate pyrolysis should be considered. The team learned that the removal of high molecular weight compounds from pyrolysis is crucial to generating gas from raw biomass for engine applications.

In addition, the testing also indicated that with raw forest feedstock (Fig.7) has a high propensity to bridge within the fixed bed reactor causing frequent shutdowns. Other issues included considerable amount of gas channeling within the entire system and hot-spots causing ash melting within the gasification zone (Fig.8). These effects reduced the control, performance and capacity of the system. In order to resolve the gas quality and bridging issues, the team is currently testing pre-torrefied biomass within the system. Torrefaction at a medium temperature reduces the condensable volatiles and creates a material with less bridging propensity. It replaces the char production function of the pyrolysis zone in the CircleDraft® reactor without increasing undesirable gas contaminants. Other future areas of gasification design research by the team include new reactor systems without bridging and channeling propensity and energy production technologies that do not require removal of high molecular weight volatiles.

Acknowledgement: Funds for this project were provided by West Biofuels and by the California Energy Commission under Agreement Number:EPC-24-014

Source: West Biofuels, LLC

- 12th International Conference on Computation Fluid Dynamics in the Oil & Gas Metallurgical and Process Industries. May 30 – June 1, 2017. The conference will focus on the application of Computation Fluid Dynamics (CFD) in the oil and gas industries, metal production, mineral processing, power generation, chemicals, other process industries and biomedical applications. The objective of the conference is to provide a forum to:
    - Explore the breadth and application of CFD modelling in the oil and gas, metallurgical and process industries
    - Identify and report on emerging CFD methods, capabilities and applications
    - Identify limitations in the existing CFD capabilities and validation sources

12th International Conference on CFD in Oil & Gas, Metallurgical and Process Industries
SINTEF, Trondheim, Norway
May 30th – June 1st 2017

CFD 2017

CFD MODELING OF A COMMERICAL-SIZE CIRCLE-DRAFT BIOMASS GASIFIER

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ABSTRACT

This work was focused on a commercial-size (2MWth.) circle-draft biomass gasifier. In this work a three-dimensional transient CFD (computational fluid dynamics) model was established to simulate the circle-draft biomass gasifier. The MP-PIC (multiphase particle-in-cell) method was applied to simulate multiphase reactive flows in the gasifier. In the MP-PIC method the large-eddy simulation (LES) was used to simulate the gas phase while the particle acceleration equation was applied to describe the particulate phase. The mass and energy transport equations were coupled with the momentum equation to simulate mass and energy transfer in the circle-draft gasifier. The heterogeneous solid-gas and homogeneous gas-phase reaction kinetics were integrated with the transport equations to simulate biomass drying, gasification, combustion, and other gas-phase reactions. The simulation results were compared with experimental data to validate the CFD model. The CFD model predicted gas species distribution, reaction zone temperatures, and producer gas composition in the circle-draft biomass gasifier.

NOMENCLATURE

Greek Symbols

α	volume fraction
ρ	density
τ	stress tensor

L Symbols

A_p	particle surface area
C_d	drag model coefficient
C_v	specific heat capacity
$C_{p,n}$	solid species n conentration
D	drag function
f	particle size distribution function
F	drag force
g	standard gravity
k_d	solid thermal conductivity
m_p	particle mass
$Mw_{p,n}$	molecular weight of solid species n
Nu	Nusselt number
u	velocity
p	pressure
P_s	model constant
T	temperature
V	computational cell volume

Subscripts

cp	close pack condition
g	gas phase
n	solid species
lam	laminar flows
t	turbulence

INTRODUCTION

Fossil fuels are still the primary energy sources in the world. Since natural resources are limited, finding alternative energy sources becomes necessary. Biomass is abundantly available in the nature and can be an alternative to fossil fuels. Additionally, biomass is a renewable energy source. Utilizing bio-energy from biomass doesn't increase CO_2 emission, which is beneficial to environmental protection (Huang, Wu, Wu and Gao 2017). Bio-energy can be released through thermal chemical processes such as biomass pyrolysis, gasification, and combustion. Among them, biomass gasification is a promising technology. During the process, biomass is utilized to generate syngas, which can be further applied to generate chemicals and electricity (Ismail and El-Salam 2017).

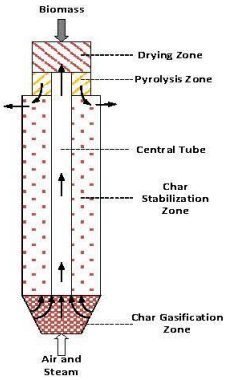

Figure 1: A circle-draft (2MWth.) biomass gasifier

In this work a circle-draft biomass gasifier was studied. As shown in Figure 1, biomass is fed at the top while air and steam are fed at the bottom of the gasifier. After biomass is fed to the gasifier, it is dried in the drying zone and then falls down to the pyrolysis zone where biomass is decomposed in to char and volatile gases. Char particles continue to fall down and go through the stabilization zone to reach the char gasification zone where char reacts with air and steam to generate syngas. The generated syngas penetrates through the solid bed and flow upwards through a central tube to reach the upper pyrolysis zone. Biomass is heated in the pyrolysis zone while the hot syngas is flowing through the zone. Finally, the syngas is extracted through 4 outlets at the side of the gasifier.

In this work a three-dimensional CFD (computational fluid dynamics) model was developed to simulate the circle-draft biomass gasifier. In this model the MP-PIC (Multiphase Particle-In-Cell) method was applied to simulate gas-solid flows in the circle-draft biomass gasifier. The heterogeneous and homogeneous reaction kinetics were integrated with the momentum, mass, and energy transport equations to predict producer gas distribution and reactor temperature profile in the circle-draft biomass gasifier.

MODEL DESCRIPTION

The MP-PIC method is an Eulerian-Lagrangian method. In this model the gas phase is described with the large eddy simulation (LES) and the particulate phase is calculated with the particle acceleration equation (O'Rourke and Snider 2014). The momentum transport equation was coupled with the mass and energy transport equations to simulate mass and energy transfer in the circle-draft biomass gasifier.

Governing Equations

The continuity and momentum equations for the gas phase are shown as follows:

$$\frac{\partial(\alpha_g\rho_g)}{\partial t} + \nabla\cdot\left(\alpha_g\rho_g u_g\right) = \delta m_p \tag{1}$$

$$\frac{\partial(\alpha_g\rho_g u_g)}{\partial t} + \nabla\cdot\left(\alpha_g\rho_g u_g u_g\right) = -\nabla p + F + \alpha_g\rho_g g + \nabla\cdot\tau \tag{2}$$

$$\tau = \mu\left(\frac{\partial u_{g,i}}{\partial x_j} + \frac{\partial u_{g,j}}{\partial x_i}\right) - \frac{2}{3}\mu\delta_{ij}\frac{\partial u_k}{\partial x_k} \tag{3}$$

$$\mu = \mu_{lam} + \mu_{eddy} \tag{4}$$

μ_{eddy} is calculated by the sub-grid scale (SGS) model (Smagorinsky 1963) as shown below:

$$\mu_t = \frac{1}{2}C\rho_g\Delta^2\sqrt{\left(\frac{\partial u_{g,i}}{\partial x_j} + \frac{\partial u_{g,j}}{\partial x_i}\right)^2} \tag{5}$$

$$\Delta = \sqrt[3]{V} \tag{6}$$

The particle acceleration equation is applied to calculate the particle velocity as follows (O'Rourke and Snider 2010):

$$\frac{du_p}{dt} = D_p\left(u_g - u_p\right) - \frac{\nabla p}{\rho_p} - \frac{\nabla\tau_p}{\rho_p\alpha_p} + g + \frac{\overline{u_p} - u_p}{2\tau_D} \tag{7}$$

The solid stress tensor, τ_D, is modeled by the following equation:

$$\tau_p = \frac{10P_S\alpha_p{}^{\beta}}{max[(\alpha_{cp}-\alpha_p),\varepsilon(1-\alpha_p)]} \tag{8}$$

The solid volume fraction, α_p, is calculated as follows:

$$\alpha_p = \iiint f\frac{m_p}{\rho_p}dm_p du_p dT_p \tag{9}$$

The interphase force between the gas and particle phase is given by:

$$F = \iiint f\left\{m_p\left[D\left(u_g - u_p\right) - \frac{\nabla p}{\rho_p}\right] + u_p\frac{dm_p}{dt}\right\}dm_p du_p dT_p \tag{10}$$

The drag function of D is described as follows (Gidaspow 1994):

$$D_{p1} = \frac{6}{8}C_d\frac{\rho_g|u_g - u_p|}{\rho_p d_p} \tag{11}$$

$$C_d = \begin{cases} \frac{24\alpha_g{}^{-2.65}}{Re}, Re < 0.5 \\ \frac{24\alpha_g{}^{-2.65}}{Re}(1 + 0.15Re^{0.687}),\ 0.5 \le Re \le 1000 \\ 0.44\alpha_g{}^{-2.65},\ Re > 1000 \end{cases} \tag{12}$$

$$D_{p2} = 0.5\left(\frac{180\alpha_p}{\alpha_g Re} + 2\right)\frac{2\rho_g|u_g - u_g|}{d_p\rho_p} \tag{13}$$

$$D_p = \begin{cases} D_{p1} & \alpha_p < 0.75\alpha_{cp} \\ \left(D_{p2} - D_{p1}\right)\left(\frac{\alpha_p - 0.75\alpha_{cp}}{0.1\alpha_{cp}}\right) + D_{p1} & 0.85\alpha_{cp} \ge \alpha_p \ge 0.75\alpha_{cp} \\ D_{p2} & \alpha_p > 0.85\alpha_{cp} \end{cases} \tag{14}$$

The mass and energy transport equations for the particulate phase are (Snider, Clark and O'Rourke 2011):

$$\delta m_p = -\iiint f\frac{dm_p}{dt}dm_p du_p dT_p \tag{15}$$

$$\frac{dm_p}{dt} = \sum_{i=1}^{N}\frac{dm_{p,n}}{dt} \tag{16}$$

$$\frac{dm_{p,n}}{dt} = \frac{\alpha_g Mw_{p,n}}{\rho_p\alpha_p}m_p\frac{dC_{p,n}}{dt} \tag{17}$$

$$C_V\frac{dT_p}{dt} = \frac{1}{m_p}\frac{k_d Nu}{d_p}A_p(T_g - T_p) \tag{18}$$

Reaction Kinetics

In the circle-draft gasifier, biomass is fed at the top and then drops into the drying zone where moisture is released from biomass. Dry biomass continues to fall into the pyrolysis zone. Volatiles are released and char is generated from biomass pyrolysis. Char particles pass through the stabilization zone and reach gasification zone. Char particles react with air and steam injected from the bottom to generate syngas. The residual char and ash fall down into the bottom region where are removed from the gasifier with an ash auger. In this model heterogeneous reactions including biomass drying, pyrolysis, partial combustion of primary char, char and CO_2 reaction, char and steam reaction, and methane formation are included. The homogeneous reactions such as water gas shift reaction and gas oxidation reactions are also considered in this model.

Heterogeneous reactions (Walker Jr, Rusinko Jr and Austin 1959, Yu, et al. 2011, Xu and Qiao 2012):

$$\text{Moisture in Biomass}_{(s)} \rightarrow H_2O_{(g)} \qquad \text{(R-1)}$$

$$r_1 = 5.13 \times 10^{10} \exp\left(\frac{-10585}{T_p}\right) m_{biomass}$$

$$\text{Biomass} \rightarrow \text{Volatiles}_1(CO, CO_2, H_2, CH_4, C_2H_4, C_2H_6) + \text{Primary char} + \text{Tar} \qquad \text{(R-2)}$$

$$r_2 = 1.49 \times 10^5 \exp\left(\frac{-1340}{T_p}\right) m_{biomass}$$

$$\text{Primary Char} + n_1O_2 \rightarrow n_2CO + n_3CO_2 + n_4H_2 + n_5H_2O + \text{Char} \qquad \text{(R-3)}$$

$$r_3 = 8.68 \times 10^6 m_{prim.char} T_p \exp\left(\frac{-29160}{T_p}\right)[O_2]$$

The primary char generated in biomass pyrolysis was defined as $CH_{1.286}O_{0.4585}$ according to experimental data. To simplify the model, char generated in the partial combustion of primary char is assumed to be pure carbon. Tar generated in biomass pyrolysis is defined as $CH_{1.331}O_{0.6979}$ (Ingram, et al. 2008).

$$C + CO_2 \leftrightarrow 2CO \qquad \text{(R-4)}$$

$$r_{4f} = 1.272 m_c T_p \exp\left(\frac{-22645}{T_p}\right)[CO_2]$$

$$r_{4r} = 1.044 \times 10^{-4} m_c T_p^2 \exp\left(\frac{-2363}{T_p} - 20.92\right)[CO]^2$$

$$C + H_2O \leftrightarrow CO + H_2 \qquad \text{(R-5)}$$

$$r_{5f} = 1.088 m_c T_p \exp\left(\frac{-22645}{T_p}\right)[H_2O]$$

$$r_{5r} = 1.044 \times 10^{-4} m_c T_p^2 \exp\left(\frac{-6319}{T_p} - 17.29\right)[H_2][CO]$$

$$C + 2H_2 \rightarrow CH_4 \qquad \text{(R-6)}$$

$$r_6 = 1.18 \times 10^{-5} m_c T \exp\left(\frac{-17921}{T_p}\right)[H_2]$$

Homogeneous reactions (Padban and Becher 2005, Gómez-Barea and Leckner 2010, Lu and Wang 2013):

$$CO + H_2O \rightarrow CO_2 + H_2 \qquad \text{(R-7)}$$

$$r_7 = 2.75 \exp\left(\frac{-10079}{T_g}\right)[CO][H_2O]$$

$$CO + 0.5O_2 \rightarrow CO_2 \qquad \text{(R-8)}$$

$$r_8 = 1.00 \times 10^{10} \exp\left(\frac{-15155}{T_g}\right)[CO][O_2]^2$$

$$H_2 + 0.5O_2 \rightarrow H_2O \qquad \text{(R-9)}$$

$$r_9 = 2.2 \times 10^9 \exp\left(\frac{-13110}{T_g}\right)[H_2][O_2]^2$$

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \qquad \text{(R-10)}$$

$$r_{10} = 2.8 \times 10^9 \exp\left(\frac{-24417}{T_g}\right)[CH_4][O_2]^2$$

Simulation Setup

The CFD model was built in Barracuda Virtual Reactor® using the MP-PIC method to simulate a 2MWth circle-draft biomass gasifier at Woodland Biomass Research Center, Woodland, California, as shown in Figure 2. The height of the gasifier is 10.4 meters and the diameter of the gasifier is 1.7 meters.

The boundary settings of the circle-draft biomass gasifier are shown in Figure 3. Biomass feeding points are defined at the top, 4 gas outlets are set at the side, and steam & air injections are defined at the bottom of the gasifier.

A central tube is built in the center of the gasifier. Note that the structure of the central tube is in the shape of a rectangular box for simplicity, instead of the original cylindrical-tube shape. The total volume of the structure is still the same as that of the original central tube, which ensures that the predicted flow pattern in the gasifier is not dramatically affected by the shape change of the central tube. In the software of Barracuda VR®, geometries are meshed by orthogonal grids. For round-shaped geometries, more gridlines and cells are needed to capture necessary geometry details. In comparison, geometries with straight edges require less gridlines and computational cells. Therefore, in this work a rectangular-box channel is built to simplify the geometry to achieve better computation efficiency.

The ultimate analysis data of biomass used in experiments are shown in Table 1 and the model settings of base case are listed in Table 2.

Figure 2: A 2MWth circle-draft biomass gasifier

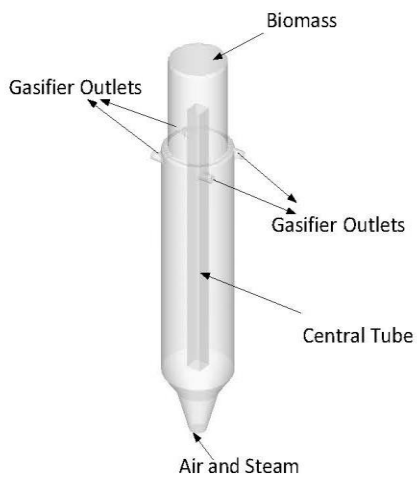

Figure 3: Boundary settings of the circle-draft gasifier

Table 1: Ultimate analysis of biomass feedstock

Elements	wt %
Moisture	17.23
C	43.16
H	5.06
O	33.26
N	0.10
Ash	1.19

Table 2: Base case settings

Description	Value
Biomass particle diameter (mm)	5.64
Biomass density (kg/m^3)	662.85
Initial solid packing	0.42
Outlet pressure (atm, abs.)	1
Biomass feeding rate (kg/h)	101.42
Air feeding rate (kg/h)	77.44

The model was solved with the control volume method. A computational grid with 111,537 grid was applied for the CFD model. A grid resolution study was implemented by using three computational grids with 88,750, 111,537, and 168,175 cells. The difference of the simulation results between the three cases are less than 5%. Considering relative low computational cost and acceptable model accuracy, the grid with 111,537 cells was selected for the base case. The simulation time was set as 1000 seconds to reach the steady-state. The size of time step is in the range of 10^{-3} to 10^{-5} seconds and is automatically controlled by the Courant-Friedrichs-Lewy (CFL) scheme(Courant, Friedrichs and Lewy 1967) to achieve a converged solution. The model was computed using the GPU-accelerated computing technology on a computer with an Intel® i7 CPU @3.50 GHz and a GeForce GTX TITAN graphics card. The 1000-s simulation took about 5 days to be completed.

RESULTS

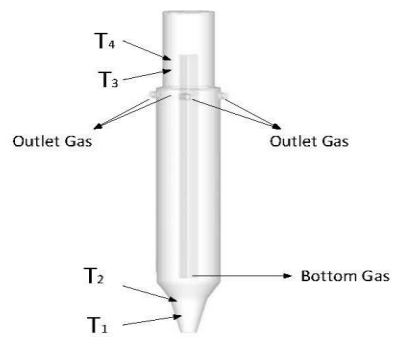

Figure 4: Temperature sensor and gas sampling locations

Figure 4 shows the locations of temperature sensors and producer gas sampling points. The temperatures of T_1, T_2, T_3, and T_4 were measured for char gasification and pyrolysis zones at the heights of 0.95, 1.44, 8.68, and 9.17 meters, respectively. Producer gas was sampled from the bottom entry point of the central tube and 4 gas outlets as the bottom producer gas and the final producer gas output, respectively.

In Figure 5, the predicted producer gas composition in the bottom region is compared with experimental data. It is observed that the gas composition prediction in the bottom region is consistent with experiment measurement.

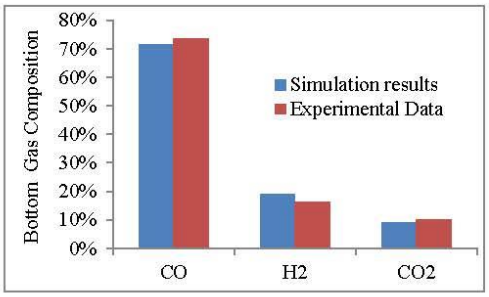

Figure 5: Comparison of bottom producer gas

The predicted outlet gas composition is also compared with experimental data. As seen in Figure 6, the difference between the simulation results and experimental data is averagely less than 3%.

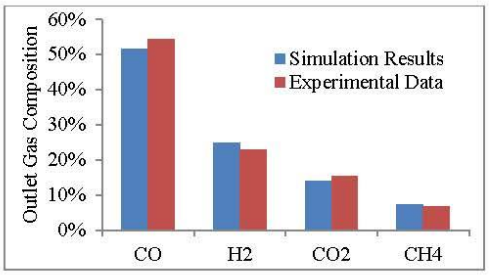

Figure 6: Comparison of outlet producer gas

Figure 7 demonstrates the comparison of the gasifier temperatures in biomass pyrolysis and char gasification zones. As seen in the figure, the temperature predictions agree well with temperature measurements.

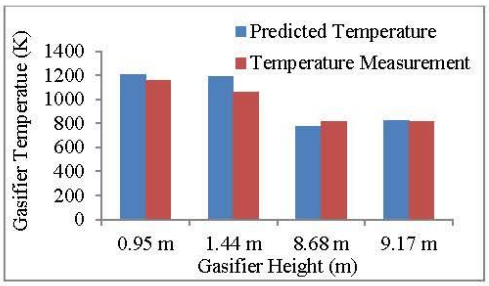

Figure 7: Comparison of gasifier temperature

Figure 8 demonstrates the transient distribution of CO in the circle-draft gasifier. As shown in the figure, CO is generated in the bottom region due to gasification and then flows through the solid bed to reach the central tube. The gas rises through the central tube to the pyrolysis zone in the upper region of the gasifier, where more CO is generated from biomass pyrolysis. Two streams of CO from the bottom and upper regions merges and accumulates in the upper region of the gasifier. Meanwhile, the rest of CO generated in the bottom region gradually penetrates through the annular region surrounding the central tube and reaches the upper region. All of CO from the bottom and upper regions is eventually extracted from 4 gas outlets at the side of the gasifier.

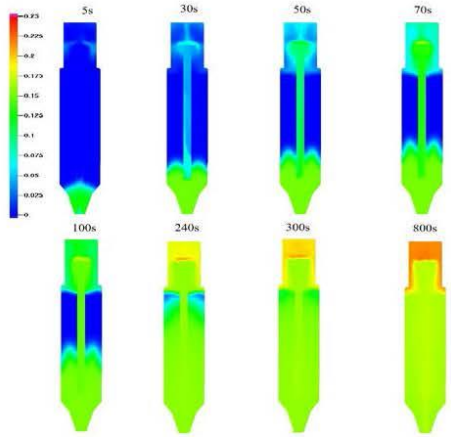

Figure 8: Transient CO distribution

Figure 9 shows transient tar distribution in the circle-draft gasifier. It is observed that tar is only generated in the pyrolysis zone which is in the upper region of the gasifier. Tar gradually accumulates in the region and finally leaves the gasifier through the gas outlets. As predicted in the model, since tar is generated in the upper region and is extracted together with other gases from the gas outlets, tar concentration in the final gas output is expectedly high, which matches our observations in the experiment.

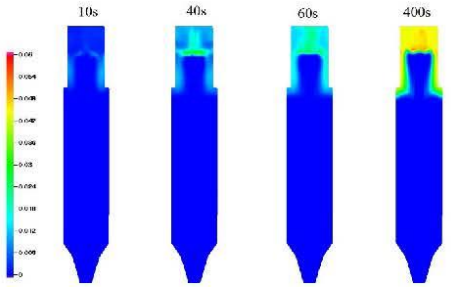

Figure 9: Transient tar distribution

The distributions of CO, H_2, CO_2, and Tar in the steady-state are shown in Figure 10. As seen in the figure, CO, H_2, and CO_2 are generated in both of char gasification and biomass pyrolysis zones. CO and H_2 are concentrated in the central region, which is mainly due to producer gas production from water gas shift reaction. On the other hand, tar is only generated from the top region and is eventually extracted together with other gases through the gas outlets.

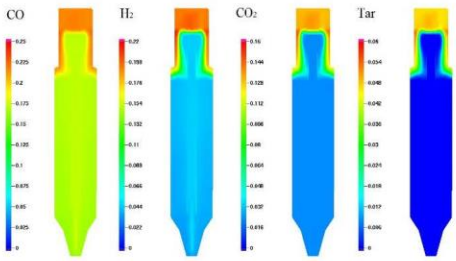

Figure 10: Steady-state producer gas composition

CONCLUSION

In this paper a transient three-dimensional CFD model was built to simulate a circle-draft biomass gasifier. The MP-PIC method was used to simulate gas-particle flows in the gasifier. The CFD model was applied to predict flow pattern, producer gas distribution, and reactor temperature profiles in the circle-draft biomass gasifier. The predicted gas composition and reactor temperatures were compared with experimental data and good agreement between the simulation results and experimental data was achieved.

ACKNOWLEDGEMENT

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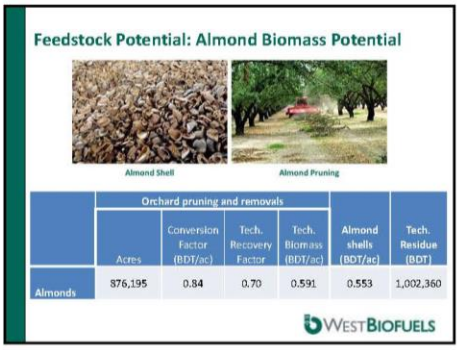
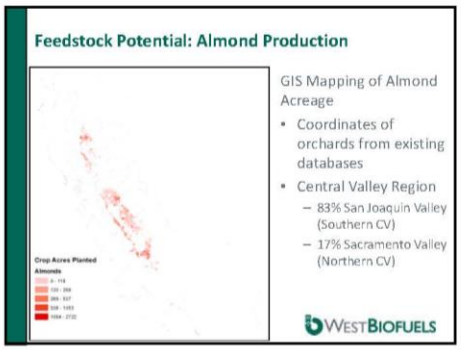
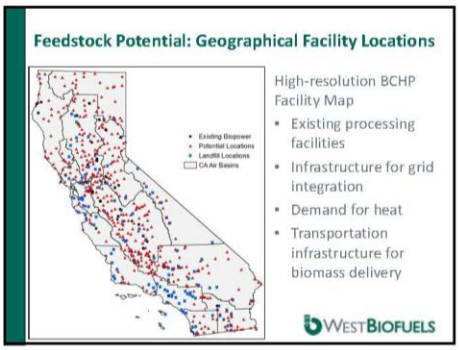
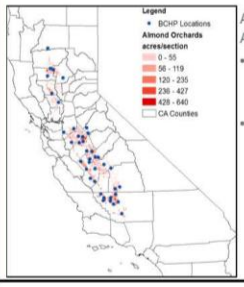
- European Biomass Conference and Exhibition (EUBCE): June 12-15, 2017. The EUBCE represents one of the key events on both a European and global scale for companies and professionals operating at the top end of the biomass and bioenergy sector. Held in a different city each year for over 30 years, the EUBCE has successfully combined a highly renowned international scientific conference with an ever-growing industry exhibition, thus rightfully earning its place as one of the world's most influential biomass sector events. West Biofuels presented at the conference.







Feedstock Potential: Geographical Facility Locations



Analysis of Potential Almond BCHP Sites

- Optimized for biomass hauling distance: Average = 26.7 km
- 41 locations found in Central Valley to support 3MWe BCHP facilities

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Property	Units	Almond Shells	Almond Prunings	Almond Hulls	Almond Sticks	Walnut Shells	Redwood Mill Byp.	Redwood Bark	Urban Wood Waste (Fiber)	Urban Wood Waste (Bagasse)
Moisture	wt% (a.r.)	6.4	9.4	12.2	9.1	8.0	32.0	55.0	10.0	13.7
Ash	wt% (dry)	4.0	2.2	8.6	4.6	1.3	0.2	2.5	3.9	0.9
Volatiles	wt% (dry)	74.5	76.5	71.2	75.0	77.0	80.5	68.9	77.8	79.3
Fixed carbon	wt% (dry)	21.5	21.3	20.2	20.4	22.0	19.3	28.6	18.3	19.9
Calorific Value	MJ/kg (HHV)	17.8	18.6	17.7	19.4	20.1	19.4	19.3	18.9	19.2
Carbon	wt% (dry)	48.1	50.0	45.2	48.6	51.9	53.0	52.9	50.3	51.3
Hydrogen	wt% (dry)	5.8	5.8	5.5	5.6	5.9	6.0	5.5	5.9	6.0
Nitrogen	wt% (dry)	0.87	0.47	0.99	0.90	0.27	0.05	0.17	0.79	0.19
Sulfur	wt% (dry)	0.027	0.029			0.020	<0.01	0.011	0.018	<0.01
Oxygen	wt% (dry)	40.2	41.8			40.2	40.7	40.0	38.7	41.5
Arsenic	ppmw (dry)	0.85	1.53							
Mercury	ppmw (dry)	<0.01	0.02							
Selenium	ppmw (dry)	<0.05	<0.05							
Ash-Melting Temperature	°C	900[2]	1318[1]	900[2]	900[2]	780[1]	1202[1]	1185[1]	1114[1]	1071[1]

Description of the items marked with footnotes:
[1]Ash fusion determined by ASTM D1857-04. The lower "Initial Temperature" of reducing or oxidizing atmosphere is shown
[2]Ash fusibility determined by fuel pellet test (Jenkins et al., 1996a, b). The temperature at which light sintering is detected is shown

Green, University of California, Davis

Feedstock Potential: Properties of Material

Quantity Measured	Units	Almond Shells	Almond Prunings	Almond Hulls	Almond Sticks
SiO2	wt% (of ash)	8.27	9.93	9.04	8.43
Al2O3	wt% (of ash)	16.14	2.91	2.06	2.40
TiO2	wt% (of ash)	0.15	0.16	0.08	0.11
Fe2O3	wt% (of ash)	0.89	1.61	0.58	1.04
CaO	wt% (of ash)	5.38	27.70	3.77	18.36
MgO	wt% (of ash)	1.34	3.42	1.96	3.71
Na2O	wt% (of ash)	1.72	5.78	0.93	1.07
K2O	wt% (of ash)	45.90	10.40	41.79	8.41
P2O5	wt% (of ash)	3.11	6.00	2.46	2.91
SO3	wt% (of ash)	0.40	1.46		
Cl	wt% (of ash)	0.51	4.62	0.39	0.05
CO2	wt% (of ash)	15.49	11.19	0.00	5.32
Ba	ppmw (of ash)	648	270	78	188
Cd	ppmw (of ash)	4	9	<0.1	0.4
Cr	ppmw (of ash)	21.7	281	14.4	44.2
Pb	ppmw (of ash)	<10	33	15	5
Ag	ppmw (of ash)	17	36	<1	<1

Data, courtesy of California Biomass Collaborative

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Feedstock Potential: Pre-Processing Steps

- Feedstock Screening and Re-Grinding

- Feedstock Drying
  - Not necessary
  - Moisture was less than 20% wb in all field samples
  - Focus on keeping material dry in storage

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Task 3: Configure and Test Gasifier System

Test Number	Test Descriptor	Testing Type*	Start Date	End Date
1	October 2015 Run	Raw Gas	10/7/2015	10/7/2015
2	November 2015 Run	Raw Gas	11/11/2015	11/12/2015
3	June 2016 Run	Conditioned Gas	6/2/2016	6/9/2016
4	October 2016 Run	Conditioned Gas	10/11/2016	10/12/2016
5	December 2016 Run	Conditioned Gas	12/6/2016	12/12/2016
6	February 2017 Run	Conditioned Gas	2/13/2017	2/14/2017
7	TBD 2017	Full Capacity, Conditioned Gas	TBD	TBD
8	TBD 2017	Conditioned Gas, Engine Tests	TBD	TBD

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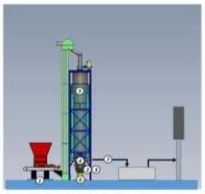
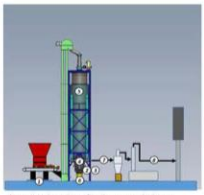
Task 3: Configure and Test Gasifier System



Sampling locations for the first phase raw gas testing.



Sampling locations for the second phase conditioned gas testing.

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Task 3: Configure and Test Gasifier System

Parameter	Units	Test #3	Test #4	Test #5	Test #6
Biomass Type		Hardwood	Hardwood	Hardwood	Hardwood
Biomass Feed Rate*	(kg/hr)	105	105	132	132
Air Flowrate	(kg/hr)	132	132	171	171
Steam Input	(kg/hr)	20	65	50	50
Biochar Removal Rate	(kg/hr)	20	30	25	25
Gasification Zone Temp.	(°C)	820-1030	650-1000	>1000	>1000
Pyrolysis Zone Temp.	(°C)	150-350	100-350	100-350	100-350

Test Matrix for the currently completed gasifier testing

Parameter	Units	Test #7	Test #8	Test #9	Test #10
Biomass Type		Hardwood	Hardwood	Softwood	Softwood
Biomass Feed Rate*	(kg/hr)	400	400	400	400
Air Flowrate	(kg/hr)	570	570	570	570
Steam Input	(kg/hr)	147	74	147	74
Biochar Removal Rate	(kg/hr)	60	60	60	60
Gasification Zone Temp.*	(°C)	950	1000	950	1000
Pyrolysis Zone Temp.	(°C)	350	350	350	350

Test Matrix for the full capacity gasifier testing to be completed

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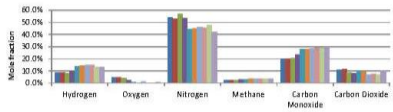
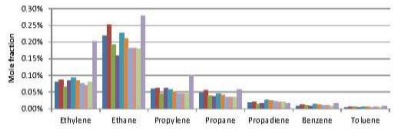
Task 3: Configure and Test Gasifier System





Tests from June Run

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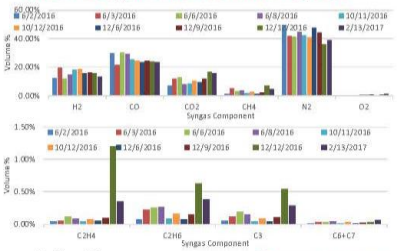
Task 3: Configure and Test Gasifier System



Tests from All Runs

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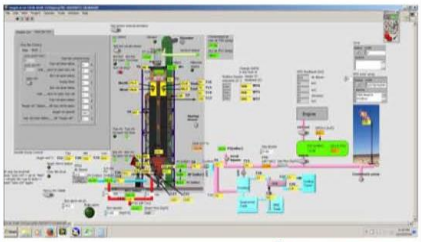
Task 3: Configure and Test Gasifier System

Control System - 10/12/2016 Run



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Feeder System Improvements:

1st generation: Airlock valve

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2nd Generation: Plug screw feeder

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3rd generation: Double Dump Feeder

- Top: 12 Inches
- Bot: 18 Inches
- Vol/fill: 4.5 CF
- Mass/fill: 67.5 lbs/fill (@ 15 lbs/cfm)
- Fill cycle: 136 seconds
- Capacity: 1800 lbs/hr

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4th generation: Roto-Valve Double Dump with Rake

- Top: 10 Inches
- Bottom: 12 Inches
- Vol/fill: 3.5 CF
- Mass/fill: 53 lbs/fill (@15 lbs/cfm)
- Fill cycle: 72 seconds
- Capacity: 2700 lbs/hr

Biochar/ash removal system

1st generation: grate system

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2nd generation: Char auger removal system

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Steam Injection system

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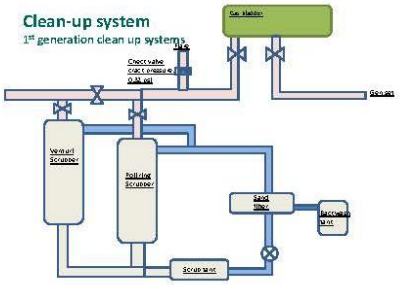
Clean-up system

1st generation clean up systems



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1st generation clean-up system:
H2O venturi scrubber -> poll ring scrubber -> segmental tank -> sand filter

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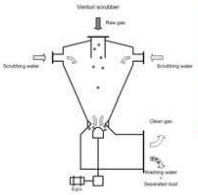
Venturi scrubber



Pall rings

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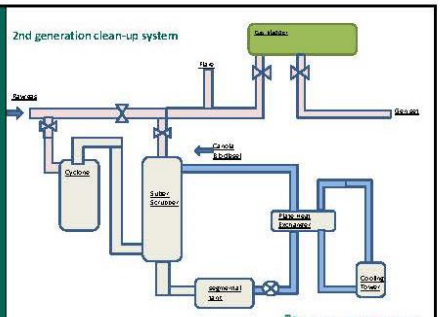
2nd generation clean-up system



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2nd generation Clean-up system
Canola biodiesel Sulzer scrubber system

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Sulzer scrubber media

Distributor

Scrubbing media

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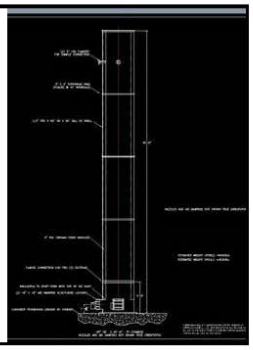
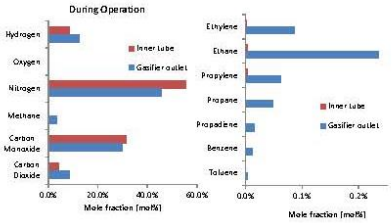
Flare System

1st generation system:
Open flare with underground gas piping

2nd generation system:
(to be installed)
Enclosed TO system with aboveground insulated gas pipe



Task 3: Configure and Test Gasifier System



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Task 3: Configure and Test Gasifier System

Gas Composition	Min	Max	Average
H_2 (vol %)	12.49%	20.28%	15.47%
CO (vol %)	23.52%	29.41%	26.59%
CH_4 (vol %)	1.47%	7.13%	3.55%
C_2H_4 (vol %)	0.00%	1.80%	0.35%
C_2+ (vol %)	0.06%	0.15%	0.10%
CO_2 (vol %)	7.39%	16.44%	10.88%
N_2 (vol%)	35.94%	46.06%	42.51%
HHV(MJ/kg)	5.31	7.78	6.29
Cold Gas Eff. (%)	57.20%	78.50%	65.20%
Syngas Productivity (kWh/dry kg)	3.05	3.97	3.51
Biochar Productivity (kg/dry kg)	0.09	0.21	0.15
Air Required (kg air/kg syngas)	0.50	0.71	0.61
Steam to Biomass Ratio	0.08	0.30	0.20

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Task 3: Configure and Test Gasifier System

Objective	Original Target	Current Testing Results	To Be Completed
Thermal Efficiency:	>70%	63-77%	Confirm at full capacity
Throughput Rate:	≥ 900 dry lb/hr	140-620 dry lb/hr	Install new TO to improve throughput
Syngas Energy Content:	≥ 150 Btu per ft³	168-210 Btu per ft³	Confirm at full capacity
Tar Content:	< 20 mg per Nm³	20 to 500 mg per Nm3	Confirm at full capacity Pyrolysis gas reduction
Tar Dew Point:	< 15°C	Method Implementation	Confirm at full capacity
Particulates:	< 5 mg per Nm³ and less than 1 micron	< 5 mg per Nm3	Confirm at full capacity
Hydrogen Sulfide:	< 50 ppm	13-40 ppm	Confirm at full capacity
Biochar Production:	≥ 72 dry lb/hr	20-75 dry lb/hr	Confirm at full capacity
Biochar Quality:	IBI Biochar Standards	Samples being tested	Confirm at full capacity

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R&D Challenges

- Gas Handling & Flare System
  - Not equipped to meet 100% capacity
  - Acquiring thermal oxidizer, needed during Task 4 engine testing
- Caterpillar's R&D Team
  - Over the last two years, Caterpillar's R&D team has been limited with their ability to research syngas engines
  - Working with Holt (local Cat Distributer) to identify appropriate test engines

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Budget Summary – Through Q3*

Category	Total Allocated	Expenditures	Remaining
Direct Labor	$639,913	$353,331.93 (55.2%)	$286,580.77 (44.8%)
Fringe Benefits	$150,379	$65,575.84 (43.6%)	$84,803.65 (56.4%)
Travel	$0	$0	$0
Equipment	$250,000	$65,296.04 (26.1%)	$184,703.96 (73.9%)
Materials/Misc.	$113,000	$39,728.49 (35.2%)	$73,271.51 (64.8%)
Subcontractors	$582,134	$252,737.45 (43.4%)	$329,396.55 (56.6%)
Indirect Costs	$264,574	$125,134.75 (47.3%)	$139,439.07 (52.7%)
Profit	$0	$0	$0
Subtotal	**$2,000,000**	**$901,804.49 (45.1%)**	**$1,098,195.51 (54.9%)**
Match	$539,914	$497,776.46 (92.2%)	$42,137.54 (7.8%)
Total	**$2,539,914**	**$1,399,581 (55.1%)**	**$1,140,333 (44.9%)**

* Pending Invoice Approval

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Proposed New Schedule

- Task 4 Engine-Generator Performance Report Draft from 3/1/2017 to 9/1/2017
- Task 4 Engine-Generator Performance Report Final from 6/1/2017 to 10/1/2017
- Task 7 Final Project Fact Sheet Draft from 3/1/2017 to 9/1/2017
- Task 7 Final Project Fact Sheet Final from 4/3/2017 to 10/1/2017

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Proposed New Schedule

- Task 7 Technology/Knowledge Transfer Report Draft from 3/1/2017 to 9/1/2017
- Task 7 Technology/Knowledge Transfer Report Final from 4/3/2017 to 10/1/2017
- Task 8 Production Readiness Plan Draft from 3/1/2017 to 9/1/2017
- Task 8 Production Readiness Plan Final from 4/3/2017 to 10/1/2017

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Proposed New Schedule

- Task 1 Final Report Draft from 6/1/2017 to 10/15/2017
- Task 1 Final Report Final from 9/15/2017 to 12/15/2017

Within the 3/31/18 Contract Date

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Thank You

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Chief Operating Officer

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Critical Project Review Meetings

The project had one critical project review (CPR), which was conducted on March 8, 2017. The CPR presentation was provided to the Energy Commission as part of the CPR meeting.

Technology Presentations to Community and Industry

Date	Participating Organizations	Location
March 3, 2015	Mendocino Forest Products	Woodland, CA
July 8, 2015	Assemblyman Brian Dahle, California Assembly	Woodland, CA
August 20, 2015	California Energy Commission	Woodland, CA
October 21, 2015	US Forest Service Region 5, TSS Consultants, Charborn, The Watershed Center, All Power Labs, California Energy Commission, CalFIRE	Woodland, CA
October 22, 2015	Nevada County Fire Safe Council	Nevada City, CA
December 4, 2015	Hat Creek Construction & Materials and Tubit Enterprises	Woodland, CA
December 16, 2015	Calaveras Healthy Impacts Products Solutions (CHIPS)	Woodland, CA
January 14, 2016	Senator Ben Allen, California Senate	Woodland, CA
January 28, 2016	Western Placer Waste Management Authority	Woodland, CA
February 1, 2016	Caterpillar and Holt of California	Woodland, CA
March 20, 2016	Governor's Office of Planning and Research	Woodland, CA
May 12, 2016	Woodland Rotary Club	Woodland, CA
May 17, 2016	San Joaquin Valley Air Pollution Control District, Western Ag Processors Association	Fresno, CA
May 20, 2016	Western Placer Waste Management Authority	Roseville, CA
June 1, 2016	Western Ag Processors Association, San Joaquin Valley Air Pollution Control District	Fresno, CA
September 7, 2016	USDA Agricultural Air Quality Task Force	Woodland, CA
September 13, 2016	Delta Diablo Sanitation District	Woodland, CA
September 16, 2016	Prima Noce	Linden, CA
April 11, 2017	Yolo County Landfill	Woodland, CA
April 11, 2017	California Energy Commission	Woodland, CA
April 14, 2017	Dalian DeeTop Industry Group (China)	Woodland, CA
May 31, 2017	12th International Confreence on CFD in Oil & Gas, Metallurgical and Process Industries	Trondheim, Norway
June 6, 2017	Yolo County Board of Supervisors	Woodland, CA
June 16, 2017	Western Agricultural Processors Association Annual Meeting	Monterey, CA
June 26, 2017	Germany-California Symposium hosted by the German American Chamber of Commerce	Sacramento, CA
June 29, 2017	Wolfgang Hillen Summer School collaboration of UC Davis and Bavaria California Technology Center, 17 students participated	Woodland, CA
September 14, 2017	TransVision (Japan)	Woodland, CA
September 22, 2015	Sonoma Pacific Company	Sonoma, CA
November 7, 2017	Central Valley Agricultural Summit hosted by San Joaquin Valley Air Pollution Control District	Parlier, CA
November 8, 2017	DTE Energy	Woodland, CA
November 9, 2017	University of New Hampshire	Woodland, CA
November 14, 2017	Western States Statewide Wood Energy Team (SWET) Regional Forum hosted by the California SWET	Fresno, CA
November 28, 2017	CarboCulture	Woodland, CA
December 6, 2017	The Wonderful Company	Woodland, CA

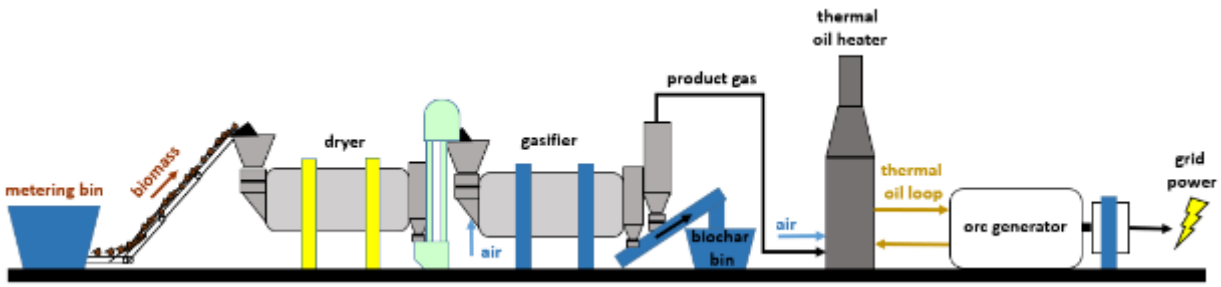
CHAPTER 8:
Production Readiness Plan

The Production Readiness Plan evaluates ability for the gasification and bio-energy production technology to scale as it is implemented on a commercial basis. The Production Readiness Plan specifically analyzes the supply chain to better understand potential constraints that will be realized as production scales.

Critical Production Processes

The research identified that system 4: Rotary Gasification System as the most economically-viable system developed in this project. Therefore, the production readiness plan is based on this modular biomass gasification system. The rotary gasification system includes four main components: dryer, gasifier, thermal oil heater, and ORC generator.

Figure 133: System 4: Rotary Gasification System



Source: West Biofuels, LLC

The West Biofuels has evaluated the production readiness of these four major subcomponents.

Dryer

The dryer is designed to utilize waste heat generated by the thermal oil heater. This heat is captured and ducted to the dryer inlet and will operate as a single-pass system to reduce the moisture content of the incoming feedstock. Feedstock driers, both rotary drum and belt driers are readily available in the commercial marketplace. A selection of experienced vendors include:

- Agroenergien Dryer (www.agroenergien.de)
- Altentech (www.altentech.com)
- Andritz Drying Solutions (www.andritz.com)
- Babcock & Wilcox (www.babcock.com)
- Baker-Rullman (www.baker-rullman.com)
- Bruks (www.bruks.com)
- Buettner Energy & Drying (www.buettner-energy-dryer.com)

- Buhler Aeroglide (www.aeroglide.com)
- De Boer (www.deboermachines.nl)
- Dieffenbacher Group (www.dieffenbacher.de)
- Dupps (www.dupps.com)
- Earth Care Drying Systems (www.ecpisystems.com)
- Energy Unlimited (www.energyunlimitedinc.com)
- FEECO International (www.feeco.com)
- GEA Barr-Rosin (www.barr-rosin.com)
- M-E-C (www.m-e-c.com)
- PacWest Global (www.pacwestglobal.net)
- Saimatec (www.saimatec.fi)
- Solagen (www.solageninc.com)
- Stela Laxhuber (www.stela.de)
- Swiss Combi (www.swisscombi.ch)
- Thompson Dryers (www.thompsondryers.com)
- TSI, Inc (www.tsi.com)

Rotary Gasifier

The rotary gasifier is configured from a rotating drum dryer system with recycled gas. A demonstrated in the previous section, the manufacturing of the gasifier vessel benefits from a long history of rotary drum dryer production, which include flue gas recirculation. Shifting from a dryer to a torrefaction reactor requires a modification to the flue gas recirculation loop to handle a torr-gas instead of flue gas from a dryer. This modification has been made by several companies and is offered commercially by, at least, TSI Inc. and Thompson Dryers.

As described in Task 3 and Task 4, West Biofuels partnered with TSI to evaluate functionality of the torrefaction system with forest feedstock. The success of the pilot system using forest feedstock while operating at gasification conditions provided the framework for the commercial system described in this Production Readiness Plan. TSI has already developed and deployed a 2 ton per hour torrefaction system in Louisiana, which has all of the components necessary to operate at gasification temperatures, except for ducting to divert excess producer gas.

Figure 134: 2 Ton/Hr Torrefaction System in Lousiana designed by TSI

Source: West Biofuels, LLC

Thermal Oil Heater

Thermal oil heater will combust the producer gas to provide heat to the next process via a heat exchanger. The torrefaction system at the TSI plant in Louisiana already includes a burner which provides heat back into the system via a heat exchanger. The scale-up of the thermal oil heater to utilize additional producer gas is a standard engineering design that is offered by multiple vendors. A selection of qualified vendors includes:

- Babcock Wanson (www.babcock-wanson.com)
- Bosch Industrial (www.bosch-industrial.com)
- Classen Apparatebau Wiesloch (www.caw-wiesloch.de)
- Cleaver-Brooks (www.cleaverbrooks.com)
- Columbia Boiler (www.columbiaboiler.com)
- Docuthek-Kromschroeder (www.docuthek.kromschroeder.com)
- Hearst Boiler (www.hearstboiler.com)
- Industrial Boiler (www.industrialboiler.com)
- National Boiler (www.nationalboiler.com)
- Parker Boiler (www.parkerboiler.com)
- Solagen (www.solageninc.com)
- Standard Burner (www.standardgasburner.com)
- TSI Inc. (www.tsi.com)

- Wayne Combustion Systems (www.waynecombustion.com)

ORC Generation

One of the critical advantages of an ORC generation system, over an internal combustion engine system, is that the ORC system runs on heat provided by the heat exchanger, therefore does not come in direct contact with producer gas. Turboden is the industry leader in the 3MW size range. Turboden has installed 269 ORC units coupled with biomass generating systems across the world, scaling from 0.5 MW to 8 MW (Figure 135).

Capacity Constraints

To implement a commercial scale project, West Biofuels serve as a system integrator working with major component manufacturers to bring modular components to the project site. West Biofuels has a 36,000-square foot manufacturing facility in Woodland, CA, allowing West Biofuels to provide critical integration support to any project in California. As identified in the sections above, there are a variety of component vendors to work with on supporting infrastructure for the gasification vessel.

Estimated Cost of Production

The estimated cost of production is provided in detail in Section 5.

Investment to Launch the Commercial Product

No additional funding is needed to launch the commercial product. West Biofuels, along with its partner suppliers, already maintain sufficient infrastructure to launch the commercial system.

Implementation Plan to Ramp Up to Full Production

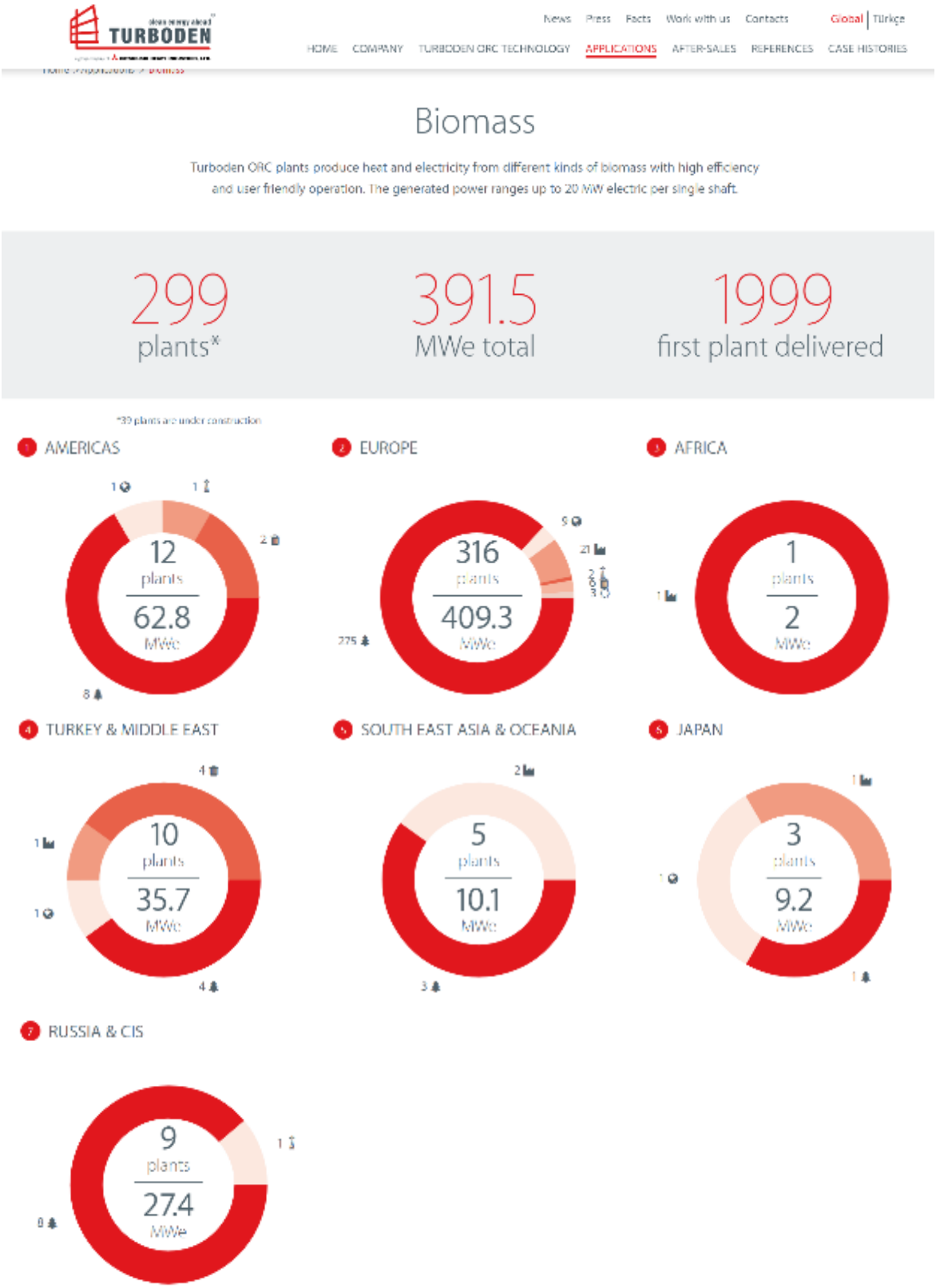
Like all bioenergy facilities, the West Biofuels gasification system is sold to a highly-developed project site that has addressed all aspects of system operations. Specifically, West Biofuels has partnered with Hat Creek Construction & Materials in Burney, CA to launch the first commercial system utilizing forest fuels. West Biofuels and Hat Creek Construction & Materials have been working together to develop the proposed site including evaluation of interconnection, land use permitting, air permitting, and feedstock contracting.

As a first-of-its-kind commercial demonstration, the project will inherently have higher risk and may need additional public funding to support institutional equity or debt investment.

Copyrights and License Agreements

While copyrights and license agreements exist on supporting system components, no copyrights, licenses, or patents were filed as a direct result of this grant program.

Figure 135: Turboden Reference Plants



Source: West Biofuels, LLC

CHAPTER 8: Conclusions & Next Steps

Based on the characteristics of the California forest resource, the most promising regions for forest biomass energy projects included the Sierran and Interior regions because they have the highest forest management activity and the most robust existing infrastructure for potential development. Specific sites were identified showing good attributes for forest bio-energy project development including local need, available forest biomass, and available grid infrastructure. The current equipment inventory available for processing and delivery of forest thinning residues is suitable for producing product to be used in gasification systems. Current screening equipment removed overs and fines from the raw delivered forest material producing a good particle size and low ash content biomass that is suitable for gasification.

The initial hypothesis of the project team was that the CircleDraft gasifier coupled with an engine generator would be a viable modular option for power production from California forest biomass. While this was not validated over the course of this R&D project, the Project Team successfully identified a commercially-viable modular configuration appropriate for forest-sourced feedstock. The challenges with the CircleDraft based system included the following:

- Problems with bridging and channeling within the fixed bed reactor reducing average feedrate and increasing down-time for the system.
- Inconsistency in gas volume and quality related to the feeding problems.
- Gas quality objectives were not met for operating with an engine generator.
- High levels of maintenance required on the engine generator system.
- Overall cost of power is much higher than power purchase contracts available in the state without very high biochar sales prices.

The project team concluded that this modular technology was not viable for commercialization in its current state.

The project team developed an alternative technology approach specifically to address the shortcomings of the gasification/engine generator approach for power production. The alternative technology overcame many of the challenges encountered with the gasifier and the engine generator system that was the original basis of this project. The system includes a rotary gasification system based on common solids drying and roasting equipment, a thermal oil heater with controlled combustion equipment and heat exchanger, and an Organic Rankine Cycle generator that uses the hot thermal oil as a heat source to operate an organic fluid turbine generator. This new approach solved many process challenges including the following:

- The rotary gasifier has a thin layer of biomass that is convection heated and problems of material flow, blockage and imprecise material temperature control are eliminated.
- Gas production is continuous, consistent and repeatable.

- The hot product gas is carried directly to the low-emissions suspension burner system without requiring cleanup eliminating stringent gas quality requirements.
- The maintenance cost on the ORC generator system is a small fraction (1/5 to 1/10) of the cost for an engine generator system and downtime is minimal on the overall system.
- Overall cost of power from this system is within the range of power purchase contracts available in the state with modest biochar sales prices.

While taking a new technical direction, the R&D project did in the end develop a viable forest bio-power technology that creates a foundation for commercial applications.

The next steps for West Biofuels is the commercialization of this technology in the forest sector with an in-state commercial demonstration. West Biofuels has been working with potential deployment partners across forested landscape to develop projects that can participate in Category 3 of the BioMAT program. In partnership with one of the project site owners identified in this study, a new entity was developed and has been issued a conditional use permit, has passed the utility interconnection process, and has been awarded a power purchase agreement for a 3MW forest bio-power facility in the Northern Sierran region. If this new project can clear financing and construction hurdles, it is likely to be the first demonstration of this technology in California. The team hopes this facility will lead to many more community-based bio-power plants in the future sprinkled in the California forest regions. If this develops, this R&D project will have been the key to enabling this important technology to advance both renewable energy and forest fire management goals in the state.

The team also has recommendations for further general research in the area of community-scale forest bio-power and gasification. The first recommendation is to fund a survey of the performance of commercial projects in other parts of the world. For example, this project team learned a great deal about capacity factor challenges with gasifier/engine generator systems and the greater success of ORC systems in terms of capacity factor in a few visits to European project sites. Since considerable experience with various types of community-scale systems (in the 1-5MWe range) has been gained in Europe, Canada, and elsewhere, California has a great opportunity to learn from this. A study to track the longer-term performance record of some of these projects and technologies would be invaluable information as California considers a future approach to forest bio-power. The second recommendation is to fund further analysis of the electrical grid in forest community areas. Since interconnection is a big barrier to project viability, identifying site locations with favorable attributes for the grid would be very helpful. This study should be in partnership with the utilities and involve utility experts in the grid. These additional research efforts are simple to implement and would be very valuable for enabling future projects in this important area.

GLOSSARY

Term	Definition
AB	Assembly Bill
abs	Absolute
amu	Atomic Mass Unit
APCD	Air Pollution Control District
APCO	Air Pollution Control Officer
AQMD	Air Quality Management District
ATC	Authority to Construct
atm	Atmosphere
BDT	Bone Dry Tons
bhp	Brake Horsepower
BioMAT	Biomass Market Adjusting Tariff
BLM	Bureau of Land Management
Btu	British Thermal Unit
C	Celsius
C_2H_4	Ethylene
C_2H_6	Ethane
CAISO	California Independent System Operator
CAL FIRE	California Department of Forestry and Fire Protection
CALVEG	Vegetation Classification and Mapping (USFS)
CARB	California Air Resources Board
CEQA	California Environmental Quality Act
CFD	Computational Fluid Dynamics
CFL	Courant-Friedrichs-Lewy
CH_4	Methane
CHIPS	Calaveras Healthy Impacts Products Solutions
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalents

Term	Definition
CPUC	California Public Utilities Commission
CUP	Conditional Use Permit
CUPA	Certified Unified Program Agency
CWA	Clean Water Act
CWHR	California Wildlife Habitat Relationship
DTSC	Department of Toxic Substance Control
DTT	Direct Transfer Trip
E	East
EGI	Electrical Generation Interconnection
EIR	Environmental Impact Report
EIS	Environmental Impact Study
EIT	Electrical Independence Test
EPA	Environmental Protection Agency
EPIC	Electric Program Investment Charge
EUBCE	European Biomass Conference and Exhibition
EVT	Existing Vegetation Type
FERC	Federal Energy Regulatory Commission
FMP	Forest Management Practices
FONSI	Finding of No Significant Impact
FRAP	Fire and Resource Assessment Program (CAL FIRE)
ft	Feet
g	Grams
GC	Gas Chromatograph
GHG	Greenhouse Gas
GIA	Generator Interconnection Agreement
GJ	Gigajoule
gpm	Grams Per Minute
GT	Green Ton
H_2	Hydrogen
H_2O	Water

Term	Definition
HHV	High Heating Value
HMBP	Hazardous Material Business Plan
hp	Horsepower
HW	Hardwood
I	Industrial (zoning)
IBI	International Biochar Initiative
IL	Light Industrial (zoning)
IOU	Investor Owned Utilities
K	Kelvin
kg	Kilograms
kJ	Kilojoule
kV	Kilovolt
kW	Kilowatt
L	Liter
LANDFIRE	Landscape Fire and Resource Management Planning Tools
lb(s)	Pound(s)
LBG	Low-Btu Gas
LCOE	Low Carbon Fuel Standard
Loc.	Location
m	Meters
M	Manufacturing (zoning)
M-1	Light Industrial (zoning)
m^3	Cubic Meter
mbar	Milli-bar
MBtu	Thousand Btus
mg	Milligram
Min	Minutes
MJ	Megajoule
mK	Milli-Kelvin
mL	Milliliter

Term	Definition
mm	Millimeter
MMBtu	Million Btus
MND	Mitigated Negative Declaration
MP-PIC	Multiphase Particle-In-Cell
MU	Multiple Use (zoning)
MW	Megawatt
MWh	Megawatt hours
N	North
N-A	Natural Resources (zoning)
NEPA	National Environmental Policy Act
Nm^3	Normal Cubic Meter
NOI	Notice of Intent
NO_X	Nitrogen Oxides
NPDES	National Pollutant Discharge Elimination System
ORC	Organic Rankine Cycle
PCC	Point of Common Coupling
PEIR	Programmatic Environmental Impact Report
PG&E	Pacific Gas & Electric
PJ	Pinyon Juniper
PM	Particulate Matter
PMH	Productive Machine Hour
PPA	Power Purchase Agreement
ppm	Parts Per Million
ppmv	Part Per Million Volume
PPR	Program Participation Request
PRD	Permit Registration Document
PS	Public Service District (zoning)
PSD	Prevention of Significant Deterioration
PTO	Permit to Operate
RC	Rural Commercial (zoning)

Term	Definition
R-R	Rural-Residential (zoning)
RPF	Registered Professional Forester
RPM	Revolutions Per Minute
RPS	Renewable Portfolio Standard
Rule 21	Electric Rule 21
RWQCD	Regional Water Quality Control District
S	South
SB	Senate Bill
SCD	Sulfur-Chemiluminescence Detector
SCE	Southern California Edison
SDG&E	San Diego Gas & Electric
SGS	Sub-Grid Scale
SIS	System Impact Study
SMARTS	Storm Water Multi-Application Report Tracking System
SMH	Schedule Machine Hour
SO_X	Sulfur Oxides
SO_2	Sulfur Dioxide
SPCC	Spill Prevention Control and Countermeasure
SPE	Solid Phase Extraction
SPI	Sierra Pacific Industries
SW	Softwood
SWET	Statewide Wood Energy Team
SWPPP	Storm Water Pollution Prevention Plan
TBD	To Be Determined
TGA	Thermogravimetric Analysis
TPY	Tons per Year
UC	University of California
µg	Micrograms
US or U.S.	United States
USFS	US Forest Service

Term	Definition
USGS	US Geological Survey
V	Volts
VOC	Volatile Organic Compounds
W	West or Watt
WDR	Waste Discharge Requirements
WDT	Wholesale Distribution Tariff
wt	Weight
yr	Year

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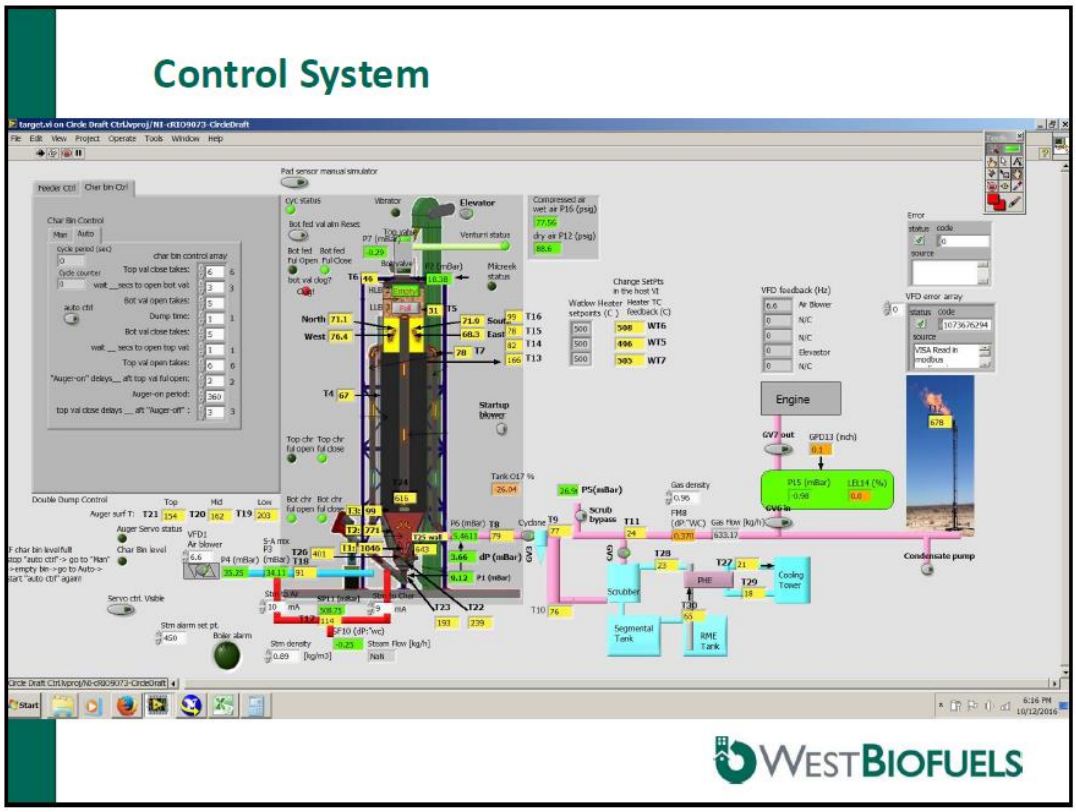
APPENDIX A: Gasifier Design Improvements

The following pictures show the multiple design and sub-systems modifications that the project team implemented to try to improve the performance of the CircleDraft gasifier system on forest residue feedstock.



Feeder System Improvements:

1st generation: Airlock valve

WESTBIOFUELS

2nd Generation: Plug screw feeder

WESTBIOFUELS

3rd generation: Double Dump Feeder

- Top: 12 inches
- Bot: 18 inches
- Vol/fill: 4.5 CF
- Mass/fill: 67.5 lbs/fill (@15 lbs/cfm)
- Fill cycle: 136 seconds
- Capacity: 1800 lbs/hr

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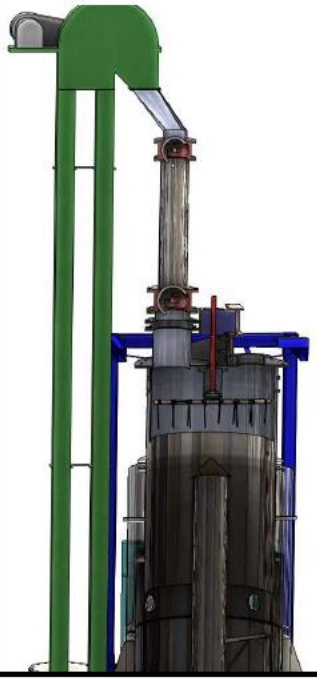
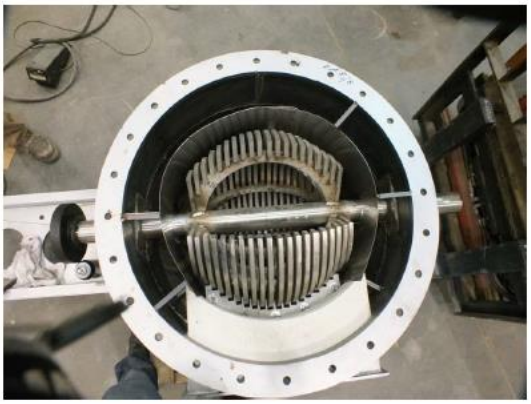
4th generation: Roto-Valve Double Dump with Rake



- Top: 10 inches
- Bottom: 12 inches
- Vol/fill: 3.5 CF
- Mass/fill: 53 lbs/fill (@15 lbs/cfm)
- Fill cycle: 72 seconds
- Capacity: 2700 lbs/hr

Biochar/ash removal system

1st generation: grate system



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2nd generation: Char auger removal system

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Steam Injection system

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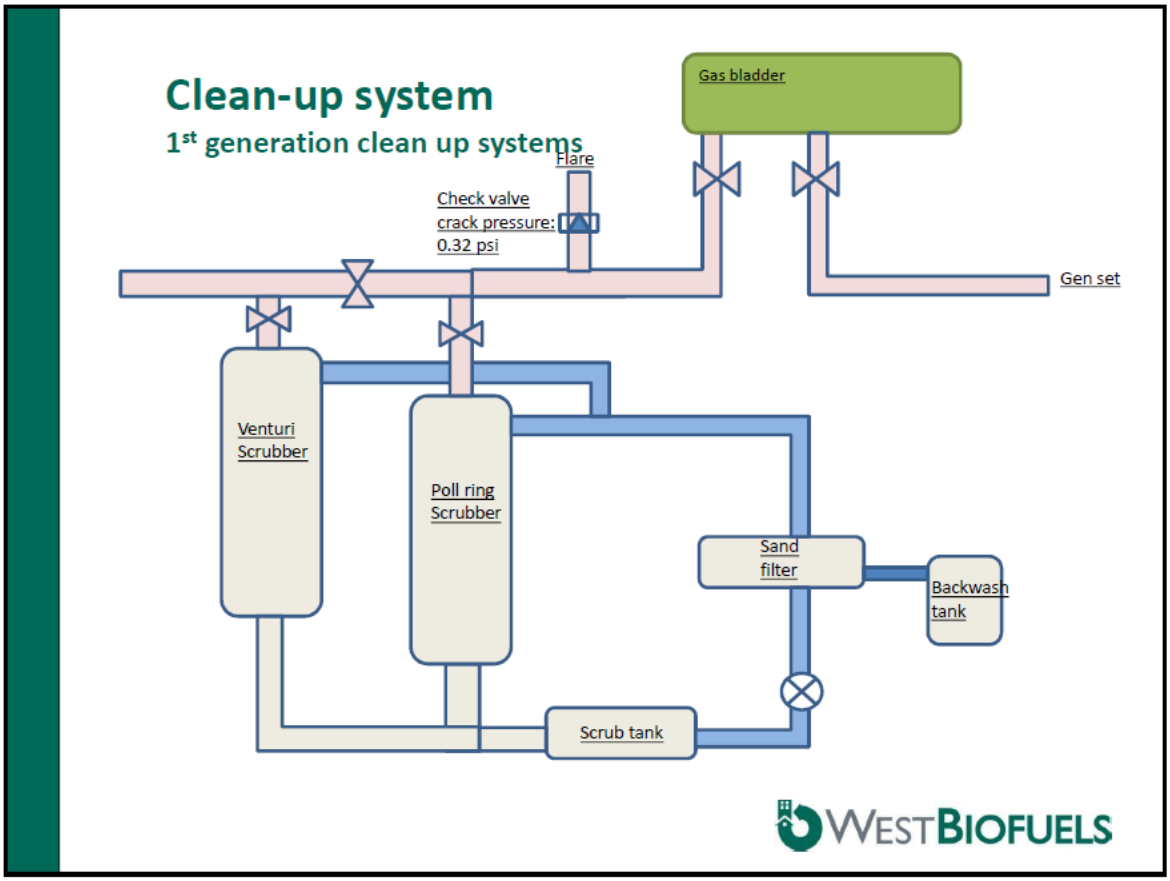
Clean-up system
1st generation clean up systems
Gas bladder
Flare
Check valve
crack pressure:
0.32 psi
Gen set
Venturi
Scrubber
Poll ring
Scrubber
Sand
filter
Backwash
tank
Scrub tank
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1st generation clean-up system:
H2O venturi scrubber -> poll ring scrubber -> segmental tank -> sand filter

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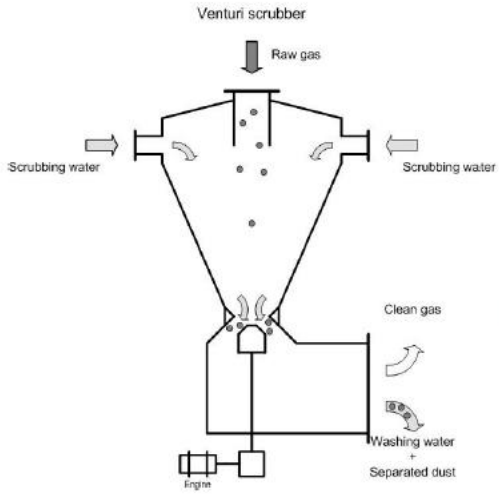
Venturi scrubber



Pall rings

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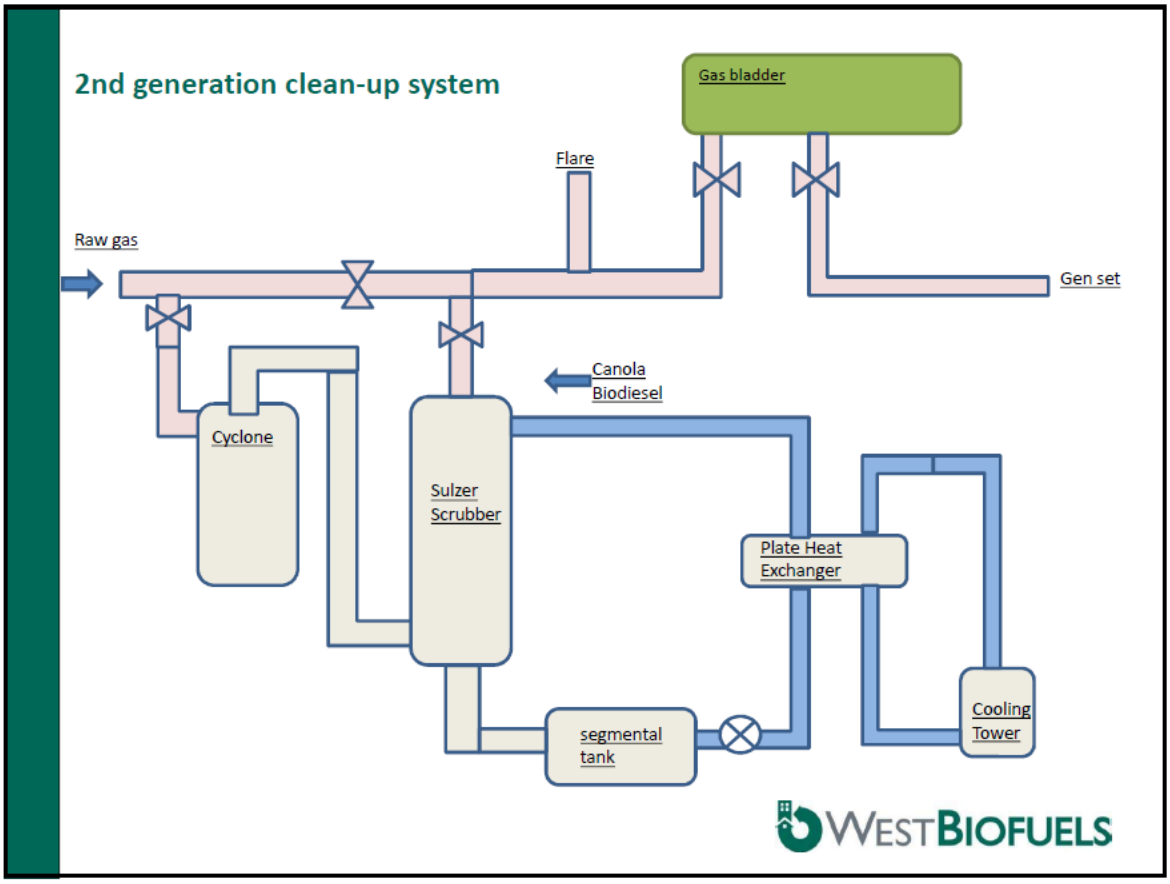
2nd generation clean-up system
Gas bladder
Flare
Raw gas
Gen set
Canola
Biodiesel
Cyclone
Sulzer
Scrubber
Plate Heat
Exchanger
segmental
tank
Cooling
Tower
WESTBIOFUELS

2nd generation Clean-up system
Canola biodiesel Sulzer scrubber system

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Sulzer scrubber media

Distributor

Scrubbing media

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Flare System

1st generation system:
Open flare with
underground gas piping

2nd generation system: Enclosed TO system with aboveground insulated gas pipe