



Technical, Economic, and Environmental Assessment of Alternative Uses of Biomass Feedstock in Humboldt County

Nancy Charco, Jonn Geer, Jesus Rincon, and Sabrinna Rios Romero

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Team Biomasssters consisting of Nancy Charco, Jonn Geer, Jesus Rincon, and Sabrinna Rios Romero has prepared this document for the use of the Redwood Coast Energy Authority (RCEA). The objective of this project is to assess the technical, economic, environmental aspects for an alternative use of biomass feedstock in Humboldt County for RCEA to address community concern about biomass combustion. Currently, the majority of Humboldt County's biomass is being combusted at two local facilities: DG Fairhaven and the Humboldt Sawmill Company. DG Fairhaven is an 18.7 MW facility and the Humboldt Sawmill Company is a 32.5 MW facility. The scope of this project does not include the energy that would need to be provided if the existing facilities stop running.

The torrefaction alternative proved to be the best nonpolluting, renewable, and yet low-cost alternative out of the four alternatives. The thermochemical process of converting biomass into solid fuel with reduced Oxygen/Carbon and Hydrogen/Carbon ratios provides a cleaner source of energy if utilized for an alternative feed source in boiler combustion. A preliminary analysis was conducted to establish the feasibility of such facility. For the analysis, a total mass of 561,600 MT/yr (at 50% moisture content) or 280,800 BDMT/yr and a density of 247 kg/m³ was assumed.

The final concept (summarized in Figure ES-1) follows a traditional torrefaction process. This heat recycling includes the recirculation of flue gas for indirect process heating within the drying process. All biomass (typically at a 50% moisture content) is fed into a drier before entering the torrefier. The dried torrefied product is then conveyed to the cooling system and eventually pelletized for distribution. The gas recycling process involves the combustion of air, fuel, and flue gas for the heat production to operate the heat exchanger.

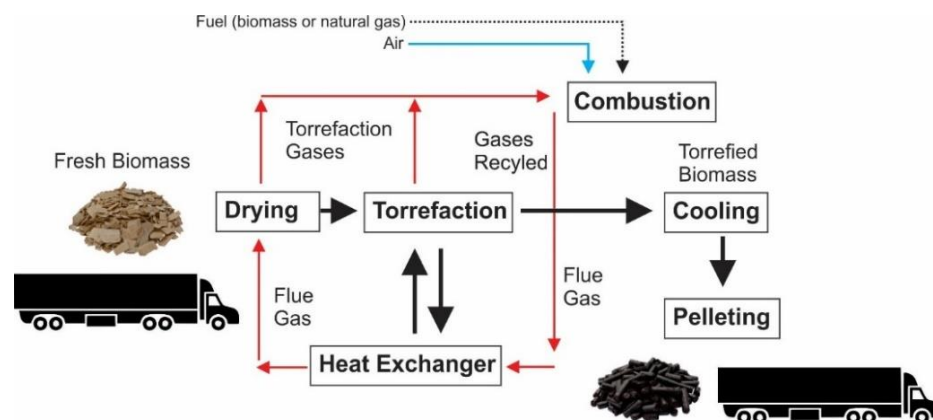


Figure ES 1:Proposed heat processing system to convert biomass into torrefied pellets.

The final product is high-quality fuel pellets, with similar characteristics to coal, with an increase in calorific value (20-24 MJ/kg) caused by the removal of moisture and some organic compounds from the original biomass (Koppejan et al. 2012). The torrefaction process is intended to maintain all volatile matter (and thereby energy) within the final torrefied pellets (Koppejan et al. 2012). The results show beneficial changes such as lower moisture content (1-5%), higher energy density, hydrophobic properties, superior handling and grindability and lastly, low biological degradation. The final recommendation is to use a rotary gasifier developed by Torr-Coal; their technology was found to be professionally researched and has records of being implemented at high capacities (30kton/yr) (Cremers 2015). Therefore, with appropriate scaling, this analysis proposes seven parallel reactors would be required to meet the design capacity. Additionally, this analysis provides estimates on the total energy input, the quantities of torrefied pellets produced, the total energy content in produced pellets, and an estimated electricity consumption to operate the facility.

The site will require about 60 acres, including storage for feedstock and final product. In addition, the implementation of a project this size would directly and indirectly result in 250 jobs including permanent operating and maintenance positions and temporary construction work. In fact, this alternative is the only, out of the four, that works within the current biomass supply line not disrupting the market but only providing a pretreatment to effectively reduce emissions. In comparison, emissions from torrefied wood are substantially smaller, estimated at 15,000 CO_{2e} compared to 282,026 CO_{2e} for Humboldt Sawmill Company and 182,858 CO_{2e} for DG Fairhaven. One key advantage of utilizing torrefied wood for co-firing is that it is considered a biogenic emission and therefore considered carbon neutral as defined by the EPA (US EPA 2018b). Lastly, a net present value analysis concluded with a payback period of eleven years, accounting for costs associated with the transportation of both the biomass feed and produced pellets, labor, energy, and the estimated capital cost. The revenue derived from produced pellets was assumed to be \$160/ton (Dovetail Partners, Inc. 2013). All estimates were derived based on the feedstock input and pellet production, thus estimating a capital cost of \$55 million, operation and maintenance of \$36 million, and revenue of \$42 million per year.

Recommendations

Although the preferred torrefaction alternative is an improvement in biomass utilization, it's recommended that a more thorough analysis be conducted for estimated system costs. For this analysis, estimates for capital cost and the associated operating and maintenance costs for the equipment were literature estimates and not directly from vendors. A reevaluation on the cost is strongly advised, this is important given torrefaction is an emerging technology and advances in technology could change the cost over time. In addition, it's recommended to seek out other financial incentives such as a carbon credits or any other renewable energy programs. Finding and taking advantage of these initiatives could effectively augment the revenue stream and help alleviate the high capital cost associated with this alternative.

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1 Introduction

Humboldt County is a major part of the California logging industry, whose timber operations consequently produce large quantities of woody biomass residues and are the primary source of biomass residual in the county. These residuals, or residues, are then transported to biomass facilities to generate energy through combustion. Redwood Coast Energy Authority (RCEA) manages the power portfolio of Humboldt County, and selects from where the power is sourced; among their sources are two biomass plants, Humboldt Sawmill Company and DG Fairhaven. Although woody biomass is considered a renewable resource in California, the community has concerns with the emissions produced via the combustion of biomass.

The objective of this project is to assess the technical, economic, environmental aspects, of alternative uses of biomass feedstock in Humboldt County for the Redwood Coast Energy Authority (RCEA). Increased complaints from the community regarding environmental and health concerns from pollutants released during incineration of biomass to produce energy has motivated the determination of alternative biomass uses. Energy and non-energy alternatives will be evaluated, and the alternative chosen will mitigate the negative effects identified. The scope of this study does not include the analysis of how RCEA will make up for the energy lost if their biomass plant sources cease to produce power. To achieve this objective, this report will be broken down into 1) background information (e.g. regulations, technologies), 2) constraints and criteria, 3) alternatives, 4) decision analysis, 5) specification of the recommended alternative, and 6) conclusion.

2 Background

The background consists of information regarding the stakeholders, regulatory framework, the current state of Humboldt County, and biomass uses. The stakeholders are impacted by the decision towards how the biomass will be used. The regulatory framework explores the permitting and standards associated with biomass utilization. The current air quality of Humboldt County is considered within the framework of current state and region plans to identify potentially hazardous pollutants and quantify GHG emissions. Lastly, the characterization of biomass and the alternatives for its uses are outlined to provide a framework to evaluate biomass alternatives.

2.1 Stakeholder Consideration

RCEA, the client of this project, is a government Joint Powers Authority (Agency) and founded in 2003. The authority works to increase the use and knowledge of sustainable renewable energies in Humboldt County. RCEA determines the sources from which energy comes from in Humboldt County and they promote integrating, and developing, renewable energies (RCEA 2019a). One of RCEA's goals is to have 100% renewable energy by 2025 (RCEA 2019a). RCEA has contracts with DG Fairhaven Power and Humboldt Sawmill Company to produce energy via biomass combustion; however, a long-term goal of RCEA is to move away from the combustion of this resource and find other means to utilize the local woody biomass (RCEA 2019a).

Humboldt County, another stakeholder, relies on RCEA to provide energy sources that comply with the county's ideals and goals, including renewable energy targets. Currently 25% to 30% of electricity in Humboldt County is from biomass power generation (Humboldt County 2017). The General Plan supports the idea of using local renewable energy, but also addresses the public opposition to the technology (Humboldt County 2017). Humboldt County depends on RCEA to develop Energy Element strategies in a Comprehensive Action Plan for Energy (Humboldt County 2017). One of the energy goals of Humboldt County is to increase the amount of renewable energy through the use of local resources, which agrees with RCEA's goals (Humboldt County 2017).

The goals outlined in RCEA's mission statement and Humboldt County's General Plan coincide with the energy goals for the State of California, another stakeholder. Senate Bill 350, also referred to as the Clean Energy and Pollution Reduction Act requires 50% renewable energy in California by 2030 (California Energy Commission 2020b). Renewable energies are defined by the Renewables Portfolio Standard (RPS) which consists of solar, wind, biomass, and geothermal (California Energy Commission 2020b). California's Fourth Climate Change Assessment outlines the policies and actions for California to prepare for the impacts associated with climate change (California Energy Commission 2020b). With 1990 as a benchmark, California is set to reduce greenhouse gas (GHG) emissions by 40% by 2030 and 80% by 2050 (California Energy Commission 2020b). This action helps mitigate the negative public health impacts which are a result of climate change (California Energy Commission 2020b).

Community members in Humboldt County are also stakeholders as they are affected by the decisions made by the mentioned entities. RCEA held community outreach workshops to gauge public perception towards energy sources. The perception of local biomass utilization was distributed between four categories: not include, minimize, include, and maximize (RCEA 2019a). About 48% of the community supports biomass, while solar power appeals to over 90%. The growing concern of emissions from the current biomass plants is the main barrier to acceptance of biomass utilization.

The two biomass power plants, Humboldt Sawmill Company (HSC) and DG Fairhaven LLC (DGF LLC), are also stakeholders. HSC, established in 1989, is a 28 MW biomass power plant located in Scotia, California, 40 miles South of Eureka (CBEA 2020b). Each year, HSC burns 150,000 to 200,000 bone dry tons of forest, sawmill, and urban biomass residues (CBEA 2020a). Sawmill waste makes up the highest portion of what is burned at the plant (California Biomass Energy Alliance 2020). DGF LLC, established in 1987, is an 18 MW biomass power plant located in Samoa, California (CBEA 2020a). Each year, DGF LLC burns 250,00 tons of woody biomass from sawmill and forest residues (CBEA 2020b). HSC reported 25 employees in 2014 while DGF LLC reported 22 direct employees and 30 indirect employees (CBEA 2020a; CBEA 2020b). Both the biomass plants and sawmill facilities are codependent on each other. If the plants cease to exist, the sawmill waste would have to be managed differently.

2.2 Regulatory Framework

This section discusses the current regulations regarding possible pathways of biomass utilization. These considerations include biomass use in combustion, thermochemical treatment (pyrolysis, solvolysis, torrefaction), gasification, and biorefinery conversion.

2.2.1 Air Quality Regulations

Air quality rules and regulations are enforced by the North Coast Unified Air Quality Management District (NCUAQMD) and the United States Environmental Protection Agency's (U.S. EPA) 40 CFR Part 70 Regulations (Federal) (NCUAQMD 2019). This makes up the California Operating Permit Program, which verify power stations are following District, State, and Federal air quality rules and regulations (NCUAQMD 2019). The program complies with requirements outlined in Title V of the Clean Air Act (42 U.S.C. 7401) which defines the minimum elements for state operating permits (NCUAQMD 2019). One requirement, is the Title V permit, which is required for any major source of pollutant emissions. A major source is defined as any source that has emission levels above established pollutant thresholds (EPA 2015). Ambient Air Quality Standards (AAQS) are specified durations of concentrations for air pollutants, established as health-based standards by the California Air Resource Board and the U.S. EPA (NCUAQMD 2008). These rules and regulations summarized in Table 1 are established to maintain and protect the Northern California Air Basin from hazardous levels of pollutants that jeopardize human health and safety (NCUAQMD 2008).

Table 1. Federal and State Air Quality Standards (NCUAQMD 2008).

Pollutant	Averaging Time	California Standards	Federal Standards
Fine Particulate Matter (PM ₁₀)	8 Hour	0.09 ppm (180 µg/m ³)	0.075 ppm (147 µg/m ³)
Fine Particulate Matter (PM _{2.5})	Annual Arithmetic Mean	12 µg/m ³	15 µg/m ³
Carbon Monoxide (CO)	1 Hour	20 ppm (23 mg/m ³)	35 ppm (40 mg/m ³)
Nitrogen Dioxide (NO ₂)	Annual Arithmetic Mean	0.03 ppm (56 µg/m ³)	0.053 ppm (100 µg/m ³)
Sulfur Dioxide (SO ₂)	24 Hour	0.04 ppm (105 µg/m ³)	0.14 ppm (365 µg/m ³)

2.2.2 Water Quality Regulations

All large-scale industrial processes that utilize and discharge water must apply for The National Pollutant Discharge Elimination System (NPDES) program (CWB 2020). This is a federal program that was implemented by the State of California and enforced by the North Coast California Water Board to protect surface waters (CWB 2020). This program started in 1969 when state legislatures passed the Porter-Cologne Water Quality Control Act, establishing regional programs within nationwide coordination and policy (US EPA 2016). These permits apply to industrial processes that utilize water for cleaning and cooling and eventually discharged these supplies into surface waters (CWB 2020). The North Coast Water Control Board provides several numerical thresholds for organic and non-organic chemical constituents that represent California's water quality standards (EPA 2016). These thresholds change based on the type of discharge such as groundwater, surface water, bay/estuary, or ocean water

discharges. In some cases, specific constituents require compliance with numerical objectives set by other water quality control plans such as the Ocean Plan, and Thermal Plan which control temperatures of coastal and interstate waters (US EPA 2016).

Additionally, federal water quality criteria, such as those specified in the National Toxics Rule and the California Toxics Rule also apply independently from the state water quality control plans (EPA 2016). These represent Section 303(c) of the Clean Water Act which sets water quality objectives that provide reasonable protection of beneficial uses (US EPA 2016). It is important that all industrial processes follow all applicable water quality objectives. Once all applicable water quality objectives and numerical thresholds have been identified, a single assessment threshold must be chosen that satisfies them all (EPA 2016).

2.3 Humboldt Air Quality

This section specifies the air quality in Humboldt County to identify potential hazardous pollutants and to help quantify Greenhouse Gas emissions (GHG). This has become an important topic given the community concerns about bioenergy use and the air quality in Humboldt County. The North Coast Unified Air Quality Management District (NCUAQMD) is responsible for enforcing regulations within Humboldt, Del Norte, and Trinity Counties (Williamson 2008). NCUAQMD uses the US EPA's AirNow.gov to monitor the levels that pertain to Title V, but this site generalizes the air quality conditions of Humboldt County. On AirNow.gov they use the Air Quality Index (AQI) to measure current conditions of Humboldt County, where if the index number is higher than 100 the air quality is not in good condition. Rather if the index value is less than 100 then air conditions are good (US EPA 2017). From the current time (February 20, 2020) the AQI is 25 for ozone and PM₁₀ AQI is 33, and both indicate good conditions (airnow.gov 2020). Though AirNow is a way to monitor the current condition in time, it does not always accurately reflect the air pollutants that contribute to air quality in Humboldt County.

The Humboldt county air basin meets State and Federal standards with the exception of PM₁₀ during winter months (Williamson 2008). One reason these standards are not met during this period is that wood-burning in fireplaces increases by 50% (Williamson 2008). Also in general, the combustion of higher moisture content increases the emissions produced through combustion (Thakur et al. 2014). This same phenomenon is observed at power plants where biomass supplies are left outdoors to accumulate moisture. This relationship of higher moisture and creating more emissions during winter months, is a reason community are concerned over bioenergy production (Williamson 2008).

2.4 Timber Harvest in California

Humboldt County is known to be one of the largest counties to harvest timber within California (Dyett et al. 2006). In 2012, there were over 1.9 million bone dry tons of woody residue in California (McIver et al. 2012). About 900,000 acres of land are utilized for harvesting in Humboldt County (Dyett et al. 2006). Increases in timber harvesting bring substantial economic value but could result in negative environmental impacts such as deforestation and habitat loss for sensitive species (Dyett et al. 2006). It is important for companies to follow best management practices to minimize environmental impacts (Dyett et al. 2006). These practices include: reduction of pollutants to bodies of waters, protection of soil, contained nutrient deliveries,

management of debris, fire prevention practices, and protection of vegetation and wetland (Dyett et al. 2006).

2.5 Biomass Overview

Biomass, or biodegradable organic material, is an energy source that can bridge fossil and renewable options (US EPA 2020, Furniss 2019). Natural processes, like photosynthesis and digestion, allow organisms to store excess energy in molecular bonds, i.e. carbon chains, fats, sugars (EIA 2018). This organic matter is generated across California from forestry byproducts, farming, and consumer waste. Biomass fuels are rich in complex carbon molecules, like cellulose and lignin (Pettersen 1984). When used in energy conversion technologies, like combustion, these molecules release energy stored in the bonds as heat, and that heat is used in machinery like steam turbines to allow biomass to be used as a fuel source. Energy, harmful emissions like CO₂ and NO_x, and particulates are generated from these energy conversion processes and must be managed to protect public health.

2.5.1 Definition of Biomass

Biomass, in the context of energy generation, is any organic matter that can be utilized for electricity generation, including, but not limited to, animal waste, wood products, and various biologically derived liquids (CEC 2020a). For the purposes of this project, biomass primarily refers to the waste from different timber operations and is comprised of various softwoods and hardwoods, including pine, redwood, madrone, and alder, amongst other species (Humboldt Redwood Company 2016). The biomass comes from three distinct sources: mill waste, thinning operations, and wildfire fuel management and are considered too low grade for quality wood building products, but high quality enough for energy recapture (RCEA 2019b).

Biomass is considered a sink and a source of CO₂ when used for electricity generation. Woody biomass sequesters carbon during photosynthesis, where CO₂ is converted into long cellulose chains resulting in new growth (BBC 2020). When the organic material dies, it is broken down into its constituents through various decomposition processes. A proximate analysis of forest residue shows a range of 68-83% volatile matter, 0-6% ash, and about 15-23% fixed carbon. An ultimate analysis of forest residues shows carbon and oxygen contents of about 47-51% and 40-45% respectively, with minor residue fractions of: Nitrogen, Sulfur, Chlorine, and Hydrogen (Jenkins and Ebeling 1985).

2.5.2 Components

There are three primary components in woody biomass: lignin, cellulose, and hemicellulose (Burhenne et al. 2013). Cellulose is a collection of long fibers made from glucose referred to as microfibrils, that are alongside the plant cell wall and provide structure (Pasangulapati et al. 2012). Hemicellulose forms hydrogen bonds by linking the other two components and is made of sugars (Pasangulapati et al. 2012). When lignin bonds with the other two components, rigidity and strength is accomplished along the plant cell wall (Li et al. 2016). From these characteristics, lignin protects the cell from degrading and decaying (Vanholme et al. 2010).

2.5.3 Current Emission Data of Local Biomass Plants

Current emissions of greenhouse gases and criteria air pollutants are important to consider since this is the source of community concern regarding biomass combustion. This section summarizes

emissions data provided by the California Air Resource Board (CARB). Table 2 below summarizes the 2018 greenhouse gas (GHG) emissions reported for both the Fairhaven and Cogeneration Power Station (CARB 2018). All categories of emissions are specified as biogenic (biomass) and non-biogenic (fossil fuels) fuel sources and are quantified in units of metric tons of carbon dioxide equivalent (CO₂e).

Table 2. Overview of 2018 greenhouse gas emissions for both power stations from the California Air Resources Board (CARB 2018).

Generator Name	System Type	Total CO₂e [MTCO₂e]	Non-Biogenic Sources and CH₄, N₂O from biogenic fuel [MTCO₂e]	Biogenic Fuels [MTCO₂e]
DG Fairhaven Power	Biomass	69,257	3,853	65,404
Humboldt Sawmill Cogeneration	Cogeneration	299,669	7,181	292,488

Table 3 and Table 4 summarize the 2016-2017 GHG and criteria pollutant emissions for both facilities. GHG emissions include carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O). Criteria pollutants include volatile organic compounds (VOC), nitrogen oxides (NO_x), sulfur Oxides (SO_x), particulate matter (PM₁₀ and PM_{2.5}), and ammonia (NH₃). This emission data do not include transportation fuel and natural gas suppliers.

Table 3. GHG emissions reported on the CARB Pollution Mapping Tool. All GHG emissions are reported in units of metric tons CO₂ equivalent per year [MTCO₂e/yr] (CARB 2016-2017).

Facility	Total GHG	Non-Biomass GHG	Biomass CO₂	CO₂	CH₄	N₂O
DG Fairhaven Power LLC (2016)	87,243	6,158	81,085	85,532	27.75	3.64
DG Fairhaven Power LLC (2017)	1,344	249	1,095	1,320	0.38	0.05
Humboldt Sawmill Company (2016)	231,566	6,132	225,435	226,819	76.95	10.1
Humboldt Sawmill Company (2017)	235,524	5,435	230,089	230,680	78.52	10.31

Table 4. 2016-2017 criteria pollutants reported on the CARB Pollution Mapping Tool. All pollutants are reported in units of tons CO₂ equivalents per year [TCO₂e/yr] (CARB 2017).

Facility	VOC	NO _x	SO _x	PM ₁₀	PM _{2.5}
DG Fairhaven Power LLC (2016)	8.9	74.8	12.7	14.3	13.3
DG Fairhaven Power LLC (2017)	0.3	3.4	0.3	0.3	0.3
Humboldt Sawmill Company (2016)	36.9	174.8	34.6	37.4	34.5
Humboldt Sawmill Company (2017)	40.7	166.8	34.5	35.7	32.9

2.6 Utilization of Biomass for Energy

Biomass can be utilized in various technologies to generate energy. Biomass is considered a source of power because it contains carbon that would have been exposed to the atmosphere from decay naturally as opposed to fossil fuels which would have not been exposed to the earth without anthropogenic involvement (Klass 1998). Though biomass is considered a renewable source of energy, there is concern about the greenhouse gas emissions and criteria air pollutants from the Humboldt community when it is used for combustion. Along with combustion, pyrolysis, solvolysis, torrefaction, and gasification are other technologies that can harness energy from biomass.

2.6.1 Combustion

Combustion, the technology currently used by DG Fairhaven and HSC Scotia, burns biomass in the presence of air and produces steam that can be used for the following applications: heat, electricity, or mechanical power (Goyal et al. 2008). The two plants produce energy by using wood waste in hog fuel boilers, and use the heat to generate steam, activating turbines (Bob Marino personal communication 2020). The moisture of biomass is ideally less than 50% (Goyal et al. 2008). Due to this standard, pre-treatment is required to reduce the moisture content below that level (McKendry 2002). The range of efficiencies for biomass combustion plants falls between 20% and 40% and in about 1.77 tons CO₂e/bone dry ton biomass, along with other pollutants like particulate matter and CO (McKendry 2002, Lee et al. 2010).

2.6.2 Pyrolysis

Pyrolysis is a thermochemical reaction that occurs at high temperatures without oxygen present and decomposes biosolids (USDA 2017). Biosolids are commonly pulverized prior to processing to obtain high heat transfer rates (Bridgwater and Peacocke 2000). This process could be applied in a wide range of temperatures and “conversion times” to produce different percentages of gas,

tar, and char bioproducts ((Hakkı et al. 2013), (Dufour 2016)). This process is unique given that the same gas produced can be utilized as a heat source for pyrolysis (USDA 2017).

Fast pyrolysis yields either large percentages of liquified tars or gases depending on the processing temperature. A temperature around 500 °C yields bio-oils/tars while a higher temperature of 1000 °C, produces a mixture of gases commonly referred to as syngas (Bridgwater and Peacocke 2000). High temperatures favor gas formation by the “cracking” of tar; to extract the syngas, the conversion time is reduced to a minimum of 2 seconds. This fast process reduces secondary reactions and promotes the formation of bio-oils after condensation (Dufour 2016). Slower pyrolysis yields higher percentages of biochar and could also be applied in high (1000 °C) and low (500 °C) temperatures (Bridgwater and Peacocke 2000). This slower process has a conversion time of 5 to 30 minutes and would typically start at room temperature and gradually increase (Lee et al. 2010). Higher yield of char is achieved at slow heating rates at approximately 7 °C/min (Goyal et al. 2008). In general, the pyrolysis process produces value-added products such as: syngas, bio-oils, adhesives, and other chemicals for agricultural uses (Bridgwater and Peacocke 2000). When pyrolysis is utilized in energy production, it can generate emissions of about 1.41 tons CO₂e/bone dry ton biomass along with some CO and PM (Lee et al. 2010). Figure 1 below provides a summary of the different percentages of gas, tar, and char at different temperatures and conversion times.

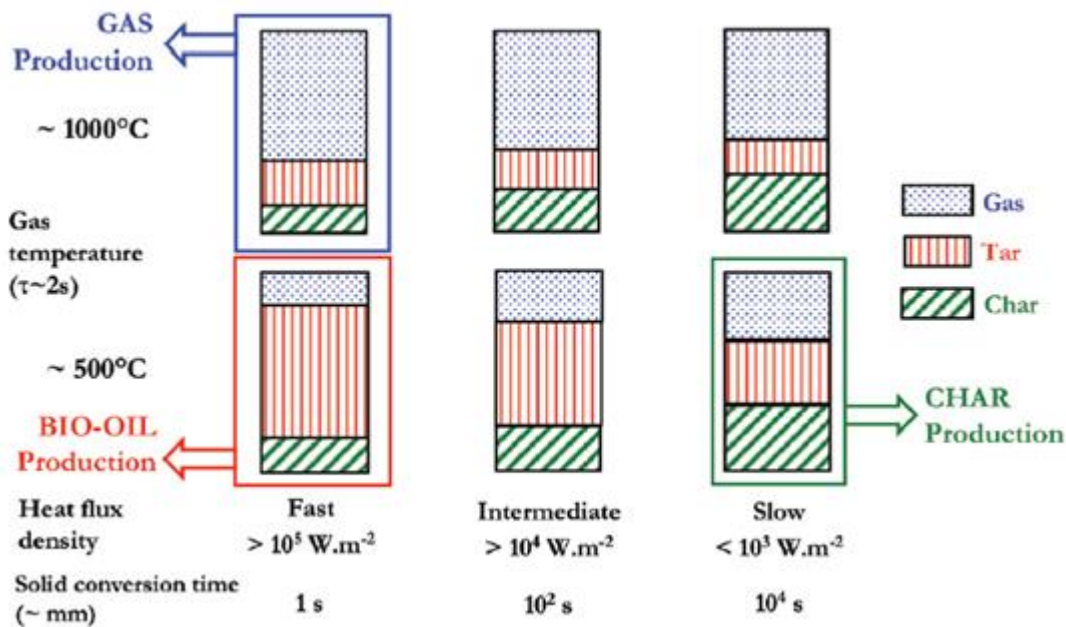


Figure 1. Variation in products for pyrolysis under different temperatures and conversion times (Dufour 2016).

2.6.3 Solvolysis

Solvolysis is also a thermochemical process that uses a solvent and/or a catalyst to dissolve biomass and occurs at temperatures ranging from 120 °C to 250 °C (Hakkı et al. 2013). Solvents that can be used in this process include, but are not limited to: water, methanol and ethanol (Mazaheri et al. 2010). Water is the preferred solvent because it is environmentally friendly,

inexpensive, and more easily recovers biomass components (Huang and Yuan 2015). When water is used as the solvent, the process is called hydrothermal carbonization, and is achieved when biomass is held for 2-6 hours at a temperature of 250 °C and pressure of 4 Mpa (Sevilla et al. 2011). Compared to pyrolysis, solvolysis has a shorter reaction time and a lower operating temperature and yields valuable liquefied biomass, with less energy inputs (Rachel-Tang et al. 2017). One of the benefits of using solvolysis is the biomass does not require drying, as the process is not affected by high moisture contents (Rachel-Tang et al. 2017). The liquefied content can be used as fuel or for raw chemical materials (Shi et al. 2016).

2.6.4 Torrefaction

Torrefaction is another technology that uses biomass for potential energy use in the future. The technology is used as pre-treatment, where contrary to combustion, biomass undergoes a thermochemical process that occurs without oxygen in temperatures ranging from 200-400°C (BTG 2019). Torrefaction is described as a lower temperature version of pyrolysis (Neupane et al. 2015). The heating rate for the process is below 50 °C/min (Bergman and Kiel 2005). The common mass yield is 0.8, and the common energy yield is 0.9 (Bergman and Kiel 2005). The remaining mass consists of water, volatiles, and gasses such as CO₂ (Basu 2018). The two components that result from the process are the torrefied material, as well as a gas which is used to run the system (BTG 2019). The heat used to run the system is from the combustion of the volatile matter in the biomass (Lottes 2014). The solid-state is described as lower moisture content resulting in a higher energy content (Ferro et al. 2004). The torrefied biomass contains similar characteristics to coal, which makes it ideal to use for combustion and gasification (Bergman and Kiel 2005).

2.6.5 Gasification

Gasification is the conversion of solid or liquid carbonaceous feedstocks into a gas (synthesis gas or syn-gas) composed of CO, H₂, methane, and lighter gaseous hydrocarbons (Molino et al. 2016). Other gases such as CO₂ and N₂ are also included in the final product since they are gases required for the gasification process (CBC 2015). Typical operating temperatures range from 600 °C to 1500 °C with little oxygen present (Goyal et al. 2008, CBC 2015). This thermo-chemical process also produces liquids (tars, oils) and solids (char, ash); gasification technology are designed to primarily generate synthesis gases that could be used for internal and external combustion engines and fuel cells (McKendry 2002, CBC 2015). Figure 2 provides a summary of the different applications of syn-gas; some applications require additional cleaning and conditioning.

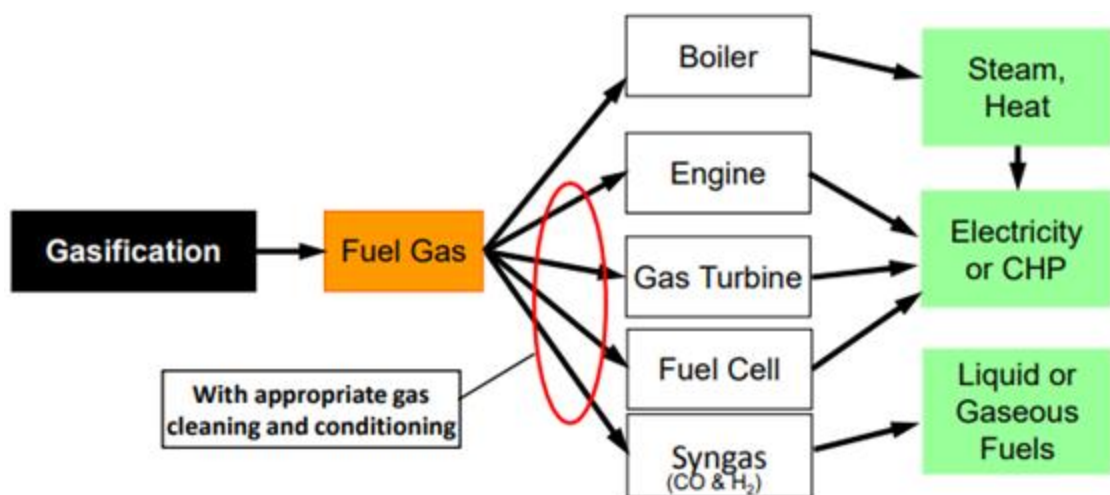


Figure 2. Applications of gasification for production of energy and fuels (CBC 2015).

Gasification is an endothermic process and requires a heat source. These systems are designed to be either directly heated (autothermal) or indirectly heated (allothermal) (CBC 2015). Directly heated applications use air to partially oxidize the feedstock, consequently diluting the product gas with nitrogen (CBC 2015). Indirect heating applications supply an external heat source through heat exchangers or heated media transfer to allow for little to no diluent nitrogen (CBC 2015). The gasification process has four primary steps: 1) oxidation, 2) drying, 3) pyrolysis, and 4) reduction (Molino et al. 2016, Kirubakaran et al. 2009). Gasifier types include fixed bed (updraft or downdraft), fluidized bed, entrained flow and dual bed reactors (CBC 2015). The different gasification medium includes air (air-blown), oxygen (oxygen-blown), steam or a combination of the three (Molino et al. 2016).

The gasification process of solids and/or combustion of synthesis gas generates the same category of pollutants as direct combustion. However, the gasification process has better control over quantities of pollution and improved conversion efficiencies (CBC 2015). Environmental concerns for this process are the production of NO_x and SO_x (Sutton et al. 2001). A case study of a gasification and combustion system reported emissions of 1.77 tons CO_2e /bone dry ton biomass, and small amounts of PM and CO (Lee et al. 2010).

2.7 Energy Production Byproducts

Biomass to energy technologies can often result in useful byproducts in addition to harmful emissions. Biochar, one of the useful byproducts, is a very adaptable material and can be used in many different applications. The use of biochar will have to address the current emissions technology of the plants and the corresponding pollutants, such as CO_2 , particulate matter (PM), and SO_2 .

2.7.1 Soil Remediation

Biomass can be used for the remediation of contaminated soils, or as a soil additive. The remediation can be applied in-situ, or at a facility, depending on the type of remediation. When biomass is cofired with contaminated soil in pyrolysis, heavy metals in the samples are fixed by the biochar produced in the burning process (Debela et al. 2012). In another study, biochar from

combusting biomass was added to several different soil types to evaluate the effect on soil and plant health (Granatstein and Sánchez 2009). This study found biochar had a minor negative effect on plant root growth, but the highest concentrations of added biochar could moderate the pH of the soil and adsorb herbicides (Granatstein and Sánchez 2009). Using biochar as an amendment was effective at increasing moisture capacity of the soil by affecting the porosity and conductivity and can sequester carbon since biochar is resistant to the natural bacteria in the soil that would normally turn it back into CO₂ (Azeem et al. 2019).

2.7.2 Biochar Building Materials

Biochar can be used in the production of various building materials, such as plaster, cement, and brickwork (Schmidt 2008). When used in plaster applications, the biochar can regulate moisture, adsorb contaminants, and provide sound insulation. Biochar is able to replace the entire sand component of cement, while retaining similar structural capacity, and reducing the weight (Schmidt 2008). When used in composite clay and plaster walls of a wine cellar, biochar helped control moisture, adsorbing excess humidity, and redistributing it as the humidity levels dropped, in a wine cellar, and was successful in the range of 60-80% humidity.

2.8 Non-Energy Biomass Utilization

Non-Energy alternatives include converting biomass into valued products that have a wide range of applications. Two such technologies are composting and biorefining, which convert the waste product into useful soil additives and chemical components respectively. By creating products from waste, economic value can be recovered from what would have been disposed.

2.8.1 Composting

Composting is a biological process where organic waste is turned into a useful soil amendment. The quality of the soil amendment is influenced by the inputs, and with certain wastes, can release heavy metals or other harmful products during the decomposition process (Meller et al 2015). If not properly aerated, the compost will generate methane (Amlinger et al. 2008). Along with temperature and oxygen regulation, moisture content, feedstock, and nutrient balance need to be maintained. Compost moisture should be kept between about 40% to 60% (Cornell University 1996), and the Carbon-Nitrogen balance should be maintained with a balance of about 25-30:1 (Furniss 2019). The natural C:N ratio in sawmill waste, the majority of biomass waste in Humboldt County, is 325:1, and the addition of nitrogen would probably be necessary (Furniss 2019). Woody biomass is also associated with carbon dioxide release and composting of this material can result in emissions of about 1.65 tons CO₂e/bone dry ton biomass, with some CO and PM emissions related to the processing and distribution of the product (Lee et al. 2010).

2.8.2 Biorefinery

In biomass conversion processes, woody biomass can be processed into its constituent molecules, primarily cellulose, hemicellulose, and lignin, and those molecules can be applied in various production industries, like biofuel, biopolymers, and paper products. Examples of uses include: paper products derived from cellulose, lignin use in biocomposites, and hemicellulose use in alcohol fermentation and production of bioplastics (Amidon et al 2008, Tong and Pullammanappallil 2019, and Will 2019). Lignin is most often used in energy production, but there is potential for lignin-based foams to replace some fossil-fuel derived plastic sources of building insulation, like polystyrene, as it is fire resistant, and has similar thermal resistance

(Tondi et al. 2016). For these foams, spent liquor from paper pulping processes are mixed with furfuryl alcohol, a catalyst, and a blowing agent, resulting in a hardened foam once cured (Tondi et al 2016). Biorefineries, in making products that can replace fossil-fuel derived products, help lessen the demand for non-renewable resources (Uihlein and Schebek 2009). Wood biorefineries are mainly used for fuel generation and can generate 0-3 kg CO₂/kg product (Kajaste 2014). This resulted in about 90 gallons of Methanol for every dry ton of wood, the density of which is about 792 kg/m³ (Chemical Rubber Company and Lide 2005), equating to about 270kg of product, and about 800 kg of CO₂. Based on the specific products of the biorefinery, the emissions may vary, but in a similar ethanol fermentation process, the system had 1.20 tons CO₂e/bone dry ton biomass, in addition to N₂O, CO, and particulate matter emissions (Lee et al. 2010).

3 Constraints

Three constraints, shown in Table 5, must be adhered to for any planned alternative. These constraints address public health goals, biomass availability, and state standards for projects. The constraints for this project, developed in partnership with the client RCEA are:

- The facility must meet all local and regional air quality standards.
- The facility will have the capacity to utilize the current biomass waste stream.
- The facility's valorized products will meet state, local, or industry standards.

Table 5. Table of constraints that apply for alternatives.

Constraint	Description
Must meet the local/regional air quality regulations (Title V if applicable).	Regulations include fine particulate matter (PM ₁₀ , PM _{2.5}), carbon monoxide (CO), nitrogen dioxide (NO ₂), and sulfur dioxide (SO ₂) regulations.
The alternative must have the capacity to meet the current demand for biomass from both local power plants (DC Fairhaven, Humboldt Sawmill Company)	Alternative biomass utilization and/or conversion must have the capacity to meet the current supply of woody biomass from the local community.
Products must meet state, local, or industry standards if applicable.	I.e. All nutrient levels must be within state standards (pH, N:C) for soil amendments, liquid or solid fuels must meet industry standards, building materials must be within standards.

4 Criteria

The criteria specified in this section are categorized as environmental, social, and economic. Table 6 below describes each environmental criterion and how the alternatives will be compared. The alternative will receive the highest score based on the least impact. The environmental criteria address three major aspects 1) greenhouse gas (GHG) emissions, 2) air pollution, and 3) land use. The social criteria will focus on including community stakeholders in the decision

process for the alternative uses of biomass. The three are 1) employment potential of a facility, 2) project feasibility based on technological maturity, and 3) public acceptance of technological use. The goal of these specified criteria is to include community, county, state, and energy provider.

The method of comparison for both GHG emissions and air pollution is through a common unit of carbon dioxide equivalents (CO₂e). Greenhouse gases adsorb and re-emit heat, water vapor, carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), and ozone (O₃). All quantities of emission are multiplied by their respective Global Warming Potential (GWP).

Table 6. Criteria that are applied to determine the best alternatives based on social, economic and environmental aspects.

Criterion	Description	Method of Comparison	Weights (1-10)
Environmental Criteria			
Greenhouse Gas (GHG) Emissions	Emissions will be compared based on percentage reduction from DG Fairhaven Power and Humboldt Sawmill Company greenhouse gas emissions.	The highest score is given to the alternative that reduces the most emissions to what is already produced through current bioenergy production normalized to using CO ₂ e/BDT (%).	4
Air Pollution	Air pollution will be compared based on the concentrations of the following pollutants: NO _x , PM ₁₀ , PM _{2.5} , and CO, and how far below they are from established regulations.	The highest score will be given to the alternative that minimizes air pollution (MTCO ₂ e).	4
Land Use	Land use will be compared based on the footprint required for development.	The highest score will be given to the alternative that revitalizes or enhances the land.	2
Social Criteria			
Employment	Employment will be compared based on the number of jobs that would be required for the	The highest score will be given to the alternative that has the highest number of employees	3

Criterion	Description	Method of Comparison	Weights (1-10)
	alternative.	needed (number of jobs).	
Maturity	Maturity will be compared based on how established an alternative is.	The highest score will be given to the alternative that has been utilized and researched the most.	2
Public Acceptance	This will be compared based on public opinion for each alternative.	The highest score will be given to the alternative that is perceived most positively based on general public acceptance gathered by surveys, journal articles, news reports, and/or any other publicly available resource.	5
Economic Criteria			
Payback Period	Payback period will be compared based on how long it takes to cover the capital cost of the investment, based on the difference between operating expenses and product revenue.	The highest score will be given to the alternative that has the lowest payback period (years).	10

5 Alternative Analysis

There are four alternatives analyzed for the utilization of local woody biomass. The first alternative is the use of pyrolysis and gasification to produce a useful product. The second method is composting which converts biomass to soil amendment. The third alternative is torrefaction as a pre-treatment method for various applications. The fourth alternative is the production of ethanol from woody biomass. The following sections consist of an introduction, operational process, operational scale and an evaluation of performance for each alternative.

5.1 Considerations

For the analysis of the preferred alternative, a total mass of 561,600 MT/yr (at 50% moisture content) or 280,800 BDMT/yr and a density of 247 kg/m³ was assumed, in order to harmonize assumptions across engineering teams (Bob Marino personal communication, 2020). For this

alternative analysis, all projects were scaled to 450,000 MT which is 80% of the capacity. The preferred alternative will be analyzed at 100% capacity.

5.2 Alternative 1: Gasification

The process of gasification is a thermo-chemical process in which feedstock (in this case sawmill residue) is heated at high temperatures, in a low oxygen environment, to promote the release of volatile gases. This works through the process of pyrolysis and gasification, releasing gaseous fuel (Syn-gas) that can be collected. Syngas is a mixture of several gases and residuals, typical components include CO, H₂, CO₂, CH₄ other less common contaminants include NH₃, H₂S and tars (CEC 2019b). The exact composition of syngas is dependent on several parameters, these include: the feedstock type, operating conditions, gasification temperatures, pressures, and gasification technology utilized (CEC 2019b). Additionally, the pyrolysis/gasification process produces a carbon based bioproduct commonly referred to as biochar. Biochar has a highly porous structure that can be used for both agricultural and industrial applications as filtration media (CEC 2019a). This biochar bioproduct is considered to have a high retail value as it's a novel market with limited supplies (WestBiofuels 2018). WestBiofuels reports retail prices of \$1,500-\$16,000 per ton.

Gasification itself is not a novel technology, according to the International Energy Agency (IEA) database, there are 114 operational biomass gasification plants globally with different functionalities (Energies 2018). Majority of the biomass facilities (106 plants) are designed for power production from biomass-derived syngas. The development and implementation of these technologies are primarily in Europe where biomass availability is high, and electricity is scarce. Although the technology is well known, biomass gasification is relatively new to the California marketplace (CEC 2019a). This alternative acknowledges that, proposing a community scale gasification application that is modular, avoiding high capital and maintenance costs compared to the industrial, highly automated systems in Europe. This alternative utilizes rotary gasification with a thermal oil heater and Organic Rankin Cycle generator. It was considered the most appropriate system because its community scale, utilizes local workforce, and produces revenue generating products such as (electricity and biochar). This alternative also works well with California's policies for healthy forest management, renewable electricity, and reduction in forest fires (CEC 2019a).

5.2.1.1 Operational Process and Scale

In 2019, the California Energy Commission published a project report for "Modular Biomass Power Systems to Facilitate Forest Fuel Reduction Treatment" (CEC 2019a). The content of the report evaluated four different systems that utilized either a CircleDraft or Rotary gasifier combined with different types of pre-treatment (drying or torrefaction), heat, and energy generation technologies. The most appropriate system for California was the rotary gasification system as it was determined to be the most robust, modular system that addresses several challenges with gasifiers, such as material flow issues, consistent gas quality, and lower engine maintenance. As Figure 3 shows, this system includes components such as 1) a solid drying and roasting pre-treatment process, 2) a thermal oil heater, 3) a heat exchanger, and 4) an Organic Rankine Cycle (ORC) generator. The report concluded that this system was the most appropriate for California, due to its efficient processing of material, and lower maintenance costs (CEC 2019a).

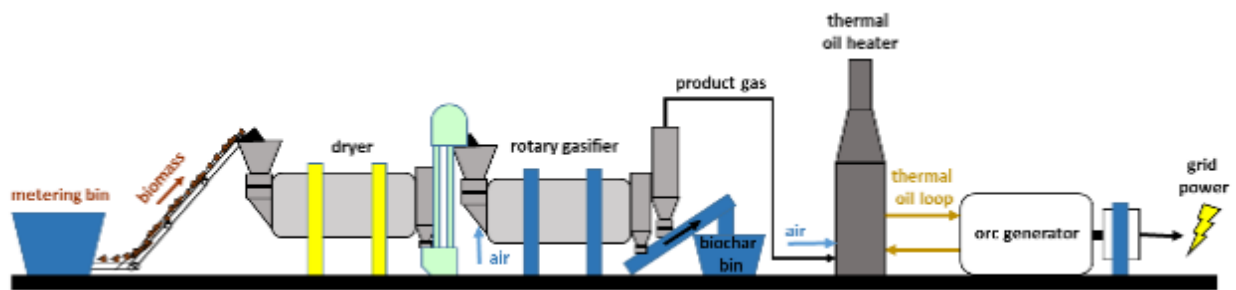


Figure 3. Community scale rotary gasifier system for biomass energy conversion (WestBiofuels 2018).

The capacity factor of an ORC generator is approximately 80-90%; the other proposed systems utilize an engine generator (operating on produced gas) with a capacity factor of 55-80% (CEC 2019a). The torrefier system, part 1, shown in Figure 4, is a 7 MMBtu/h multi-fuel burner which is capable of processing hundreds of different materials over thousands of hours of operation (CEC 2019a). These two items make the efficiency of the system higher and reduces pollutant emissions through the pre-processing and heating (CEC 2019a).



Figure 4. TSI Portable Torrefaction System (CEC 2019a).

The thermal oil (TO) heater, part 2, is configured with burners to convert low-BTU gas, like producer gas, into heat (CEC 2019a). The TO heaters has a higher tolerance for combustion of condensable and particulate matter when compared to gas engines (CEC 2019a). TO heaters also include design advantages such as adaptable control combustion and could be easily for further particulate filtration and catalytic reduction (CEC 2019a). As Figure 5 shows, the system consists of both a radiant and convective chamber for heating thermal oil. All solids, after combustion is deposited at the bottom from both sides of the heat exchanger surface (CEC 2019a). Flue gas is designed to exit the thermal oil section and preheat air prior to combustion. This gas is also designed to re-circulate to assist in optimizing flame characteristics and heat transfer (CEC 2019a).

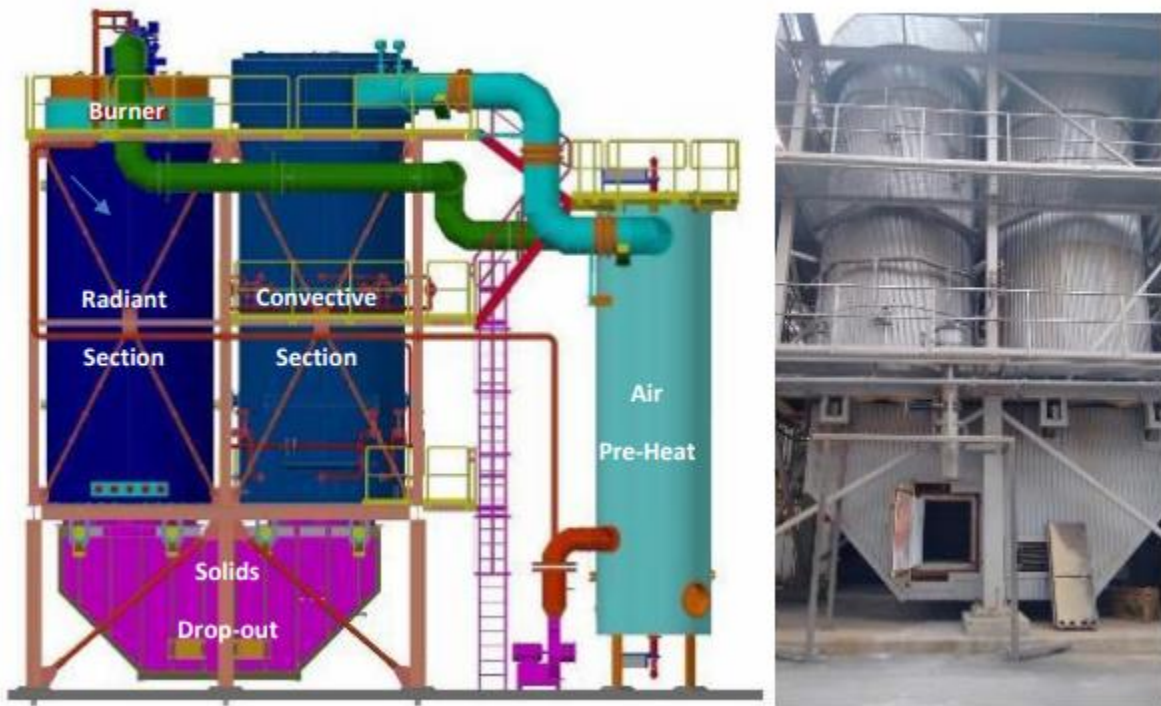


Figure 5. LBG Thermal Oil Heater System (CEC 2019a).



Figure 6. Modular scale, Organic Rankine Cycle (ORC) system (Turboden 2020)

The recommended energy generating system is the Organic Rankine Cycle (ORC) generator, shown in Figure 6, which works through the Rankine thermodynamic principle. This system works as a conventional steam turbine where it transforms thermal energy, to mechanical, and finally into electrical energy using an electric generator (Turboden 2020). Instead of steam, the ORC system vaporizes an organic fluid which slowly turns the turbine, at a lower pressure, with

no erosion to the metal parts or blades (Turboden 2020). The exhaust vapor then is used to preheat the new, evaporating liquid and then condensed to be recirculated again. A diagram of this thermodynamic system is found in Figure 7, the overall process allows for energy generation without additional emissions (WestBiofuels 2018).

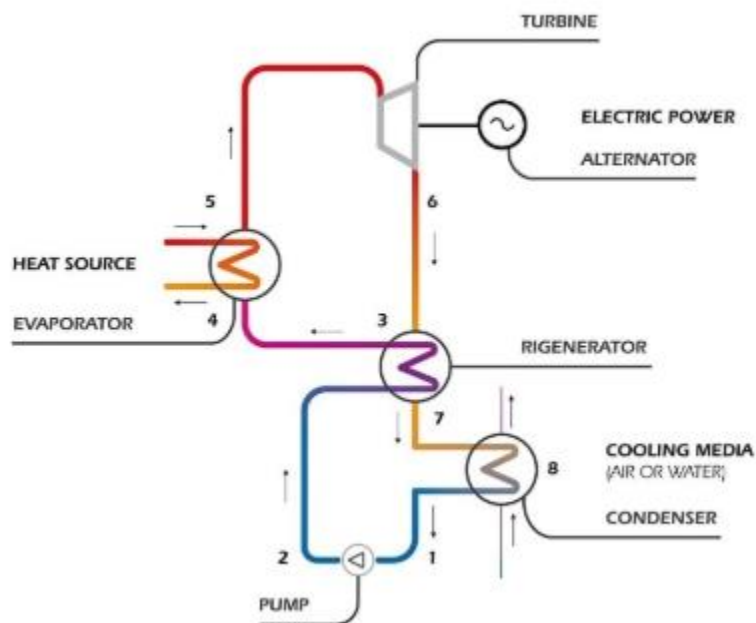


Figure 7. Organic Rankine system thermodynamic cycle (Turboden 2020).

5.2.2 Evaluation of Performance

The performance of this gasification system was evaluated using data from the California Energy Commission Report (CEC 2019a) and several case studies. The evaluation quantifies each criterion summarized in Table 6, these values are later compared and weighted in a Delphi matrix. One key constraint was to utilize 80% of the total biomass demand already established in Humboldt County. A summary of the quantifiable indicators is shown in Table 9.

5.2.2.1 Greenhouse Gases (GHG)

The gasification process itself is known to reduce the amount of both GHGs and air pollutants when combined with a thermal oil heater (TO) (WestBiofuels 2018). The TO heater is efficient in the combustion of particulate matter and includes pollutant reduction methods such as particulate filtration and catalytic reduction. Therefore, the primary source of both GHG and air pollutants are from the formation syn-gas and not combustion. Each facility has an estimated feedstock rate of 4,350 kg of biomass per hour, with only 45% of the initial feedstock eventually converting into syn-gas. The produced syn-gas consists of CO, H₂, CO₂, and CH₄, which are all released used for heating. The proposed rotary gasification system (by WestBiofuels) produces 21% CO, 2.2% CH₄, and 34.5% CO₂ by dry volume. The contribution of greenhouse gases (CH₄

and CO₂) were separately calculated and summarized in Table 9; all other gases were accounted as air pollutants.

5.2.2.2 Air Pollution

As specified in the earlier sections, major air pollutants such as NO_x and PM_x are not directly generated in the Rotary gasifier system due to the use of a thermal oil heater. However, the preprocessing, drying component of the system is known introduce some level of pollution. Therefore, this analysis approximated air pollution based on the Burney-Hat Creek bioenergy facility that utilizes a similar drying process (CEC 2019b). This facility is also scaled for producing 3 MW of electricity at a community scale. It estimates a pollution rates of 0.79 and 1.36 MT per year of NO_x and PM₁₀ for a conservative estimate of 8,760 operating hours (CEC 2019b). The final quantified values for air pollution include both those created during the drying process and generated as a result of gasification (syn-gas 21% CO).

5.2.2.3 Land Use

Land use estimates are based on a dimensional layout provided by WestBiofuels for a modular Organic Rankine Cycle (ORC) system (WestBiofuels 2018). Figure 8 shows the typical lengths for a 3 MW facility. In total, a single facility has a footprint of 1.1 acres. Therefore, 12 modular systems, located in different locations, would result in an approximate footprint of 12.7 acres.

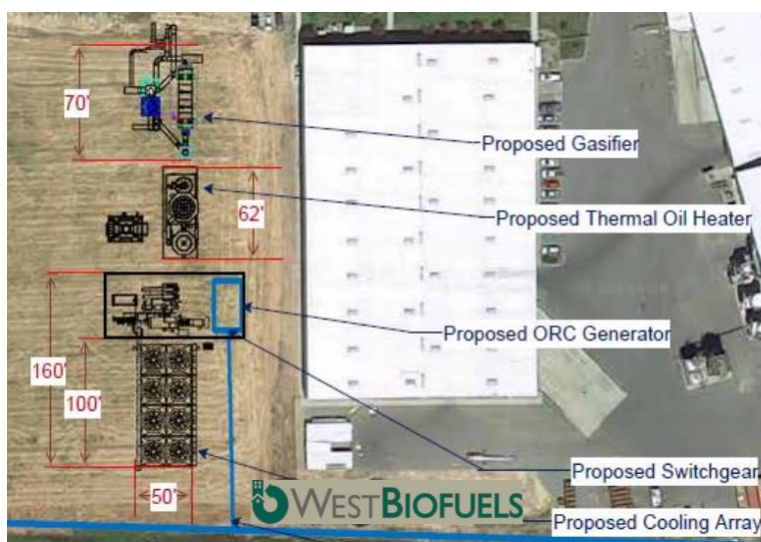


Figure 8. Proposed layout for a single Modular scale, Organic Rankine Cycle (ORC) system (WestBiofuels 2018).

5.2.2.4 Employment

Employment was estimated based a 3 MW biomass facility located in Oroville, California. This biomass power plant uses a typical direct combustion boiler/steam turbine system but operates at a similar capacity of 3 MW (The Beck Group 2015). They assumed a staff of 8 people would be required to operate a 3 MW biomass facility. This includes 1 facility manager, 1 maintenance technician, 4 plant operators, and 2 fuel operators (The Beck Group 2015). Given that roles such as maintenance technicians and fuel operators would most likely be dynamic positions (moving to different sites). A conservative value of 8 employees was chosen to be representative for each

rotary gasification facility. Therefore, with 12 facilities, this allows for a conservative estimate of 94 full-time jobs.

5.2.2.5 Maturity

Maturity was based on a Technology Readiness Level (TRL), which is a number one through nine that represents how well established a technology where one indicates a brand-new technology and nine indicates a technology with the highest level of maturity (Dunbar 2017). Technologies already implemented by WestBiofuels are considered to have a TRL of 6-7 (Molino 2018). Majority of the already implemented demonstrations for wood to energy systems are only community scale with 5 ton/day capacities (Molino 2018). Therefore, this alternative is given a TRL of 6.5, an average within the range.

5.2.2.6 Public Acceptance

Public perception was quantified based on the percent of positive feedback received during a facility tour in Davis CA. This is assumed to be a sample of the population who are familiar with different forms of biomass technology and are knowledgeable of other alternatives. General comments on woody biomass utilization were neutral, only 6 comments out of 12 were positive with others being negative or neutral (Mayhead 2010). Therefore, this alternative is allocated a 50% acceptance value. A general sense from these comments suggests the public considers the north coast an ideal location for biomass utilization but the cost of such facility (gasification) and underdevelopment of the technology is concerning. Some key comments are summarized below (Mayhead 2010).

“I believe that our region (Mendocino County - North Coast) has the biomass material to make a biomass project(s) possible. I believe this region can supply the feedstock necessary for appropriately sized project(s).”

“I am having trouble visualizing woody biomass becoming a viable energy source at any time. Even the producing process seems like a limited benefit other than to cover forest ecology/fire suppression benefits. To proceed with char would require more info on its benefits and possible commercial uses and financial breakdowns.”

“It is good to hear what is going on with the development of biomass. I think that as far as woody biomass goes it isn't economical.”

5.2.2.7 Payback Period

This evaluation utilized the simple payback period by considering the initial capital cost, maintenance cost, and subtracting both the revenues generated from energy and biochar production. The price of energy and biochar production was assumed to be \$199/MWh for forestry derived energy and \$250/BDT for biochar (WestBiofuels 2018). The biochar is priced at its wholesale price and is conservative from the range provided (\$250-\$1000 per BDT). With these assumptions, the initial capital cost was estimated at \$147,000,000 for 12 community scale facilities. This results in a maintenance cost of \$8,300,000 per year for all 12 facilities. Revenue was estimated at \$20,600/yr for energy production and \$19,125,000/yr for biochar production. This results in a simple payback period of 14 years; this estimate for the return period is highly sensitive to the biochar market price.

5.3 Alternative 2: Compost

Composting is the aerobic decomposition of organic matter mediated by micro-organisms to produce a soil amendment (David Border Composting Consultancy 2002). Composting goes through different processes and needs to be in optimal condition to compost at a faster rate than will be further explained below.

Composting goes through two types of processes that include mesophilic and thermophilic (Tchobanoglous and Kreith 2002). For mesophilic composting the temperature ranges between 5°C to 45°C while thermophilic process ranges between 45°C to 75°C and usually there is a combination of these processes, starting with thermophilic going to mesophilic (Tchobanoglous and Kreith 2002). The higher temperature provides a way to remove pathogens (BCC and REE 2016). There are two systems primarily used for composting, windrow and in-vessel (Tchobanoglous and Kreith 2002).

A windrow system can be defined as organic material that is placed in rows and frequently turned, which provides aeration to the system (Tchobanoglous and Kreith 2002). Some advantages of windrow composting are it is a simple process, low cost, can break down multiple types of organic waste, and utilize larger volumes of organic material (BCC and REE 2016). Some disadvantages include the area use, as the rows take up large amounts of space and can produce odor problems if not managed correctly (BCC and REE 2016). An in-vessel system is defined as a forced aeration system where organic material is contained in a closed vessel with a stirring mechanism (Tchobanoglous and Kreith 2002). The advantages of in-vessel composting that it is also a simple system capable of receiving mixed organic material as windrow system (BBC and REE 2016). The disadvantages for in-vessel composting include a higher cost and a limitation on the amount of organic material the vessel can hold (Tchobanoglous and Kreith 2002 & BCC and REE 2016). Based on research, window composting has more advantages and therefore specification focused on this type of composting technology.

For successful composting, optimal physical and chemical characteristics of the feedstock are needed. The optimal physical and chemical characteristics include the C: N ratio of 20-40 to 1, moisture content levels between 40%-60%, and a density less than 600 kg/m³ (Tchobanoglous and Kreith 2002 & USDA 2000). The optimal condition helps minimize odor and speed the process (David Border Composting Consultancy 2002 and Brodie et. al 2000). The speed of the process also depends on the size of the organic waste, the smaller the particle size of the waste the faster the microbial breaks the organic waste (Tchobanoglous and Kreith 2002).

5.3.1 Operational Process and Scale

The operational process of the potential facility was scaled will be further explained. The process for a new facility starts with gathering the woody biomass and other organic material which then is transported to the facility. Then the organic material is deposited to preliminary storage and inspected to determine if the material is suitable for the windrow piles (BCC and REE 2016). Then the organic material is shredded into smaller pieces to make it easier to

decompose (BCC and REE 2016). After this the feedstock is either inspected again through screens or is placed in piles to create the optimal condition for the feedstock used for composting, and this is representing by pre-composting in Figure 9 (BCC and REE 2016). Once placed in piles they are frequently turned to provide aeration throughout the mass (BCC and REE 2016). Then feedstock goes through thermophilic and mesophilic stages while being turned to then produce compost that can be the sold (BCC and REE 2016). The entire process can be followed in Figure 9

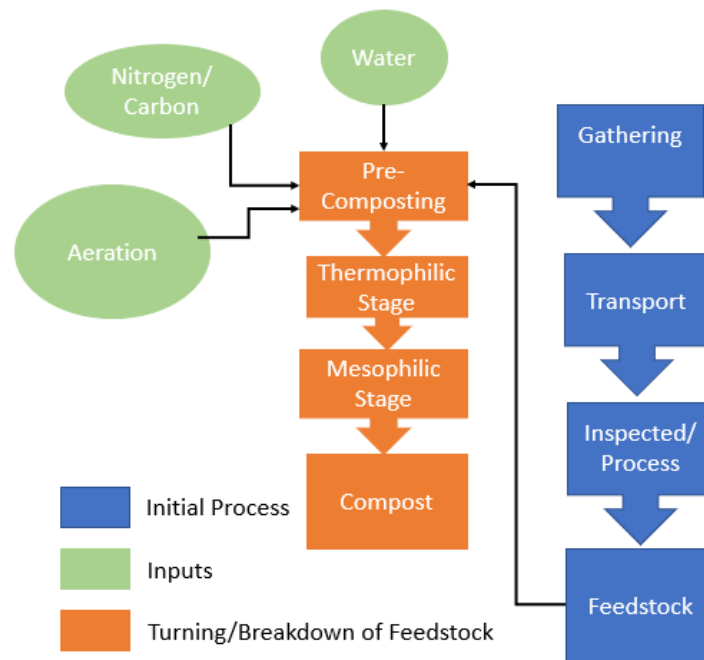


Figure 9: The process of how composting occurs (Image adapted from David Boarder Composting Consultancy and Lee et al 2010).

For scaling the facility there were multiple articles that were used to calculate the amount of Greenhouse gas emissions, air pollutions, land use, employment, the maturity of technology, and public acceptance, and lastly, the payback period of the potential facility using the woody biomass.

5.3.2 Preliminary Evaluation of Performance

Composting as mention before requires optimal conditions. An optimization analysis was calculated based on the optimal physical and chemical characteristic. For this analysis, it was calculated based on the input amount of woody biomass and its assumed properties. The woody biomass, high in carbon, would need nitrogen-rich material like food waste, yard waste, cattle manure, and grass clipping. The nitrogenous material required would be about 8,610 kg/wk to reach a 40:1 C:N ratio. The facility was then scaled based on this total amount. It was assumed that multiple organic materials were available in sufficient quantities to meet this requirement.

5.3.3 Evaluation of Performance

This section will evaluate the performance of the windrow composting alternative.

5.3.3.1 Greenhouse Gases

The first criterion analyzed under the Environmental Criteria was GHGs. The values that were used to scale the amount of woody biomass were obtained from research on yard waste and manure (Vergara and Silver 2019). Though our facility will depend on woody biomass and food waste, the latter of which has high levels of nitrogen elements similar to manure and yard waste. The values calculated from the study were the net of $100 \text{ g CO}_2 \text{ kg}^{-1}$ and median of $1.7 \text{ g CH}_4 \text{ kg}^{-1}$ and both had a moisture content of 50% (Vergara and Silver 2019). These values were then converted to $\text{MTCO}_2\text{e/BDT}$ and then scaled by multiplying the total amount of food waste and woody biomass, then divided by the woody biomass to determine a per unit of woody feedstock basis. The values then calculated to be $2.7\text{E-}01 \text{ MTCO}_2\text{e/BDT}$ and $1.2\text{E-}01 \text{ MTCO}_2\text{e/BDT}$ for CO_2 and CH_4 , respectfully.

5.3.3.2 Air Pollution

The second item analyzed under the Environmental Criteria was air pollution which was broken into four categories, NO_x , PM_{10} , $\text{PM}_{2.5}$, and CO . Values were calculated based on the study called, "Large Scale Aerobic Composting of Source-Separated Organic Wastes: A Comparative Study of Environmental Impacts, Cost, and Contextual Effects" and a total amount of PM of 0.018 kg/ton , divided into 0.009 kg/ton for PM_{10} and 0.009 kg/ton for $\text{PM}_{2.5}$ (Haaren 2009). The values for NO_x and CO were 0.16 kg/ton , 0.082 kg/ton , respectfully (Haaren 2009). These values were converted to MT/BDT units then scaled the total amount of feedstock needed for this alternative. The values were calculated to be $2.1\text{E-}05 \text{ MT/BDT}$, $2.1\text{E-}05 \text{ MT/BDT}$, $3.7\text{E-}04 \text{ MT/BDT}$, $1.9\text{E-}04 \text{ MT/BDT}$, for PM_{10} , $\text{PM}_{2.5}$, NO_x , and CO , respectfully.

5.3.3.3 Land Use

For land use, it was difficult to obtain from individual case studies so for this calculation the book, called the *Handbook of Solid Waste Management* were used (Tchobanoglous & Kreith 2009). In the book the faculty values used were from the two-yard waste composting facility and the values give was 12 acres (Tchobanoglous & Kreith 2009). From this value, it was calculated to be 22 acres.

5.3.3.4 Employment

An article from EPA called "Life Cycle Inventory and Cost Model for Mixed Municipal and Yard Waste Composting," describes that there is a correlation of 100 employees for every 1000 ton per day, so a multiplier of 0.1 was used (Komilis et al. 2004). With this information, it was calculated that around 479 jobs would be created.

5.3.3.5 Maturity

To compare maturity for each alternative the technology readiness level (TRL) was researched was reached for this technology. Technology readiness level is scaled 1-9, 1 referencing to new technology, and fewer studies on it, rather 9 represents a technology that has been there for a while and has more studies. The higher level the more research there is for the technology. The TRL for the windrow composting was determined to be 9 (BCC & REE 2016).

5.3.3.6 Public Acceptance

Composting is a technology that has been used and seen as a “good public image” because it diverts food waste and other organic material from being landfilled (Schaub & Leonard 1996). A survey sponsored by the National Waste & Recycling Associates found that 77% of people agree that composting has a positive impact on the environment (Solorazano et al. 2013).

5.3.3.7 Payback Period

Lastly, the cost was scaled based on a yard waste composting facility with minimal capital cost (Tchobanoglous & Kreith 2009). This capital cost and operation and maintenance were scaled to the current feedstock to calculate a simple payback period which was about 12 years. From this analysis all the values are demonstrate on Table 9 and the raw data used for this analysis can be found in Appendix B: Alternative 2.

5.4 Alternative 3: Torrefaction

Torrefied biomass results from a thermochemical process, which results in a higher energy content and lower moisture content product referred to as biochar (Batidzirai et al. 2013). The O/C ratio of the biomass is lowered during torrefaction due to volatile components being dissipated in the process (Nanou et al. 2015). The resulting product is easier to store than untreated biomass due to its hydrophobicity, which would otherwise begin rotting (Van der Stelt et al. 2008). Torrefaction is considered a pre-treatment method, where it is conducted without the presence of oxygen and at temperatures ranging from 200 °C to 300 °C (Nanou et al. 2015). An appealing aspect to torrefaction is that the gas produced can be used to fuel the system and provides circularity to the process (Koppejan et al. 2012). There are multiple applications of the torrefied biomass. The product can be used as a fuel for energy production, since less grinding energy would be required in comparison to untreated biomass (Eseyin et al. 2015). Biochar can also be used in construction materials to adsorb carbon dioxide and therefore lower emissions of carbon in buildings (Gupta and Kua 2017). Pelletized biomass from torrefaction can result in higher efficiencies in gasification (Koppejan et al. 2012). Biochar can also be used in soil improvement applications (Schmidt 2012).

France studied the torrefaction process around 1930 (Van der Stelt et al. 2008). Multiple pilot and demonstration scales of torrefaction have been carried out in Europe (Thrän et al. 2015). Torrefaction is becoming more popular and has recently moved from the research and development stage to introduction in the market and operation commercially (Koppejan et al. 2012).

5.4.1 Operational Process and Scale

Figure 10 contains a schematic of the torrefaction process and each input, output and associated parameters at each step. Thermal decomposition of the following components of biomass occurs: hemicellulose, cellulose, and lignin (Barskov et al. 2019). The degradation of hemicellulose is the main contributor to the formation of gasses that have high oxygen content (Medic et al. 2011). The first step in torrefaction is heating of the biomass to reach the drying temperature for evaporation of the humidity to occur (Ribeiro et al. 2018). The next step is pre-drying conducted at 100 °C, in which water on the biomass starts to evaporate (Ribeiro et al. 2018). Post-drying consists of temperature rising until reaching 200 °C, where all water is evaporated (Ribeiro et al. 2018). Torrefaction is the step that results in the highest amount of mass reduction and is

conducted at 200 °C (Ribeiro et al. 2018). There are 6 different types of reactors in which torrefaction can be conducted: fixed bed torrefaction reactor, microwave reactor, rotary drum reactor, and fluidized bed torrefaction reactor (Ribeiro et al. 2018). Lastly, cooling takes place to decrease below the torrefaction temperature and stabilize to room temperature before being exposed to the air (Ribeiro et al. 2018). Torrefaction is most commonly carried out in the absence of oxygen to minimize reactions (Barskov et al. 2019). The resulting product consists of mostly cellulose and lignin and has the following characteristics: brittle, hydrophobic, resistant to microbial degradation, and a higher energy density (Medic et al. 2011).

In Europe, there are eight torrefaction industrial facilities planned to operate with capacities ranging from 8,000 tons per year to 100,000 tons per year (Ribeiro et al. 2018). Currently the facilities that exist mainly use sawdust, but there are some facilities that can handle larger particles of woody biomass (Koppejan et al. 2012). The first torrefaction plant in the United States being built as of 2018 is in Oregon for the company Oregon Torrefaction with an expected capacity of 100,000 tons per year (Banse 2018 and Oregon Torrefaction, LLC 2018).

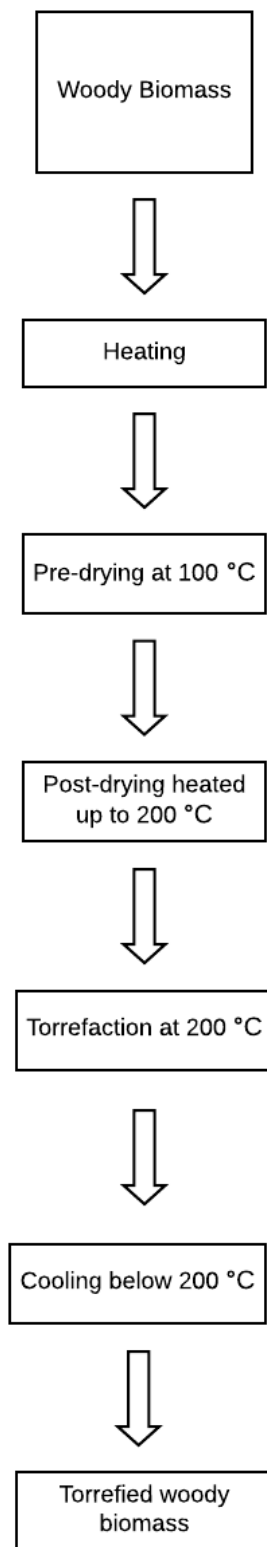


Figure 10. Operational process for torrefaction of woody biomass (Image adapted from Ribeiro et al. 2018).

5.4.2 Evaluation of Performance

This section outlines the approach and results from quantifying each criterion from Table 6. A summary table of all the results are shown in the Table 9. It is assumed that Torrefaction will be conducted at 270 °C. It was also assumed that for every 1.328 kg of woody biomass, 1 kg of torrefied wood was produced (NETL 2012).

5.4.2.1 Greenhouse Gases

Carbon dioxide and methane were the two greenhouse gases calculated. A study was conducted where 1.328 kg of biomass was converted to 1 kg of torrefied wood (NETL 2012). Emission factors were reported in the study for both greenhouse gasses in units of kg of the greenhouse gas per kg of torrefied wood. The raw data from this study is shown in Table C1 of Appendix C. Greenhouse gas emissions of torrefied pellets compared to conventional pellets are lower due to the higher energy product that results from torrefaction (Thrän et al. 2015).

5.4.2.2 Air Pollution

From the same study used to quantify the greenhouse gas emission, there were also emission factors listed for the following pollutants: PM₁₀, CO, and NO_x (NETL 2012). Torrefaction removes volatiles from the biomass, which explains the result of this alternative releasing a lower amount of criteria pollutants in comparison to combustion.

5.4.2.3 Land Use

To determine the amount of land required for a torrefaction facility, the parcel feature on Google Earth was used on the Oregon Torrefaction plant with an area of 20.6 acres (Google Earth 2020).

5.4.2.4 Employment

The number of job openings from the Oregon Torrefaction plant is 39 (Hanners 2019). It is important to consider that for land use and employment that these are possibly smaller values since the amount of torrefied wood for Oregon Torrefaction is 280,000 BDT/year less than the proposed alternative.

5.4.2.5 Maturity

An average was taken between three studies found that provided a maturity level for torrefaction. The results of these studies are shown in Table C2 of Appendix C. An averaged value of TRL 5 was determined (European Commission 2017, E4tech et al. 2014, BIOCORE 2014, RHC 4014, Stafford et al. 2014, Dodwall 2015).

5.4.2.6 Public Acceptance

Public acceptance was difficult to measure since there are no specific studies on how torrefaction is perceived. Workshops from RCEA as well as a biomass utilization workshop conducted by the University of California, Berkeley were used to determine whether torrefaction had a negative or positive public view (Mayhead et al. 2012 and RCEA 2019b). Since torrefaction is pyrolysis conducted at lower temperature, the two terms were used interchangeably when analyzing the public comments. Two comments on the Berkeley workshop had a positive sentiment towards use of pyrolysis to densify woody biomass. Torrefied wood is similar to biochar, so the

perception towards biochar was assumed to be the same. In a study, there was a 73% support towards production of biochar (Bergman et al. 2018).

5.4.2.7 Payback Period

A study focusing on the cost analysis of torrefaction was used to quantify the simple payback period associated with this alternative (Cherry et al. 2013). The capital costs of three existing facilities were scaled up to a cost that would meet the biomass demand and were then averaged. The raw data from this study is shown in Table C3 and Table C4 of Appendix C. Costs added to this averaged value were: electricity, operating labor, maintenance labor, operating expenses, and thermal processing cost which were found in the same study. A revenue of \$40 per ton of torrefied wood was assumed since this is the expected price of this product (Ortiz et al. 2011).

5.5 Alternative 4: Biomass to Ethanol

Biomass-to-liquid (BTL) fuel is an alternative that would transform raw woody residues into a fuel product that could be used in energy generation or as a replacement for fossil-fuel derived equivalents like gasoline. An simplified flowchart of the processes is shown in Figure 11 below; the process breaks woody biomass up into its constituents, lignin, cellulose, and hemicellulose, and then into C₅ and C₆ sugars, which are fermented and distilled into ethanol (Valdivia et al. 2016). While ethanol is the main pathway, there are additional pathways adjacent-to, and utilizing waste products of, the primary product stream, producing valuable resins, adhesives, and additional energy products (Dufour 2016). There are two types of biomass fuel sources, first- and second-generation. Amid the food versus fuel debate, the acceptance of food-grade feedstock has dwindled, in favor of second-generation feedstocks, like forest residues, grasses, and algae, which are widely abundant and cheap, and can produce bio-oils and lignocellulosic ethanol, two products that can be utilized to replace fossil-fuel equivalents (Naik et al. 2010).

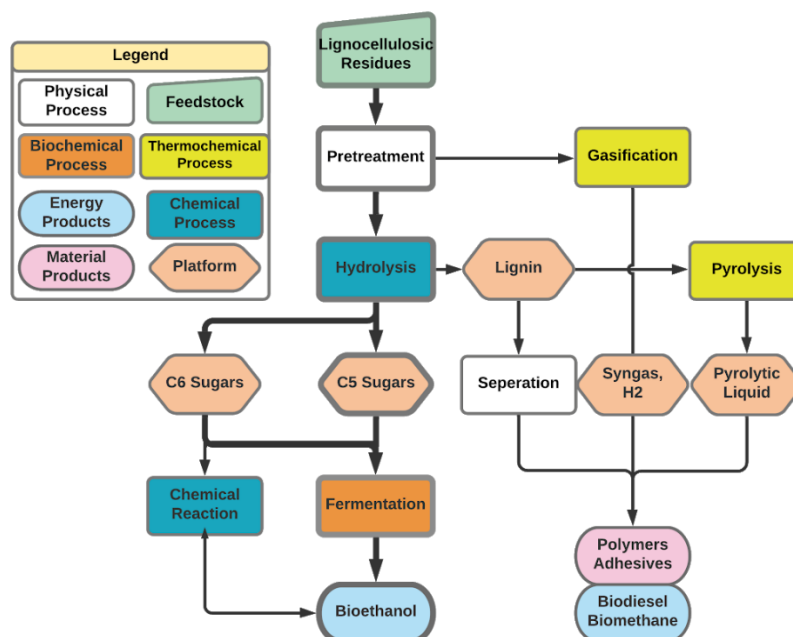


Figure 11: Simplified Biomass-to-Ethanol input and output pathway, with the main pathway bolded (Adapted from Dufour 2016 and Naik et al. 2010).

5.5.1 Operational Process and Scale

One of the difficulties in using second-generation feedstocks, like woody biomass, is separating the cellulose from the lignin of the lignocellulosic material, which is resistant to degradation (Rosales-Calderon and Arantes 2019). Through different chemical, physicochemical, and biological processes, the two components can be separated and processed independently. These processes can include, but are not limited to, ozonolysis, CO₂ explosion, and microorganism pretreatment (Zabed et al. 2016). Acid catalyzed steam explosion with Sulfuric Acid is a common physicochemical separation method, utilizing sulfuric acid with steam at temperatures of about 160 to 220°C (Zabed et al. 2016). One of the typical pathways is shown in Figure 12 below. The biomass goes through enzymatic hydrolysis, where enzymes break the newly freed cellulose up into sugar molecules (Valdivia et al. 2016). The sugar molecules can then be utilized by yeast through fermentation; The product is separated and distilled into ethanol and lignin-rich stillage and can be fed through additional valorization processes (Valdivia et al. 2016).

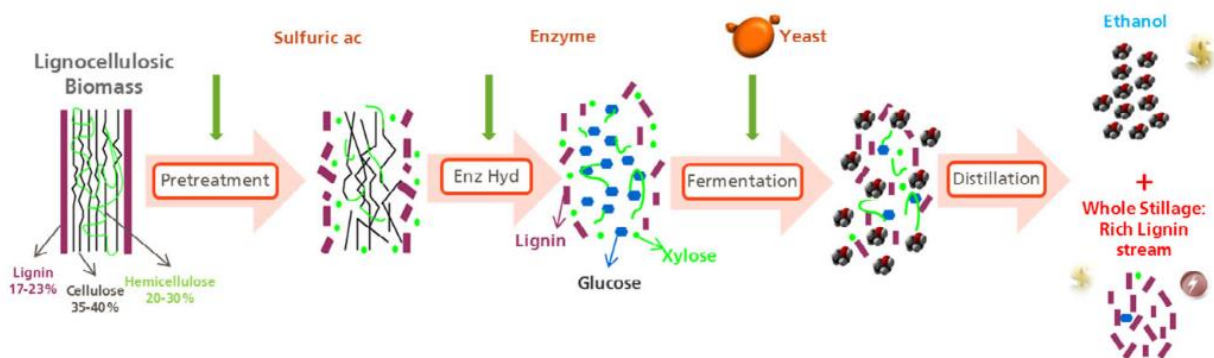


Figure 12: Lignocellulosic feedstock to Ethanol chemical processes (Valdivia et al. 2016).

As food-grade feedstocks are at the heart of the food-vs-fuel debates, second-generation ethanol plants have risen in popularity (Naik et al. 2010). Projects can be standalone, bolt-on, or integrated. Current first-generation plants have taken advantage of integrated systems, where the process encompasses many pathways in one facility. The projects start with a standalone process, focusing on one of those pathways, before making use of auxiliary facilities located nearby to increase value from additional waste streams (Valdivia et al. 2016). While ethanol plants that use corn are highly abundant and proven, there are proven ethanol plants that use woody feedstock, mostly in the Nordic Regions. Domsjö Fabriker, in Sweden produces bioethanol and other products from spruce and pine waste, processes over a million cubic meters of wood a year and employs about 350 people (Domsjö Fabriker 2019). In addition, Aemetis, Inc. has an existing biomass to ethanol processing facility in Keyes, CA building improvements to accommodate orchard wastes, accommodating the 1.6 million tons of orchard waste produced every year by 2022 (Martin 2020). The generalized wood biomass to ethanol train can have yields around 89.5 gallons per ton of feedstock results in a theoretical yield of about 40 MGY (BRDB 2008).

5.5.2 Evaluation of Performance

The performance of an Ethanol facility will be evaluated in this section using various studies and test cases. The evaluation quantifies each criterion from Table 6. The alternative must be able to handle the total Humboldt biomass demand. A summary of the quantifiable indicators is shown

in the Table 9. It is assumed that the process will follow a dilute acid hydrolysis and fermentation route.

5.5.2.1 Greenhouse Gases

Greenhouse gases for this analysis included carbon dioxide and methane. Using the Bluefire Ethanol Facility environmental assessment, greenhouse gas emissions were estimated on a unit basis with respect to feedstock tonnage. The study converted about 425,000 tons of biomass to ethanol and resulted in GHG emissions of about 399,000 and 35.8 tpy of CO₂ and CH₄ respectively (AECOM 2010). Warming Potential was used with methane to determine its equivalents in metric tons of CO₂e per BDT, and then added together before being compared to the baseline emissions. If compared on CO₂ alone, the liquid fuel production would about equal to the combustion of the plants, but the higher CH₄ emissions make the alternative slightly worse in terms of GHG emissions. This could be reevaluated as more information is obtained.

5.5.2.2 Air Pollution

The same study was used to quantify the air pollution potential in tons/year including: NO_x, PM₁₀, PM_{2.5}, and CO (AECOM 2010). Emission factors were estimated using the tons of biomass feedstock processed and the air pollution generated. Using these estimated emission factors, the Humboldt Biomass demand was used to obtain the potential for the theoretic ethanol facility. Overall, the air pollution was estimated as higher than the current technology in all four categories. The addition of extra control technology compared to the Bluefire Facility, would be recommended. Compared to the high capital costs of these types of projects, it is likely the budget could have some flexibility with additional equipment.

5.5.2.3 Land Use

The land use was determined using a study of three different sources, two facilities, and one government guidance document. The first facility had an area of about 15 acres, the second about 14 acres, and the guidance document recommended 10-15 acres (US DOE 2005, AECOM 2010, CFDC 2006). An average of these values resulted in about 14 acres.

5.5.2.4 Employment

The employment was determined by using two surveys, and three example facilities, one of ethanol refineries in Nebraska, and another by Agriculture and BioFuels Consulting. These surveys resulted in 60 and 50 jobs per facility (Grimes 2019, Urbanachuk 2019). Another job analysis was performed using three facilities, which had employees of about 60, 32, and 67 respectively (Humbird et al 2011, US DOE 2005, AECOM 2010) The number of jobs was divided by the ton capacity of the facility to obtain a job/ton basis, which was applied to the theoretical Humboldt facility. The average of this analysis was about 51 jobs. The overall average was about 52 jobs for a general ethanol to liquid fuel facility.

5.5.2.5 Maturity

The Technologic Readiness Level was used to measure maturity, and ranged from TRL4, Pilot, to TRL8, First-of-its-kind commercial demo, with many projects across the US and Globe having the latter distinction (UNCTAD 2016). An average was taken of the ethanol facilities that used lignocellulosic, forest, and wood residues. An average of 6.41 was found from the 11

facilities using those waste products. This TRL falls in the range of technological demonstration and system model in a relevant environment, essentially full-scale prototyping (ARENA 2014)

5.5.2.6 Public Acceptance

Public acceptance was difficult to quantify without a public perception survey, which time and current social conditions make difficult; however, biomass alternatives have been addressed in a few related studies. A CAPE comment on the RePower Humboldt plan indicated biodiesel and ethanol should be encouraged (RCEA 2019b). UC Berkeley sponsored a series of regional workshops on biomass utilization from 2007-2010, and comments from the Eureka region spoke positively of incorporating local ethanol production from the local biomass, but more research on the current attitudes of the public should be further explored. (Mayhead et al 2010).

To better quantify this value, studies were sought for the general perceptions of the renewable fuel industry, biodiesel, and ethanol. General studies in North America and Europe have found public perception for alternative transportation fuels to range between 59 and 81% (Jensen et al 2012, Savvanidou et al 2010, IRENA 2019, Revelator 2019, Austin 2010). The average for all regions was 67%, while the average for the two US regions was 62%.

5.5.2.7 Payback Period

Costs for this process were difficult to determine. For the capital estimations, two case studies and a scaled analysis were used to determine an average cost/ton for a biomass to ethanol facility. One case is a well quantified NREL case study and was also used to scale the process to the Humboldt Biomass demand, and the other facility was Bluefire Ethanol in Mississippi (Humbird et al 2011, AECOM 2010). The NREL test case used about 2000 tons/day, so the facility's equipment was scaled in half and rounded up, using the assumption the bundled equipment would be able to be scaled. The equipment that one, or an odd number, was required of was rounded up after halving. After totaling the cost of equipment, the values were corrected from their 2007 values to 2020 values using the Producer Pricing Index (PPI). The jobs and salary were scaled in a similar way, using the ratio of Humboldt biomass compared to the test case facility biomass, and rounded up. The operating costs were estimated using the feedstock costs, which incorporated current market prices where available, and scaled from 2007 values using the PPI when not available, and the facility's feedstock use to estimate a yearly operating budget. The costs were scaled to Humboldt's biomass requirement, and then corrected using the PPI. Overall, capital costs were estimated at an average of \$577/ton or about 260 million dollars for the Humboldt facility. There is the Rural Energy for America Program (REAP), which assists renewable energy improvements with financial assistance, and in which this facility and location would be considered eligible for aid up to \$25 million, and the Biorefinery Assistance Program can provide funding up to \$250 million or 80% of the capital costs (USDA 2020b, USDA 2020a). Using the scaled analysis yearly costs were estimated at about 55 million dollars. The market price of ethanol in March of 2020 was about \$1.19/gal (USDA 2020c). 37 MGY of ethanol projected from the scaled analysis would result in about 44 million dollars a year. An available fuel credit brings the value of ethanol up \$1.01/gal to \$2.20/gal (U.S. Code § 40A). Even with this additional credit, if the income tax rate is still assumed to be 35%, like in the NREL test case, additional credits or tax breaks of about \$0.46 would be required to achieve a payback period of 30 years, which is the typical lifetime of these types of plants (Humbird et al

2011). There is current legislation favoring the technology with tax credits, Aemetis was awarded a sales and tax exclusion amounting to about \$12.7 million for their biofuels projects (Aemetis 2019).

6 Alternative Decision Process

The alternative decision process section consists of the Pugh Method and Delphi Method to determine the best alternative based on the designated constraints and criteria developed from the client and the Biomasssters team.

6.1 Pugh Method

There are five steps to conduct the Pugh Method followed by multiple iterations of the steps. The criteria are listed, a baseline is chosen, the alternatives are listed, either a plus or minus sign is assigned for each alternative in comparison to the baseline, and then the scores are combined (MSG 2020). A plus indicates that the alternative is better than the baseline while a minus indicates the opposite. Once the alternative with the highest overall weighted score is determined, another iteration is conducted where the winning alternative becomes the baseline. If all other alternatives remain with a negative score, it proves that the designated baseline alternative is the best.

In this case, the baseline for the first iteration is the current status of the DG Fairhaven and Scotia biomass plants. Table 7 contains the first iteration of the Pugh Method showing that Alternative 2 is the best. Alternative 2 had a total weighted score of positive six, followed by Alternative 1 with a score of positive 5, Alternative 4 with score of 4, and Alternative 3 with a score of two. The second iteration is shown in

Table 8 where Alternative 2 is shown to be on par with Alternative 3. It is important to note that this method does not take into account the weights set by the client, which is why the Delphi Method was used to consider the importance of the different aspects to the client.

Table 7. Iteration one of the Pugh Method.

Criteria	Baseline = DG Fairhaven+Scotia Plant	Alternative 1	Alternative 2	Alternative 3	Alternative 4
Environmental Criteria					
CO₂	0.89	1	1	1	1
CH₄	2.48E-04	1	-1	1	-1
PM₁₀	1.22E-04	1	1	1	1
PM_{2.5}	1.13E-04	N/A	1	N/A	1
CO	-	N/A	N/A	N/A	N/A
NO_x	5.87E-04	1	1	1	1
Land Use	20	1	1	0	1
Social Criteria					

Criteria	Baseline = DG Fairhaven+Scotia Plant	Alternative 1	Alternative 2	Alternative 3	Alternative 4
Employment	47	1	1	-1	1
Maturity	TRL-8	-1	1	-1	-1
Public Acceptance	-	N/A	N/A	N/A	N/A
Economic Criteria					
Payback Period	NA	N/A	N/A	N/A	N/A
	Sum of positives	6	7	4	6
	Sum of negatives	-1	-1	-2	-2
	Total weighted score	5	6	2	4

Table 8. Iteration two of the Pugh Method.

Criteria	Baseline = Alternative 2	Alternative 1	Alternative 3	Alternative 4
Environmental Criteria				
CO2	5.17E-02	1	-1	1
CH4	9.53E-02	1	1	1
PM10	2.07E-05	-1	1	1
PM2.5	2.07E-05	N/A	N/A	1
CO	1.89E-04	1	1	-1
NOx	3.68E-04	1	1	1
Land Use	3	-1	-1	-1
Social Criteria				
Employment	479	-1	-1	-1
Maturity	TRL-9	-1	-1	-1
Public Acceptance	77%	-1	1	-1
Economic Criteria				
Payback Period	12.0	-1	-1	-1
	Sum of positives	4	5	5
	Sum of negatives	-6	-5	-6
	Total weighted score	-2	0	-1

6.2 Delphi Method

The Delphi method was used make the final alternative determination. This method uses scoring bins to assign values to each alternative with respect to the different quantifiable criteria. Using the individual analysis, the indicators were combined in Table 9 below. These indicators were then used to develop the scoring matrix in Table 10 and used to determine the allocated score for each criterion and alternative.

Table 9. Quantifiable indicators for each alternative by criteria

Criteria	Alternative 1	Alternative 2	Alternative 3	Alternative 4
GHG (MTCO₂e/BDT) (% Change)	-100.0%	-56.45%	-94.08%	-99.66%
Air Pollution (MT/BDT)	7.7E-05	5.8E-04	1.3E-04	2.9E-03
Land Use (Acres)	12.7	3	20.6	14
Employment (Jobs)	94	479	39	52
Maturity (TRL)	7	9	5	6
Public Acceptance (%)	50%	67%	>90%	62%
Payback Period (Years)	14	12	4	30

Table 10. Scoring table for each criterion.

Score	1 – 2	3 – 4	5 – 6	7 – 8	9-10
Criteria	Poor	Less than Average	Average	Greater than Average	Excellent
GHG (MTCO₂e/BDT) (% Reduction)	<80%	80 - 85%	85% - 90%	90%-95%	>95%
Air Pollution (Total MT/BDT)	>.0004	0.0004-0.0003	0.0003-0.0002	0.0002-0.0001	<0.0001
Land Use (Acres)	>30	20 to 30	15 to 29	10 to 14	<10
Employment (Jobs)	<10	10-30	30-60	60-90	>90
Maturity (TRL)	TRL 1-2	TRL 3-4	TRL 5-6	TRL 7-8	TRL 9
Public Acceptance (+/-)	0-20%	20-40%	40-60%	60-80%	80-100%
Payback Period (Years)	30+	20 to 30	10 to 20	5 to 10	<5

The client was solicited for weighting the individual criteria, and these weights were then used with the allocated scores to generate weighted scores each criterion. These scores were then summed together to determine the overall alternative score, with the highest combined score as the chosen alternative. The results of the final Delphi Matrix are shown in Table 11 below.

Table 11. Delphi summary table for all four alternatives.

Criteria	Weight	Gasification		Composting		Torrefaction		Liquid Fuel	
		Allocated	Weighted	Allocated	Weighted	Allocated	Weighted	Allocated	Weighted
Environmental Criteria									
GHGs	4	10	40	4	16	8	32	9	36
Air Pollution	4	10	40	2	8	8	32	6	24
Land Use	2	8	16	1	2	4	8	6	12
Social Criteria									
Employment	3	9	27	10	30	5	15	6	18
Maturity	2	7	14	9	18	5	10	6	12
Acceptance	5	5	25	7	35	10	50	7	35
Economic Criteria									
Payback	10	6	60	10	100	9	90	1	10
Score	High	222		197		237		147	

7 Specification of Solution

7.1 Basis of Design

The torrefaction alternative proved to be the best nonpolluting, renewable, and yet low-cost alternative. Economically, the implementation of a project this size and the production of a low-cost fuel source gave this alternative an advantage. For the analysis of the preferred alternative, a total mass of 561,600 MT/yr (at 50% moisture content) or 280,800 BDMT/yr and a density of 247 kg/m³ was assumed, in order to harmonize assumptions across engineering teams (Bob Marino personal communication, 2020).

The thermochemical process of converting biomass into solid fuel with reduced Oxygen/Carbon and Hydrogen/Carbon ratios provides a cleaner source of energy. Apart from reducing emissions from energy production, torrefaction also indirectly reduces emission from transportation given that this process increases the energy density. Therefore, more potential energy is being delivered per truckload of torrefied wood compared to the current untreated biomass.

The final products are high-quality fuel pellets, with similar characteristics to coal, with an increase in calorific value caused by the removal of moisture and some organic compounds from the original biomass (Koppejan et al. 2012). The torrefaction process is intended to maintain all volatile matter (and thereby energy) within the final torrefied pellets (Koppejan et al. 2012). Table 12 summarizes a comparison between wood, wood pellets, and torrefied pellets (Koppejan et al. 2012). The results show beneficial changes such as lower moisture content, higher energy density, hydrophobic properties, superior handling and grindability and lastly, low biological degradation. These properties are crucial for long term storage, transportation, and reduction in GHG emissions.

Table 12. Summary of fuel characteristics for wood, wood pellets and torrefied pellets (Koppejan et al. 2012).

Property	Wood	Wood Pellets	Torrefied Pellets
Moisture content (% wt)	30-45	7-10	1-5
Lower heating value (MJ/kg)	9-12	15-18	20-24
Volatile matter (% db)	70-75	70-75	55-65
Fixed carbon (% db)	20-25	20-25	28-35
Energy density (GJ/m ³)	2.0-3.0	7.5-10.4	15-18.7
Hydroscopic properties	Hydrophilic	Hydrophilic	Hydrophobic
Biological degradation	Yes	Yes	No
Handling	Special	Special	Good
Grindability	Poor	Poor	Good

Torrefaction is relatively new but has several well developed and currently available reactors in the market. There are nearly 100 patents and more than 50 technology developers with several torrefaction technologies (Dhungana 2012). Generically, the choice of a reactor is characterized by the design. This includes distinct modes of heat transfer and the gas-solid or solid-solid mixing patterns in the reactor. Two of the most common reactors are direct and indirect heated reactors. Directly heated reactors have biomass in direct contact with heated media completely free of oxygen; a common example is a fluidized bed reactor. Indirect methods keep both the heating element and the biomass separate, providing no presence of oxygen in the reactor (Dhungana 2012). There is a wide selection of different reactors but all produce torrefied wood. A summary is provided in Table 13 of a few designs with the respective supplier for the client's convenience.

Table 13. A summary of different Torrier technologies with suppliers. This includes suppliers from different countries; each country is abbreviated in parenthesis (Dhungana 2012).

Torrefier Type	Technology Supplier	Reactor Type
Rotary drum reactor	CDS (UK), Torr-coal (NL), BIO3D (FR), EBES AG (AT), 4Energy Invest (BE), BioEndev/EPTS (SWE), Atmosclear S.A. (CH)	Rotary
Screw conveyor	BTG (NL), Biolake (NL), FoxCoal (NL), Agritech (US), Allied Blower, Picheney	Rotary
Fluidized bed	Toppel (NL)	Entrained
Microwave	Rotawave Ltd (UK)	Microwave
Moving bed	ECN (NL), Thermya (FR), Buhler (US)	Convective
Belt conveyor	Strampoy Green Investment (NL), NewEarth Eco Technology (US)	Convective

7.2 Design Specifications

The proposed, general design for the torrefaction facility could be applied with various reactor concepts but follows a traditional feedstock input and results in heat processing of biomass, densification, and incorporates heat recycling methods to reduce dependency on fossil fuels. This heat recycling includes the recirculation of flue gas for indirect process heating within the drying process.

Figure 13 provides an overview of the complete system, all biomass (typically at a 50% moisture content) is fed into a drier before entering the torrefier. The dried torrefied product is then conveyed to the cooling system and eventually pelletized for distribution. The gas recycling process involves the combustion of air, fuel, and flue gas for the heat production to operate the heat exchanger. This heat loop flows hot gas through the torrefier to indirectly heat the biomass consequently producing additional torrefied gas (for further combustion and cycling). Figure 14 shows an overview of the different temperatures required for torrefaction for all stages.

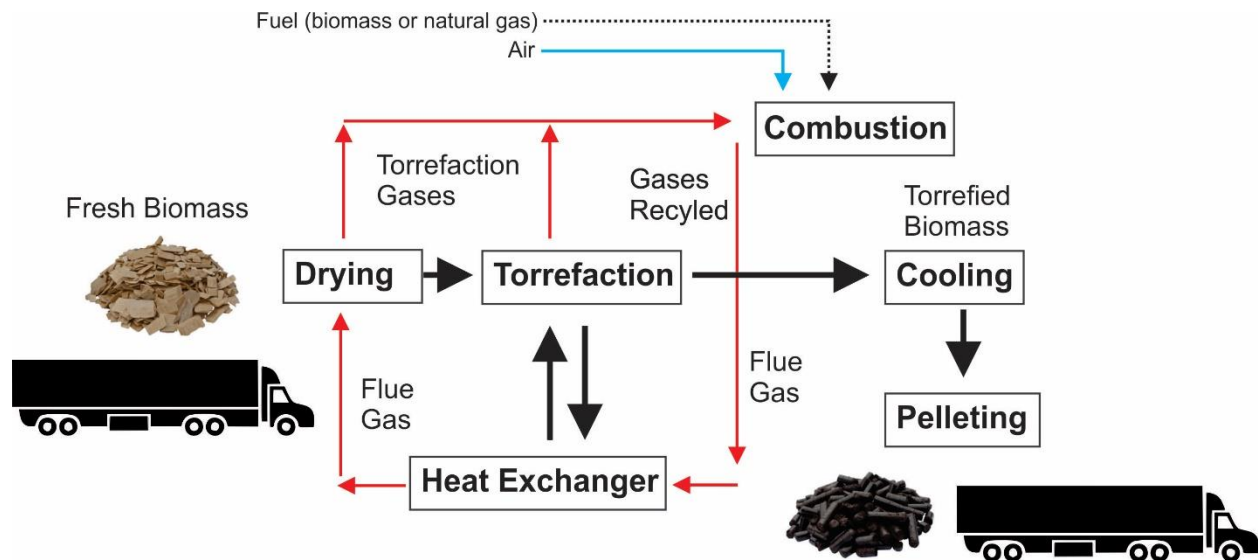


Figure 13. Total system schematic for processing biomass (at 50% moisture) to torrefied pellets (modified from Cremers 2015).

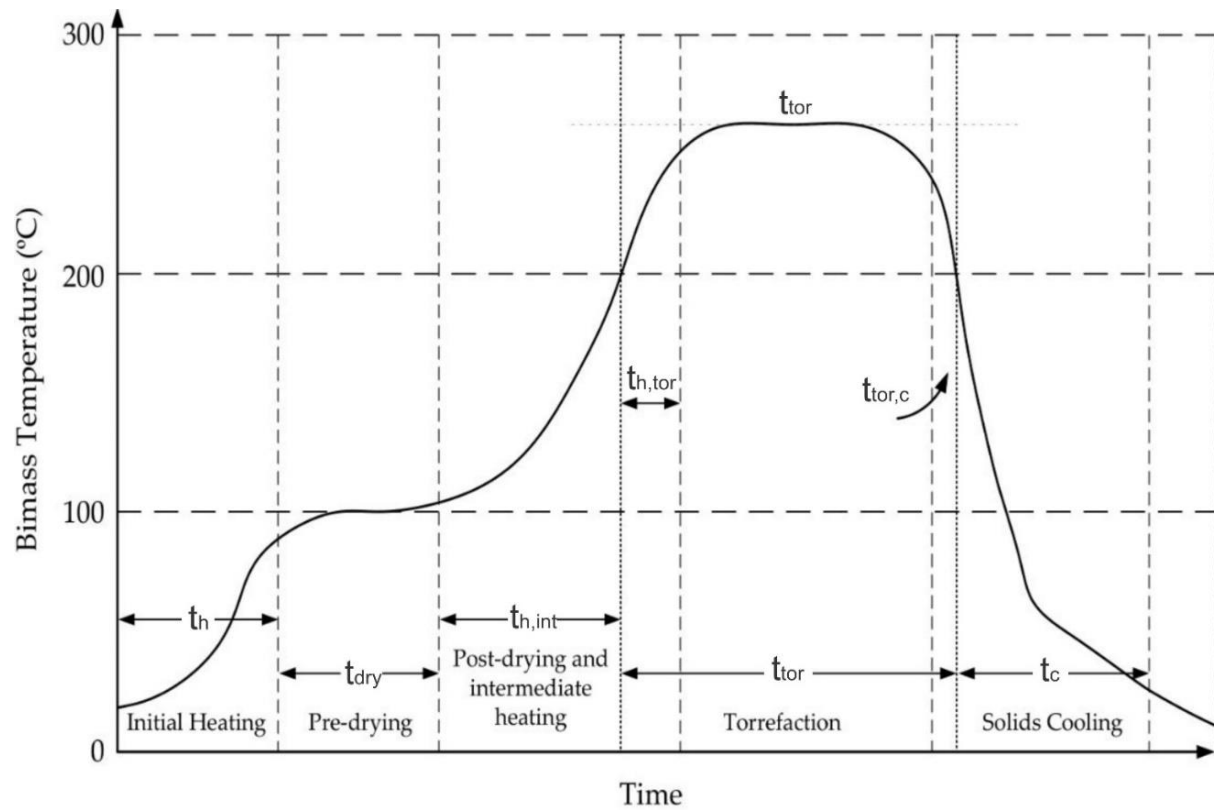


Figure 14. Shows the different torrefaction stages based on temperature. This includes the drying, torrefaction, and solids cooling phases of the process (modified from Ribeiro 2018).

The recommended reactor for this system is a rotating drum torrefier which is considered best for applications where torrefaction is carried out offsite and transported (Dhungana 2012). This is justified given that this reactor produces pellets with a higher energy density compared to other common reactors (Dhungana 2012). This results in a reduction in transportation costs (measured in \$/MJ/km transported) and emissions given that fewer truckloads are required for the same energy content. Figure 15 shows a schematic of how this reactor works regarding the mixing and heating process. The drum is designed to rotate at low speeds (2.9 rpm) as it is indirectly and directly heated with hot flue gas and radiative heaters to provide the necessary temperatures and inert atmosphere for the torrefaction process (Dhungana 2012). These reactors typically have a capacity of 50,000-25,000 ton/year; the reactor works best with externally dried biomass to reduce the moisture content (Shoulaifar 2015). Temperatures within the reactor reach 250-300 °C with a residence time of 30 minutes.

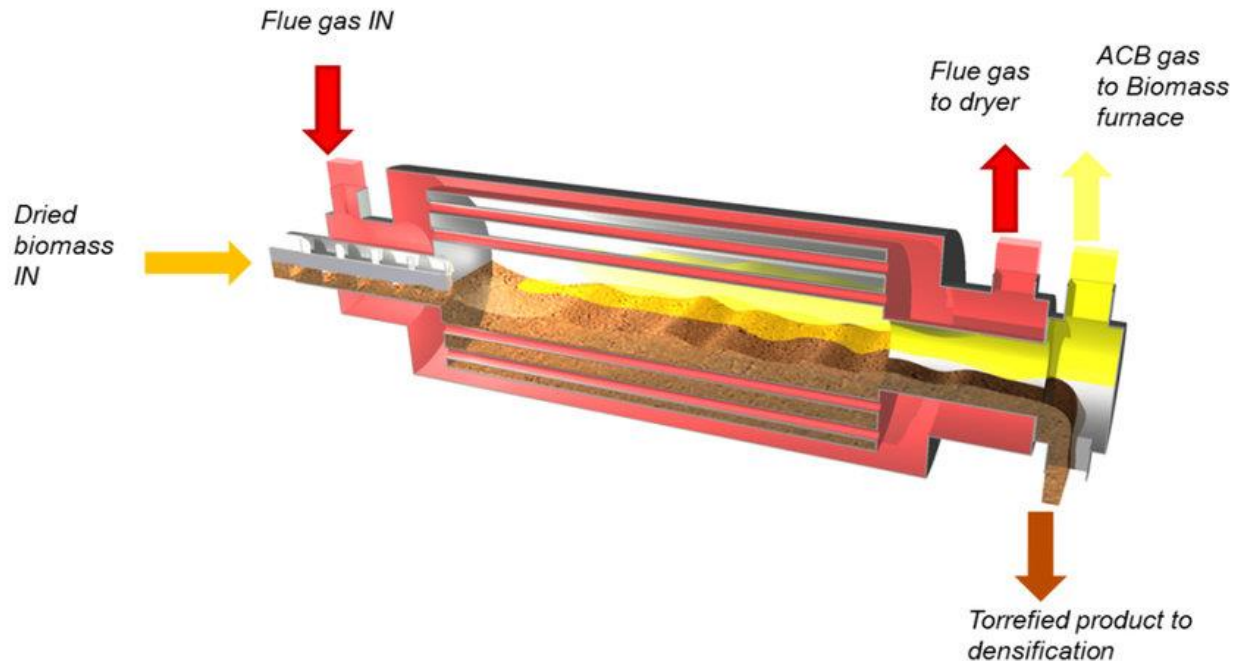


Figure 15. Rotating drum arrangement showing the rotating drum inside the reactor with the indirect heating of flue gas and production of torrefied woody biomass (Shoulaifar 2015).

Supporting Case Studies

This section specifies examples of case studies where this process (or similar) is being implemented specifically with the use of a rotary reactor. Earth Care Products Inc. (ECP) is the primary example with a system consisting of drying, torrefaction (rotary drum), combustion, cooling, and material handling/densifying. ECP provides a mobile torrefaction system that has a capacity of 60 t/day (20,000 t/yr) and could receive feedstock less than 1/4" thick with a moisture content of 40%. Biomass is feed directly to the rotary dryer which is heated by a biomass burner. The drying process reduces the moisture content to 3-4% moisture with temperatures ranging between 120-130°F. That is then torrefied with a rotary drum with the use of hot gases to maintain the high temperatures and oxygen starved environment. The biomass undergoes devolatilization, releasing VOC's. These are then conveyed to the biomass burner for incineration heating gases that are used for heating the reactor by conduction. This loop, as shown in Figure 13 helps minimize heat loss and improves total efficiency. After torrefaction, biomass is transferred to cool within a continuously circulated water jacket. The biomass is then densified into pellets, increasing the bulk density 50-75% its original density.

Final System Design and Specifications

All scaled estimates for performance are derived from the SECTOR (Production of Solid Sustainable Energy Carriers from Biomass by Means of Torrefaction) project, a European research program for technological development and demonstration (Thr  n 2016). In this study they conducted a large-scale mass and energy balance for a complete torrefaction system. The study seemed representative of the preferred schematic, (shown in Figure 13) given that it includes drying, pelleting, biomass derived heat sources and cooling process. It must be noted

that this study modeled a moving bed reactor and not the preferred rotary drum reactor. Given that the pyrolysis process of biomass to biofuel is the same (both at 270°C) the only difference was assumed to be the feedstock rates. These rates are 50-100 kg h⁻¹ for moving bed reactors compared to 4500 kg h⁻¹ for the rotary drum reactors (Thr  n 2016).

We propose using a rotary torrefied (as the one developed by Torr-Coal); their technology was found to be professionally researched and has been included in projects that convert large feedstocks (30kton/yr) (Cremers 2015). Therefore, with appropriate scaling, this analysis suggested 7 parallel reactors would be required to meet the design capacity. It is important to note that 7 reactors do indeed meet the design capacity (561,600 MT/yr at 50% moisture content); however, the system does have the capability of operating at maximum capacity. Additionally, this analysis provided estimates on the total energy input, the quantities of torrefied pellets produced, the total energy content in produced pellets, and estimated electricity consumption to operate the facility. All these values are summarized in Table 14. They have been calculated for a single reactor, the proposed 7 reactors, and the proposed 7 reactors at their maximum capacity, which exceeds the Humboldt biomass demand. The calculations concluded with 1.47 kg of biomass required to produce 1 kg of torrefied wood; this is similar to literature reporting 1.33 kg of biomass for 1 kg of torrefied product (NETL 2012). This reduction in mass is due to three things, loss of moisture from drying, generation of gas from pyrolysis, and combustion of generated gas for internal heating and drying.

Table 14. Summary of model input/output design specifications

I/O	Properties	(Single Reactor) Torr-Coal B.V. System	(Proposed) Torr-Coal B.V. System	(Max Capacity) Torr-Coal B.V. System
Inputs:	Biomass Feed Rate (ton/yr)	92,223	561,600	645,560
	Biomass Feed Rate (kg/hr)	9,551	64,110	66,854
	Heat Source Feed (kg/hr)	546	3,663	3,820
	Total Biomass Feed (kg/hr)	10,096	67,773	70,674
	Electricity Consumption (kWh/kg)	576	4,103	8,206
Outputs:				
	Biomass conversion rate	0.47	0.47	0.47
	Pellets Produced (kg/hr)	4,500	30,207	31,500
	Energy Output (Pellets) (kW)	24,736	166,044	173,152

7.3 Technical Analysis

7.3.1 Area

The area of the proposed plant was initially estimated at 20 acres, based on an existing torrefaction plant, Malhuer Lumber located in John Day, Oregon (Hanners 2019). This analysis, however, failed to incorporate some areas for log storage and a leachate pond. The area of the plant was initially estimated at about 20 acres, which was estimated using a simple spatial analysis of Malhuer Lumber, the first commercial scale torrefaction operation in the United States, located in John Day, Oregon (Hanners 2019). The plant has incorporated new torrefaction

equipment to take advantage of the established pelleting system, and takes up a relatively small footprint compared to the log decks, chipping, storage, truck dump, scales, and finished loading area (personal communication with U.S. Endowment for Forestry and Communities Vice President Matt Krumenauer, May 2020). The full size of the lot is about 60 acres, and the torrefaction equipment was integrated into the existing footprint of the plant, utilizing under one acre of previously unoccupied space (personal communication with U.S. Endowment for Forestry and Communities Vice President Matt Krumenauer, May 2020) (Google Earth 2020) (Shaffner 2019). The installed equipment has the capacity to produce 12 tons/hr of torrefied product, or about 100,000 tons/year, indicating about 3 times the area would be required for Humboldt's plant. A 2100-ton storage pad for green material would correspond to about 1 acre. If 561,600 tons/year of feedstock are processed, then the storage pad would have 1.3 days of storage and would correspond to a storage area of about 6 acres for 8 days of storage (Carp 1987). More area should be reserved for storage to accommodate different sizes of feedstock and feedstock build-up during non-operation days. A high-end estimate of 15 acres for the plant itself, including office space, with additional area requirements of up to 40 acres storage, should be sufficient for start-up and future expansion (AFDP 1977) (Mody 2012).

If the plant proposed to lease property, instead of purchase, costs can be approached using lease rates and site area. A Humboldt County study on the potential for using historic mill sites for a utility-scale photovoltaic project used known lease rates for sites in the county. The study found land cost in the county to be about \$400/acre/month (Avcollie 2018). Utility-scale projects are usually approached with a project lifetime of about 20-30 years (NREL 2020). If a safe estimate for the plant site is about 15 acres and a storage estimate of about 40 acres would result in a total area of about 55 acres, similar to that of the established plant at Malheur Lumber, and would cost 6.6 million dollars over the equipment's lifetime of 25 years.

If a site was to be purchased, parcels zoned M (industrial) could be used for this type of facility plant location should be optimized for distance away from residents, and close to biomass sources and final pellet destinations. Using GIS, the parcel map of Humboldt County, and tax assessor records, a possible site on Samoa Peninsula was found. Using a minimum site size of 40 acres, in case the area estimate is too large, possible locations were found. The vacant industrial parcel 401-131-004-000, outlined in Figure 16 below, has an area of about 60 acres, and could be an ideal location for the torrefaction plant, as it is close to one of the main possible users of the project, DG Fairhaven, and is located close to the bay, where the product could be exported. The site is valued at \$64,345 as of January 2019 (Humboldt County 2019).



Figure 16: Possible 60-acre site location for the Humboldt torrefaction plant located on Samoa Peninsula.

7.3.2 Jobs

A 2008 survey of the North American torrefaction and pelletization industry stated there were a total of 2300 jobs across 111 mills, therefore about 21 employees at each facility. For a facility manufacturing 100,000 tons per year of torrefied pellets from 121,000 dry tons of biomass, there were full-time equivalent positions of 0.36, 0.24, and 0.50 per 1000 tons of fuel for harvesting, operating and maintenance and construction positions respectively (Lambrecht et al. 2011). With the assumed 280,800 bone dry tons there would be 84 harvesting jobs, 56 operation and maintenance positions, and 116 bodies needed for construction, resulting in a total job count of about 250 jobs. Indirect and direct jobs estimate for the two facilities (DG Fairhaven and Scotia) were found at calbiomass.org. Additional information regarding indirect employment estimates for HRC Scotia, was found in a Power Purchase Agreement between PG&E and HRC Scotia (CBEA 2020a, CBEA 2020b, Randolph 2012). The employment the plants support is estimated in Table 15 at about, totaling 96 positions. If these numbers are accurate, the total number of jobs for the torrefaction plant should exceed the number of jobs that are currently provided by the current facilities.

Table 15: Number of jobs provided by the current biomass power plants (CBEA 2020a, CBEA 2020b, Randolph 2012).

Plant	P, MW	Direct	Indirect	Total
DG Fairhaven	18	22	19	41
HRC Scotia	28	25	30	55

7.4 Emissions

The emissions calculated for the preferred alternative include: production of the torrefied pellets, transportation to a combustion facility, and combustion of the torrefied pellets for energy.

7.4.1 Process Emissions

The same emission factors from the NETL study used in the first analysis were used. In the study, an acceptable range of 5 to 50 percent moisture content was defined (NETL 2012). Greenhouse gas and air pollutant emissions for the two combustion plants versus the proposed torrefaction facility are shown in in Table 16 and

Table 17. The data shown from the existing facilities are the median value of what was reported in the CARB Pollution Mapping Tool. In comparison to the existing practices, the emissions that result from producing torrefied pellets are much smaller. The reason for this is that emissions stemming from torrefaction are recirculated into the system.

Table 16. Greenhouse gas emissions for current facilities in comparison to updated torrefaction greenhouse gas emissions (CARB 2008-2017).

Facility	MW	CO ₂ e (MTCO ₂ e/year)	CH ₄ (MTCO ₂ e/year)
Humboldt Sawmill Company	32.5	282,000	2,200
DG Fairhaven	18.7	183,000	1,400
Alternative 3: Torrefaction	NA	15,000	3

Table 17. Air pollutants emitted for current facilities in comparison to updated torrefaction air pollutants (CARB 2008-2017, CARB 2015).

Facility	NO _x (tons/year)	PM ₁₀ (tons/year)	CO (tons/year)
Humboldt Sawmill Company	160	36	640
DG Fairhaven	160	31	1340
Alternative 3: Torrefaction	1.6	0.04	2.3

7.4.2 Transportation

A radius of 50 miles is the assumed distance the torrefied pellets would be transported to reach a combustion facility. Assuming 25 tons per truckload and an output of 291684 tons of torrefied pellets per year would require 32 trucks. Yearly transportation emissions from CO₂, CH₄, and N₂O are shown in Table 18. Emission factors for CH₄ and N₂O were gathered from an EPA greenhouse gas inventory for gasoline heavy-duty vehicles (US EPA 2018a). The emission factor for CO₂ is that of a heavy bulk truck listed in a freight guidebook (Mathers et al. 2014).

Table 18. Transportation emissions assuming a 50-mile radius and 32 trucks.

GHG pollutant	Metric tons of pollutant per year
CH ₄	2
N ₂ O	1
CO ₂	100,180

7.4.3 Emissions from Combusting Torrefied Pellets

The biogenic emissions from using biomass as a fuel source for energy production are considered carbon neutral as defined by the EPA (US EPA 2018b). Emission factors associated with co-firing of coal and torrefied wood were found and multiplied by the energy that the pellets are capable of producing (Vega et al. 2015). The comparison of emissions from the co-firing and the existing facilities are shown in Table 19.

Table 19. Current technology emissions and co-firing of torrefied pellets and coal emissions (CARB 2008-2017, CARB 2015, Vega et al. 2015).

Pollutant	DG Fairhaven [metric tons/year]	Humboldt Sawmill Company [metric tons/year]	Co-firing of torrefied pellets and coal [metric tons/year]
CO ₂	165,900	255,850	1.8×10^{-3}
N ₂ O	7	12	1.6×10^{-5}
CO	1,200	580	1.9×10^{-7}
NO _x	145	150	7.6×10^{-6}
CH ₄	56	88	3.5×10^{-5}
PM ₁₀	28	32	1.7×10^{-5}
PM _{2.5}	26	30	1.2×10^{-5}

7.5 Cost Analysis

The Cost Analysis section consists of the capital cost, including design and implementation, operation and maintenance cost (energy, labor, and other expenses based on the individual system), and payback period.

7.5.1 Implementation Costs

This section will explain the process of the cost analysis in determining the payback period. The process starts with an introduction to the values research from studies related to the cost of torrefied systems. The second process calculated was averaging values to use within the net value cost analysis. The implementation cost is representative of the capital costs required for all equipment involved within the proposed system. Based on the study “Systematic Review of Torrefied Wood Economics,” the capital cost ranges from \$92/MT to \$322/MT (Radics et. al. 2017). Operation cost was explained to be between \$46.08/BDMT to \$213.30/BDMT and this includes the cost of electricity, labor, and transportation (Radics et. al. 2017). From the article “Biomass Energy in Grant County: Case Studies” the value of pellets was \$160/ ton, and this was the value used to calculate the revenue (Dovetail Partners, Inc 2019). A discount rate and nominal rate was found to be 3% and 2.4%, respectively, from “Energy Price Indices and Discount Factors for Life-Cycle Cost Analysis” (Lavappa et. al. 2017).

The net value cost analysis consists of capital, operation, maintenance, and the discount rate to calculate the payback period. The capital cost was the average of the range given from the study, or about \$207/MT. The averaged operation and maintenance used was \$130/BDMT. The nominal rate was used to calculate the discount rate using Equation 1 below (Mussatti 2002).

$$\text{Discount Rate} = \frac{1}{(1 + i)^n} \quad \text{Equation 1}$$

Where i represent the nominal interest rate and n represents the year number (Mussatti 2002). Revenue was calculated by the number of pellets multiplied by the unit value of pellets. From these values, we were able to calculate a capital cost of about \$55 million, an operational and maintenance cost of \$36 million, and revenue of \$43 million. The last calculations are the net cash flow, which includes the revenue minus the sum of capital cost and the operational and maintenance cost for each year. The next step was to obtain the present value, calculated by multiplying the net cash flow with the discount rate of each year except the initial (the 0th year), as that year refers to the capital cost, which is not discounted. Lastly, the net present value for each year was used to calculate a payback period of 11 years, shown in Figure 17.

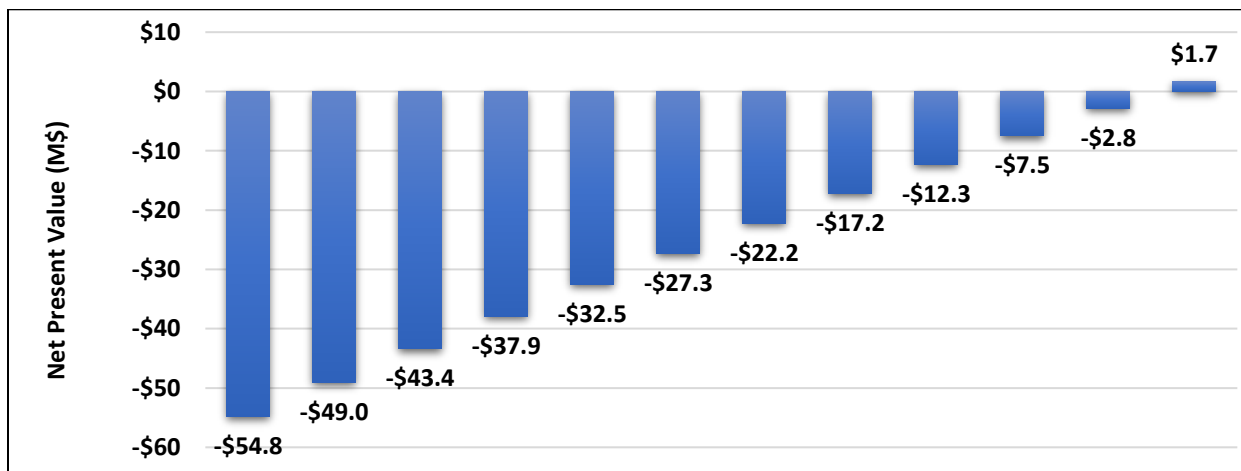


Figure 17: Demonstration of the cash flow analysis and shows the payback period of 11 years.

7.5.2 Sensitivity Analysis

This section summarizes a sensitivity analysis conducted on the selling price of pelletized torrefied wood, capital cost, operation, and maintenance analysis. According to literature, global market prices range from \$131-182/ton for facilities with capacities of 5-500 ton/yr, and Malhuer Lumber, the first commercial torrefaction plant, who originally sold their untorrefied pellets for \$160/ton (Visser 2019 and Dovetail Partners, Inc 2013). Actual prices are subject to change given that torrefied wood pellets would be new in the Northern California marketplace. To investigate this potential impact, a sensitivity analysis was conducted by varying the pellet price within the specified range to assess the sensitivity of the return period. When referring to negative percentage change it is referring to a lower change from the original baseline used. From this analysis, there was a mostly linear correlation between the payback period with a capital cost. As for the value of the pellets and the operation and maintenance costs the analysis was more sensitive. This can be shown in Figure 18; when prices for the pellets go up, there is a shorter payback period.

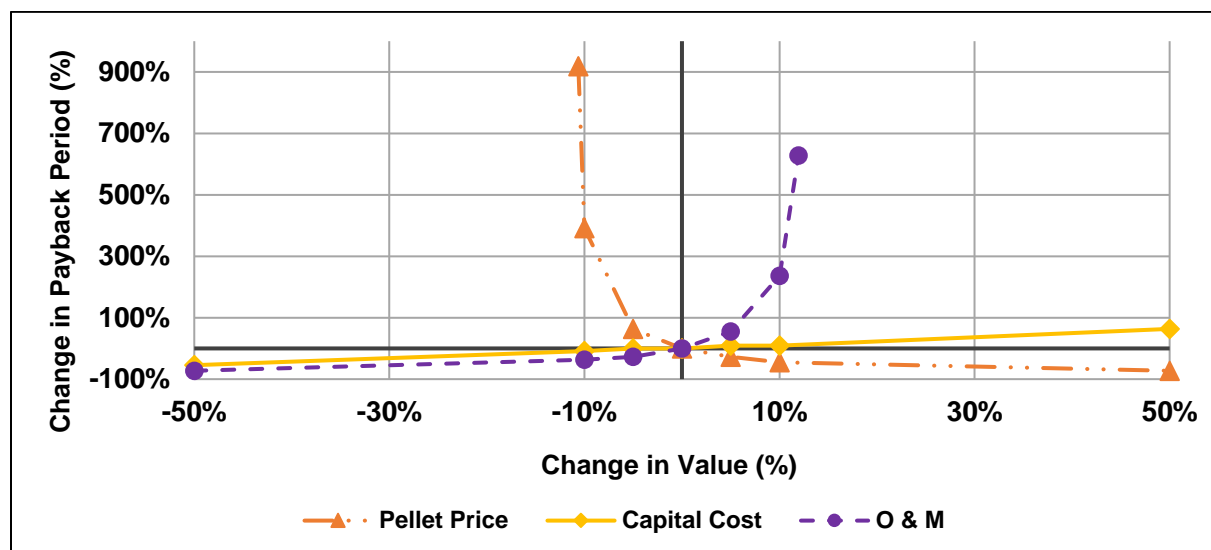


Figure 18: Sensitivity analysis was conducted on the capital cost and operation and maintenance.

7.6 Applications of Torrefied Wood

The proposed torrefaction alternative and its formation of dried fuel, is not only beneficial in its applications but also does not alter or compete with the current biomass utilization facilities like Humboldt Sawmill Company (HSC) and DG Fairhaven LLC. It keeps the best interest of our stakeholder by preprocessing woody biomass, rather than providing a complete alternative that replaces these facilities. Keep in mind this alternative has a variety of applications and is not suggesting being implemented with direct combustion. However, the torrefaction of wood as a product, could be utilized by these facilities to lower GHG emissions and increase energy efficiencies for these facilities. The following summarizes improvements that results as a benefit of using torrefied pellets rather than unprocessed biomass. 1) Torrefaction of biomass would result in 5-15% improvement in efficiency, 2) would reduce ancillary power requirements and fuel use (given its higher energy density), 3) Would lower emissions and improve boiler operational efficiencies. Additionally, with the avoidance of conflicting interests, this would prevent possible job losses and would only provide additional jobs for this independently owned

preprocessing alternative. There are a variety of applications that torrefied wood would be used for which include: energy production, building products, home fuel replacement, and soil amendment. This project assumed all the torrefied wood will be used for energy production by combusting the pellets.

8 Conclusion

This is a promising technology for the residual biomass in Humboldt County. While the technology is relatively immature compared to what is already implemented, the incorporation of torrefaction could prove to be very beneficial in reducing the amount of greenhouse gasses and particulate matter emitted from the combustion of the biomass. This technology could be implemented as a stand-alone project, however there could be benefits to scaling down the production of pellets to incorporate other uses for the biomass, like building materials or compost. Further research is needed to determine an accurate estimate for initial investment and yearly expense. In addition, the possible site should be evaluated for compatibility with the proposed alternative, giving strong consideration to equipment dimensions and a site layout.

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10 Appendices

10.1 Appendix A: Alternative 1

10.1.1 GHG Emissions for Gasification (CEC 2019)

			Mass (MT/yr)	(MTCO ₂ e/BDT)
CO	dry vol%	21.0%	9.47	2.1E-05
H ₂	dry vol%	0.3%		
CH ₄	dry vol%	2.3%	0.60	2.8E-05
N ₂	dry vol%	37.3%		
CO ₂	dry vol%	34.8%	27.25	6.1E-05
C ₂ H ₄	dry vol%	1.0%		
C ₂ H ₆	dry vol%	0.0%		
Higher Heating Value (HHV)	(MJ/kg)	2.7		
Producer Gas generation	(mass% of dry input)	45		
Biochar Production	(mass% of dry input)	17		
water vapor	mass% of dry input	38%		
Thermal Efficiency		0.64		

10.1.2 Pollutants associated with Gasification (CEC 2019b).

	MT/yr	MT/BDT, casestudy
NO _x (tons/year)	0.79	2.07E-05
PM ₁₀ (tons/year)	1.36	3.57E-05

Casestudy, biomass demand 24000 BDT/yr

10.1.3 Land Use requirement for gasification (WestBiofuels 2018).

Footprint Area=	46720	ft ²
Footprint Area for a single facility=	1.07	acres
Footprint Area for all 12 facilities=	12.7	acres

10.1.4 Capital, Operational and Return Period (WestBiofuels 2018).

Truck Unloading/fuel yard	\$	200,000.00
Feedstock sizing equipment	\$	350,000.00
Metering and Conveyance	\$	200,000.00

Feedstock dryer	\$	600,000.00
Rotary Gasifier	\$	2,500,000.00
1 MWe Engine Generator	\$	1,200,000.00
Thermal Oil Heater	\$	2,600,000.00
3 MWe ORC Generator	\$	4,000,000.00
Interconnection gear cost	\$	300,000.00
Site Improvement Costs	\$	500,000.00

Total Capital Cost	147024091	\$
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Fixed Operational Costs	280000	\$/yr
Fixed Maintenance Costs	420000	\$/yr

Total O&M Cost	8266415	\$/yr
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Simple Payback Period=	14	yr
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10.2 Appendix B: Alternative 2

Table B1: These are the values that were used to scale the amount of feedstock that would produce GHGS.

Item Compost	Units	
g CH ₄ Kg-1 wet	1.7	(Vergara & Silver 2020)
g CO ₂ Kg-1 wet	100	(Vergara & Silver 2020)

Table B2: These values were used to scale up to the total amount of feedstock input to compost facility.

Air Emissions (Haaren 2009)					
Item Compost	Units/Method of Compost	Moisture	Particulates	NOx	CO
Yard Waste Feedstock	(kg/ton)/Windrow Composting	0.35	1.8E-02	1.6E-01	8.2E-02

Table B3: Below are the values used to scale the amount of jobs a composting facility would be able to produce.

Employment (Komilis and Ham 2000)		
TPD	Operator	Scale
1000	100	0.1

Table B4: This value was used to compare to the other alternative for technological readiness level.

Maturity (BCC and REE 2016)
TRL
9

Table B5: This the cost that was used for the analysis of composting facility.

Cost (Tchobanoglous and Kreight 2000)	
Initial Investment Costs	
Construction	\$116,750
Engineering	\$48,600
Utility Hookup	\$40,000
Equipment	\$260,000
Total Investment Cost	\$463,350
Amortized Investment	
Annual O& M	\$75,730
Total Annual Cost	\$265,000
Annual Revenues	
Sale of Compost	\$331,730
	\$70,000

Net Annual Cost	\$261,730
Net Unit Costs (\$ /ton yard waste)	\$28

10.3 Appendix C: Alternative 3

The emission factors used for calculating greenhouse gas and air pollution emission associated with torrefaction are shown in Table C1. Table C2 shows the TRL values from three different studies. The values ranged from TRL 1 to TRL 8.5. For the second and third study listed in the table, the middle value was chosen. Table C3 contains the capital cost quantification to a facility that would be capable of handling Humboldt County's woody biomass. Equation 1 was used to scale the existing facilities and a scaling factor of 0.6 was used since this is what was used in the study (Cherry et al. 2013). Table C4 contains the remaining associated cost with the plant that were included in the payback period calculation.

$$\frac{C_2}{C_1} = \left(\frac{Q_2}{Q_1} \right)^x \quad [\text{Equation 1}]$$

Where:

C_2 = Cost of facility 2 to be estimated with known capacity Q_2

C_1 = Known cost of facility 1 with capacity Q_1

Q_2 = Known capacity of facility 2

Q_1 = Known capacity of facility 1

x = Scale factor for technology of facility 2 and 1

Table C1. Emission factor values used for greenhouse gas and air pollution quantification (NETL 2012).

Airborne Emission	Value [kg/kg torrefied biomass produces]
CO ₂	6.98E-02
CH ₄	5.62E-07
PM ₁₀	1.86E-06
CO	9.59E-05
NO _x	6.84E-05

Table C2. TRL values for torrefaction averaged to determine maturity.

maturity	Source
TRL1	(European commission 2017)
TRL 6-7	(Dowdall 2015)
TRL 8-9	(E4tech et al., 2015, BIOCORE, 2014, RHC, 2014, Stafford et al., 2017)

Table C3. Capital cost data scaled up (Cherry et al. 2013).

Companies	production rate [ton/hour]	fixed capital cost [\$ million]	Capital cost scaled to 20 ton/hour [\$ million]	Capital cost scaled to 50 ton/hour using x = 0.6
Agri-Tech Producers	5	5	11.5	19.91
HM3 Energy	11	20	28.6	49.61
Depot Case at 230 °C (report case)	20	21.1	24.9	36.56

Table C4. Raw data incorporated into the payback period (Cherry et al. 2013).

Cost component	Treatment at 270 °C [\$/year]
electricity	200000
operating labor ("* Estimated to be 4 workers/shift using Peters et al. table 6-13 and figure 6-9. Svanberg et al. (2013) estimate in their Figure 2 a need for 18 workers at a 150,000 ton/year plant, equal to four shifts of 4.5 workers each")	1800000
maintenance labor and materials	1800000
operating expenses	2000000
thermal processing cost [\$/ton]	33

10.4 Appendix D: Alternative 4

10.4.1 Jobs

Table D 1: Jobs provided by an ethanol plant (Humbird et al 2010)

Plant	Tpy	Employment	Jobs/ton
NREL Benchmark Case Study	730000	60	8.21918E-05
Ethanol Plant, Jasper County, Indiana	472500	32	6.77249E-05
BlueFire Fulton Renewable Energy	427680	67	0.000156659
Humboldt Theoretical	450,000	46	0.000102192
		51	Average
Study			
ABF Economics Study		50	Average
Nebraska Survey		60	Average
Average of the Averages		52	

10.4.2 Land Use

Table D 2: Land use for ethanol facilities

Source	Acres
Ethanol Plant, Jasper County, Indiana	15
BlueFire Fulton Renewable Energy	14
USDA Ethanol Plant Guidance	12.5
Average	13.8

10.4.3 Maturity

The maturity of the technologies was determined using Table D 3

Table D 3: Maturity of biomass to ethanol technologies

Feedstock	TRL
Lignocellulosic residue	4.50
Woody Biomass	4.5
Lignocellulosic residue	4.5
Lignocellulosic residue	8
Forest Residue	8

Wood Waste	8
Wood Waste	8
Lignocellulosic residue	4.5
Wood Pulping Residue	8
Lignocellulosic residue	4.5
Forest Waste	8
Average	6.41

10.4.4 Perception

Table D 4: Perception of biomass to ethanol production.

Region	%	Note
EU	60	poll participants think public perception is positive towards advanced biofuels
Greece	80.9	Willing to adopt biofuels
US	59	increase ethanol as nation's fuel
Iowa	65	positive opinion of biodiesel
Canada	69	support replacing fossil fuels with ethanol and biodiesel
Total Average	67	
North America Average	64	
US Average	62	

10.4.5 Wages

Table D 5: Jobs from a scaled biomass to ethanol facility from the NREL test case

Number of Jobs for 1000 ton/day facility	
=report case/1.7 (rounded up)	
Theoretical 1/2 scale	
1000 tons/day	
Employees	2007 Wages (\$)
1	141569
1	67414
1	54894
7	502989
1	53931
1	38522
1	38522
2	92453
12	462266

5	192611
2	53931
2	69340
36	\$1,800,000.00
2020 Projected Salary	\$2,570,000.00

10.4.6 Emissions

Table D 6: Emissions for biomass to ethanol using the GREET model.

GREET Model Analysis	Gals/Year	BDT/year	
	36900000	425000	
Emissions - Well to Use	Value	Unit	mass/bdt
CO2 Total	1114	t	2.62E-03
CO2	38810	t	9.13E-02
CO2_Biogenic	-37696	t	-8.87E-02
VOC	4782.21	kg	1.13E-05
CO	46.81	t	1.10E-04
NOx	72.69	t	1.71E-04
PM10	4066.3	kg	9.57E-06
PM2.5	1436.37	kg	3.38E-06
SOx	60.08	t	1.41E-04
CH4	6870.14	kg	1.62E-05
N2O	3581.64	kg	8.43E-06
BC	231.11	kg	5.44E-07
POC	255.66	kg	6.02E-07

10.4.7 Costs

Table D 7: Capital costs of biomass to ethanol facilities

	Current Year	Production Volume	Facility Capital Est.
	2020 (M\$)	Tons/year	M\$/ton
NREL Test Case Scaled	223	450000	0.000495556
NREL Test Case Unscaled	292	730000	0.0004
BlueFire, LLC (Aecom 2010)	357	427680	0.0008
	Humboldt Biomass	450000	0.0005

	Estimated Capital (MM\$)	260
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Table D 8: Feedstocks for biomass conversion

	bdt/day	Days	Annual MT			
NREL Case 1	2083	350	730000			
Humboldt	1284	-	450,000		NREL Case 1	Humboldt (450,000 tons/yr)
Item	\$/ton	lb/hr	ton/hr	\$/hr	MM\$/yr	MM\$/yr
Feedstock	60.35	229688	114.84	6930.39	58.3	35.9
Sulfuric Acid 93%	143.2	4367	2.18	312.68	2.63	1.62
Ammonia	499	2317	1.16	578.09	4.86	3.00
Corn Steep Liquor	200	2554	1.28	255.40	2.15	1.32
(NH ₄) ₂ HPO ₄	445	313	0.16	69.64	0.59	0.36
Sorbitol	1230	98	0.05	60.27	0.51	0.31
Glucose	46.39	5332	2.67	123.68	1.04	0.64
Corn Steep Liquor	200	363	0.18	36.30	0.31	0.19
Ammonia	499	254	0.13	63.37	0.53	0.33
Host Nutrients	929.46	149	0.07	69.24	0.58	0.36
SO ₂	394.28	36	0.02	7.10	0.06	0.04
Caustic	490	4966	2.48	1216.67	10.23	6.31
Boiler Chems	5654.08	1	0.00	2.83	0.02	0.01
FGD Lime	75	1973	0.99	73.99	0.62	0.38
Cooling Tower Chems	3884.31	5	0.00	9.71	0.08	0.05
Makeup Water	0.33	324443	162.22	53.36	0.45	0.28
Ash	41.27	12623	6.31	260.49	2.19	1.35
				Sub Total	26.9	16.6

Total	MM\$/yr	85.1	52.5
	Jobs cost MM\$/yr		2.57
	Total Variable Costs MM\$/yr		55.1

Table D 9: Conversion efficiency for different ethanol facilities

Case	Tons/Yr	Tons/day	Output (Mgal)	Efficiency (gal/ton)
NREL Case 1	730000	2000	65.5	89.7
NREL Case 2	349305	957	27.7	79.2
Scaled Case 1 (Humboldt)	450000	1233	36.9	82.0
BlueFire, LLC	427680	700	18	70.5

Table D 10: Ethanol market price, fuel credits, and typical income tax rate used for payback period.

Ethanol Price \$/gal	1.19
Tax Credit \$/gal	1.01
Additional Credit \$/gal	0.4508
Total (\$/gal)	2.20
Income tax rate	0.35

Table D 11: Payback period for the ethanol facility. Additional credits of 0.46

Cash Flow				
	Case 1	Humboldt	Case 2	Bluefire
Tons/day	2000	1232.877	957	700
Process Yield (gal/ton)	89.7	81.97728	79.2	70.4501
gal/day	179400	101067.9	75794.4	49315.07
Mgal/year	65.481	36.88978	27.66496	18
M\$/year no credit	77.92239	43.89883	32.9213	21.42
M\$/year w/credit	144.0582	81.15751	60.8629	39.6
Costs (MM\$/yr)		55.05123		
After-tax Profit (MM\$/yr)		52.75238		
Projected Revenue (MM\$/yr)		-2.29885		
Capital Cost (MM\$)		259.5438		
Payback Period (Years)		-112.902		

For 30 yr payback				
With Additional Credits				
M\$/year w/credit	97.78742			
After-tax Profit (MM\$/yr)	63.56182			
Revenue Calculated (MM\$/yr)	8.510592	Revenue (MM\$)		
Revenue Needed (MM\$/yr)	8.651459			
Capital (MM\$)	259.5438			
Payback (years)	30	Theoretical		
Additional Credits (\$/gal)	0.4508			

10.4.8 Capital Cost Scaling

For this analysis the cost estimates from a reference case in a NREL study from 2010, shown in Table D 12 , for a bioethanol plant of 2000 tons/day of feedstock were used. I removed any rows in the data that were labeled "INCLUDED" or had \$0 in the Inst Cost in Proj Year column. To scale the data, the values were not simply cut in half, as this technology is affected by an economy of scale. To accommodate this, the values were rounded up, as half units are like are not available. Lower volume units may be available, but the time required to individually quote parts is not budgeted. Through both the unused capacity in volumetric units, and the rounding up the number required of units, the costs might be reasonably estimated compared to analysis where the costs where simply halved. More research will need to be done to ensure the equipment will be able to manage the specific biomass feedstock composition (Humbird et al 2010)

Table D 12:Scaling of capital costs from the NREL test case of 2000 tons/day feedstock, to 1000 tons/day feedstock.

Mechanical Equipment List								Scaled Installed Costs											1/2 Scale Plant	
EQPT NO	EQUIPM ENT TITLE	VENDOR	DESCRIPTION	HP	MATERIAL	NUM REQD	\$	Year of Quote	Scaling Variable	Scaling Val	Units	Scaling Exp	Inst Factor	Now Val	Size Ratio	Scaled Purch Cost	Purch Cost in Proj year	Inst Cost in Proj year	NUM REQD	Inst Cost in Proj year
C-101	Transfer Conveyor	Dearborn Midwest	160 MTPH ea., enclosed, 60 in. x 65 ft. long	20 hp ea.	CS	2	\$5,397,000	2009	STRM.101	94697	kg/hr	0.6	1.7	104167	1.1	\$5,714,628	\$5,752,952	\$9,780,018	1	\$4,890,009
C-104	Dome Reclaim System	Cambelt	100 MTPH ea.	45 kw ea.	CS	2	\$3,046,000	2009	STRM.101	94697	kg/hr	0.6	1.7	104167	1.1	\$3,225,265	\$3,246,895	\$5,519,721	1	\$2,759,861
M-101	Truck Scale	St. Louis Scale	10' x 70', 200,000 lb		CONCRETE	2	\$110,000	2009	STRM.101	94697	kg/hr	0.6	1.7	104167	1.1	\$116,474	\$117,255	\$199,333	1	\$99,667
M-102	Truck Dumper	Jeffrey Rader	70' x 55 ton x 63 degree	2 x 50 hp	CS	2	\$484,000	2009	STRM.101	94697	kg/hr	0.6	1.7	104167	1.1	\$512,485	\$515,922	\$877,067	1	\$438,534
M-103	Truck Dumper Hopper	Jeffrey Rader	3500 cu.ft. hopper w/ drag chain conveyor	50 hp ea.	CS	2	\$502,000	2009	STRM.101	94697	kg/hr	0.6	1.7	104167	1.1	\$531,544	\$535,109	\$909,685	1	\$454,843
M-104	Concrete Feedstock Storage Dome	Domtec	98 ft. dia., 160 ft. high., 4000 MT		CONCRETE	2	\$3,500,000	2009	STRM.101	94697	kg/hr	0.6	1.7	104167	1.1	\$3,705,984	\$3,730,388	\$6,342,424	1	\$3,171,212
M-105	Belt Scale	Tecweigh	Scale plus processor		CS	2	\$10,790	2009	STRM.101	94697	kg/hr	0.6	1.7	104167	1.1	\$11,425	\$11,502	\$19,553	1	\$9,777
M-106	Dust Collection System	Sly	8500 ACFM	25 hp ea.	CS	6	\$279,900	2009	STRM.101	94697	kg/hr	0.6	1.7	104167	1.1	\$296,373	\$298,360	\$507,213	3	\$253,607
								Area 100 Totals								\$14,114,178	\$14,208,833	\$24,155,014		\$12,077,507

Mechanical Equipment List								Scaled Installed Costs											NUM REQ	Inst Cost in Proj year
EQPT NO	EQUIPMENT TITLE	VENDOR	DESCRIPTION	HP	MATERIAL	NUM REQ	\$	Year of Quote	Scaling Variable	Scaling Val	Units	Scaling Exp	Inst Factor	New Val	Size Ratio	Scaled Purch Cost	Purch Cost in Proj year	Inst Cost in Proj year		
A-201	In-line Sulfuric Acid Mixer	KOMAX	Kynar Lined - 600 gpm H2O - 5 gpm acid		SS304	1	\$6,000	2009	strm.a200.214	136260	kg/hr	0.5	1	38801	0.28	\$3,202	\$3,223	\$3,223	1	\$3,223
A-204	Flash Tank Agitator	UET Mixers	Side-mounted, 3 x 75 hp. (170 kW)	170 kW	316LSS	3	\$90,000	2009	strm.a200.254	252891	kg/hr	0.5	1.5	278194	1.1	\$94,395	\$95,028	\$142,542	2	\$95,028
A-208	Oligomer Hold Tank Agitator	UET Mixers	Side-mounted, 3 x 75 hp. (170 kW)	170 kW	316LSS	3	\$90,000	2009	strm.a200.222	264116	kg/hr	0.5	1.5	292060	1.11	\$94,641	\$95,276	\$142,914	2	\$95,276
A-209	Ammonia Addition Tank Agitator	Lotus		10 hp	SS	1	\$21,900	2009	strm.a200.228	410369	kg/hr	0.5	1.5	429554	1.05	\$22,406	\$22,556	\$33,835	1	\$33,835
A-210	Ammonia Static Mixer	KOMAX			SS	1	\$5,000	2009	strm.a200.275	157478	kg/hr	0.5	1	151360	0.96	\$4,902	\$4,935	\$4,935	1	\$4,935
H-201	Pretreatment Water Heater	Mueller	29.9 MMBtu		304SS	1	\$92,000	2010	Heat.A200.QH201	8	Gcal/hr	0.7	2.2	-9	1.15	\$101,545	\$97,091	\$213,600	1	\$213,600
H-244	Waste Vapor Condenser	Mueller	Copied H-201		304SS	1	\$34,000	2009	Heat.A200.QH244	2	Gcal/hr	0.7	2.2	7	3.98	\$89,346	\$89,946	\$197,880	1	\$197,880
M-207	Pretreatment Reactor	Andritz	2600 mm x 9000 mm (9' x 30') - 2 min. residence time		Incoloy 825-CLAD; CS	3	\$19,812,400	2009	DRY101	83333	kg/hr	0.6	1.5	83333	1	\$19,812,448	\$19,945,315	\$29,917,973	2	\$19,945,315
P-201	Sulfuric Acid Pump	Goulds	9 GPM, 245 FT TDH		316SS	1	\$8,000	2009	strm.710	3720	kg/hr	0.8	2.3	198	0.53	\$4,832	\$4,864	\$11,187	1	\$11,187
P-203	Blowdown Tank Discharge Pump	Viking	1900 GPM, 150 FT TDH	125	316SS	1	\$25,635	2010	strm.a200.222	292407	kg/hr	0.8	2.3	292060	1	\$25,611	\$24,487	\$56,321	1	\$56,321
P-204	Flash Tank Discharge Pump	Viking	900 GPM, 150 FT TDH	75	316SS	1	\$30,000	2009	strm.a200.254	204390	kg/hr	0.8	2.3	278194	1.36	\$38,391	\$38,649	\$88,892	1	\$88,892
P-208	Oligomer Hold Tank Discharge	Viking	900 GPM, 150 FT TDH	75	316SS	1	\$17,408	2010	strm.a200.223	292407	kg/hr	0.8	2.3	292060	1	\$17,391	\$16,629	\$38,246	1	\$38,246
P-209	Hydrolyzate Pump	Goulds	1771 GPM, 150 FT TDH	100	316SS	1	\$22,500	2009	strm.a200.228	402194	kg/hr	0.8	2.3	429554	1.07	\$23,716	\$23,875	\$54,913	1	\$54,913
T-201	Sulfuric Acid Tank		12,800 gal, 24hr residence time		PLASTIC	1	\$6,210	2010	strm.710	1981	kg/hr	0.7	3	198	1	\$6,209	\$5,937	\$17,810	1	\$17,810
T-204	Flash Tank		23' x 48' - 110,000 gal.		SS316	1	\$511,000	2009	strm.a200.223	264116	kg/hr	0.7	2	292060	1.11	\$548,271	\$551,948	\$1,103,895	1	\$1,103,895
T-208	Oligomer Conversion Tank		2.6 atm, 130C operating 30 min. hold = 30,000 gal		SS316	1	\$203,000	2009	strm.a200.223	264116	kg/hr	0.7	2	292060	1.11	\$217,806	\$219,267	\$438,534	1	\$438,534
T-209	Ammonia Addition Tank		118,000 gal, 1hr residence time		SS304	1	\$236,000	2009	strm.a200.228	410369	kg/hr	0.7	2	429554	1.05	\$243,670	\$245,304	\$490,609	1	\$490,609

								Area 200 Totals								\$21,348,782	\$21,484,330	\$32,957,310			\$22,889,499
Mechanical Equipment List								Scaled Installed Costs													
EQPT NO	EQUIPMENT TITLE	VENDOR	DESCRIPTION	HP	MATERIAL	NUM REQD	\$	Year of Quote	Scaling Variable	Scaling Val	Units	Scaling Exp	Inst Factor	New Val	Size Ratio	Scaled Purch Cost	Purch Cost in Proj year	Inst Cost in Proj year	NUM REQD	Inst Cost in Proj year	
A-300	Ethanol Fermentor Agitator	Lotus		30 hp	SS304	1	\$52,500	2009	inumsscf	1	ea	1	1.5	12	12	\$630,000	\$634,225	\$951,337	1	\$951,337	
A-301	Seed Hold Tank Agitator	Lotus		15 hp	SS304	1	\$31,800	2009	STRM.A300.304	4041	kg/hr	0.5	1.5	42607	1.05	\$32,651	\$32,870	\$49,305	1	\$49,305	
A-304	4th Seed Vessel Agitator	Lotus		7.5 hp	SS	2	\$26,000	2009		2	ea	0.5	1.5	2	1	\$26,000	\$26,174	\$39,262	1	\$19,631	
A-305	5th Seed Vessel Agitator	Lotus		10 hp	SS	2	\$43,000	2009		2	ea	0.5	1.5	2	1	\$43,000	\$43,288	\$64,933	1	\$32,467	
A-306	Beer Surge Tank Agitator	Lotus		20 hp	SS304	2	\$68,300	2009	strm.501	425878	kg/hr	0.5	1.5	450740	1.06	\$70,265	\$70,737	\$106,105	1	\$53,053	
A-308	Enzyme-Hydrolysate Mixer	GLV	inline mixer 1673 gpm	100 hp	SS316	1	\$109,000	2009	strm.a300.t310fd	379938	kg/hr	0.5	1.7	443391	1.17	\$117,751	\$118,540	\$201,519	1	\$201,519	
F-300	Ethanol Fermentor	Mueller	1,000,000 gallon ea		304SS	12	\$10,128,000	2009	inumsscf	12	ea	1	1.5	12	1	\$10,128,000	\$10,195,921	\$15,293,882	6	\$7,646,941	
F-301	1st Seed Fermentor	A&B Process	20 gallon skid complete - \$37,700 ea		304SS	2	\$75,400	2009		2	ea	0.7	1.8	2	1	\$75,400	\$75,906	\$136,630	1	\$68,315	
F-302	2nd Seed Fermentor	A&B Process	200 gallon skid complete - \$58,300 ea		304SS	2	\$116,600	2009		2	ea	0.7	1.8	2	1	\$116,600	\$117,382	\$211,288	1	\$105,644	
F-303	3rd Seed Fermentor	A&B Process	2000 gallon skid complete - \$78,800 ea		304SS	2	\$157,600	2009		2	ea	0.7	1.8	2	1	\$157,600	\$158,657	\$285,582	1	\$142,791	
F-304	4th Seed Fermentor	Mueller	20,000 gallon, incl. coil - \$176,000 ea		304SS	2	\$352,000	2009		2	ea	0.7	2	2	1	\$352,000	\$354,361	\$708,721	1	\$354,361	
F-305	5th Seed Fermentor	Mueller	200,000 gallon, incl. coil - \$590,000 ea		304SS	2	\$1,180,000	2009		2	ea	0.7	2	2	1	\$1,180,000	\$1,187,913	\$2,375,827	1	\$1,187,914	
H-300	Fermentation Cooler	Alfa Laval	Plate & frame		304SS	12	\$86,928	2009	inumsscf	12	ea	1	2.2	12	1	\$86,928	\$87,511	\$192,524	6	\$96,262	

H-301	Hydrolyzate Cooler	Fox Engineering	Plate & Frame 32.5 MMBtu/hr		SS 304	1	\$85,000	2010	heat.a300.qc30	8	Gcal/hr	0.7	2.2	11	1.3	\$101,972	\$97,500	\$214,500	1	\$214,500
P-300	Fermentation Recirc/Transfer Pump	Goulds	340 GPM, 150 FT	20	316SS	5	\$47,200	2009	inumsccf	12	ea	0.8	2.3	12	1	\$47,200	\$47,517	\$109,288	3	\$65,573
P-301	Seed Hold Transfer Pump	Goulds	190 GPM, 150 FT TDH	10	316SS	1	\$8,200	2009	strm.a300.304	43149	kg/hr	0.8	2.3	42607	0.99	\$8,117	\$8,172	\$18,795	1	\$18,795
P-302	Seed Transfer Pump	Goulds	190 GPM, 615 FT TDH	40	316SS	2	\$24,300	2009	strm.a300.304	43149	kg/hr	0.8	2.3	42607	0.99	\$24,055	\$24,217	\$55,698	1	\$27,849
P-306	Beer Transfer Pump	Goulds	2152 GPM, 171 FT TDH	125	316SS	1	\$26,800	2009	strm.501	488719	kg/hr	0.8	2.3	450740	0.92	\$25,120	\$25,289	\$58,165	1	\$58,165
P-310	Saccharification Transfer Pump	Goulds	352 GPM, 150 FT TDH	20	316SS	5	\$47,200	2009	strm.a300.306	421776	kg/hr	0.8	2.3	443391	1.05	\$49,125	\$49,455	\$113,746	3	\$68,248
T-301	Seed Hold Tank	Mueller	300,000 gallon		316SS	1	\$439,000	2009	strm.a300.304	40414	kg/hr	0.7	1.8	42607	1.05	\$455,540	\$458,595	\$825,471	1	\$825,471
T-306	Beer Storage Tank	Mueller	500,000 gallon		316SS	1	\$636,000	2009	strm.501	425878	kg/hr	0.7	1.8	450740	1.06	\$661,768	\$666,206	\$1,199,170	1	\$1,199,170
T-310	Saccharification Tank	Caldwell	250,000 gal each - 19' dia. x 120' tall		304SS	8	\$3,840,000	2009	strm.a300.306	421776	kg/hr	0.7	2	443391	1.05	\$3,976,717	\$4,003,386	\$8,006,772	4	\$4,003,386
Area 300 Totals																\$18,365,811	\$18,483,821	\$31,218,520		\$17,390,694
A-400	Cellulase Fermentor Agitators	Lotus		800	SS316		\$580,000	2009	CLVESSEL	1	ea	1	1.5	9	9	\$5,220,000	\$5,255,007	\$7,882,510		\$7,882,510
A-401	Cellulase Fermentor Agitators	Lotus		0.75hp	SS316		\$3,420	2009	ICLSEED	1	ea	1	1.5	4	4	\$13,680	\$13,772	\$20,658		\$20,658
A-402	Cellulase Fermentor Agitators	Lotus		8hp	SS316		\$63,000	2009	ICLSEED	1	ea	1	1.5	4	4	\$252,000	\$253,690	\$380,535		\$380,535
A-403	Cellulase Fermentor Agitators	Lotus		80hp	SS316		\$11,000	2009	ICLSEED	1	ea	1	1.5	4	4	\$44,000	\$44,295	\$66,443		\$66,443
A-406	Cellulase Nutrient Mix Tank Agitator	Lotus		3hp	CS	1	\$4,800	2009	strm.a400.416	174	kg/hr	0.5	1.6	224	1.29	\$5,446	\$5,482	\$8,772	1	\$8,772
A-410	Cellulase Hold Tank Agitator	Lotus		10hp	SS316	1	\$26,900	2009	strm.422	10930	kg/hr	0.5	1.5	13836	1.27	\$30,266	\$30,469	\$45,703	1	\$45,703
F-400	Cellulase Fermentor	Mueller	80,000 gal, 1 atm, 28 °C, Internal coil		SS316		\$400,500	2009	CLVESSEL	1	ea	1	2	9	9	\$3,604,500	\$3,628,673	\$7,257,345		\$7,257,345

F-401	1st Cellulase Seed Fermentor	A&B Process	80 gallon skid complete - \$46,000 ea		304SS		\$46,000	2009	ICLSEED	1	ea	1	1.8	4	4	\$184,000	\$185,234	\$333,421		\$333,421
F-402	2nd Cellulase Seed Fermentor	A&B Process	800 gallon skid complete - \$57,500 ea		304SS		\$57,500	2009	ICLSEED	1	ea	1	1.8	4	4	\$230,000	\$231,542	\$416,776		\$416,776
F-403	3rd Cellulase Seed Fermentor	A&B Process	8,000 gallon skid complete - \$95,400 ea		304SS		\$95,400	2009	ICLSEED	1	ea	1	1.8	4	4	\$381,600	\$384,159	\$691,486		\$691,486
M-401	Fermenter Air Compressor Package	Dresser Roots	8000 SCFM @ 16 psig		CS	2	\$350,000	2009	strm.a400.450	33168	kg/hr	0.6	1.6	32583	0.98	\$346,282	\$348,604	\$557,767	1	\$278,884
P-400	Cellulase Transfer Pump	Goulds	59 gpm, 100 FT, TDH SIZE 2X1-10C	3	316SS	1	\$7,357	2010	strm.a400.420	13399	kg/hr	0.8	2.3	13836	1.03	\$7,549	\$7,218	\$16,600	1	\$16,600
P-401	Cellulase Seed Pump	Goulds	3 GPM, 100 FT TDH SIZE 2X1-10	2	316SS	4	\$29,972	2010	strm.a400.409	681	kg/hr	0.8	2.3	770	1.13	\$33,045	\$31,596	\$72,670	2	\$36,335
P-406	Cellulase Nutrient Transfer Pump	Viking	Gear Pump 2 GPM, 100 FT	1	316SS	1	\$1,500	2009	strm.a400.416	454	kg/hr	0.8	2.3	224	0.49	\$852	\$858	\$1,974	1	\$1,974
P-410	Cellulase Feed Pump	Viking	Gear Pump	1	316SS	1	\$1,500	2009	strm.a400.422	18168	kg/hr	0.8	2.3	13836	0.76	\$4,584	\$4,615	\$10,614	1	\$10,614
P-420	Anti-foam Pump	Viking	Gear Pump 2 GPM, 100 FT	1	316SS	1	\$1,500	2009	strm.a400.444	11	kg/hr	0.8	2.3	13.4	1.26	\$1,805	\$1,817	\$4,179	1	\$4,179
T-406	Cellulase Nutrient Mix Tank	Harrington	HDPE, 8,000 gal		HDPE	1	\$9,000	2010	strm.a400.416	224	kg/hr	0.7	3	224	1	\$9,000	\$8,605	\$25,815	1	\$25,815
T-410	Cellulase Hold Tank	Mueller	80,000 gal		304SS	1	\$248,070	2009	strm.a400.422	10930	kg/hr	0.7	1.8	13836	1.27	\$292,589	\$294,551	\$530,192	1	\$530,192
									Area 400 Totals							\$10,661,197	\$10,730,186	\$18,323,460		\$18,008,242
Mechanical Equipment List									Scaled Installed Costs											
EQPT NO	EQUIPMENT TITLE	VENDOR	DESCRIPTION	HP	MATERIAL	NUM REQD	\$	Year of Quote	Scaling Variable	Scaling Val	Units	Scaling Exp	Inst Factor	New Val	Size Ratio	Scaled Purch Cost	Purch Cost in Proj year	Inst Cost in Proj year	NUM REQD	Inst Cost in Proj year
A-530	Filtrate Tank Agitator	Lotus		7.5 hp	SS	1	\$26,000	2009	strm.a500.evap.572	337439	kg/hr	0.5	1.5	355024	1.05	\$26,669	\$26,848	\$40,272	1	\$40,272
C-501	Lignin Wet Cake Conveyor	KWS/Barnard-Boe	Belt 100 ft. long x 24" wide, enclosed	10	SS304	1	\$70,000	2009	strm.a500.571	28630	kg/hr	0.8	1.7	36538	1.28	\$85,082	\$85,653	\$145,610	1	\$145,610

C-502	Lignin Wet Cake Screw	KWS/Barnard-Boe	Screw conveyor - 25 ft lg x 14" dia	15	SS304	1	\$20,000	2009	strm.a500.571	02863	kg/hr	0.8	1.7	36538	1.28	\$24,309	\$24,472	\$41,603	1	03	\$41,6
D-501	Beer Column	Megtec	14' dia. x 76' tall, 32 trays, 24" spacing		316SS	1	\$3,407,000	2009	strm.a500.511	93037	kg/hr	0.6	2.4	29213	0.96	\$3,327,914	\$3,350,232	\$8,040,557	1	57	\$8,040,5
H-505	Rectification Column Condenser	GEA Rainey	92.2 MM Btu/hr 3 cells	300 tot	CS	1	\$487,000	2010	heat.a500.qcd502	23	Gcal/hr	0.6	2.8	23	1	\$486,746	\$465,399	\$1,303,116	1	16	\$1,303,1
M-503	Molecular Sieve Package (9 pieces)	Delta-T			SS	1	\$2,601,000	2009	strm.a500.515	72268	kg/hr	0.6	1.8	21808	0.96	\$2,540,057	\$2,557,091	\$4,602,764	1	64	\$4,602,7
M-505	Pressure Filter Pressing Compr	Atlas-Copco	460 SCFM, 300 psig	150 hp		1	\$75,200	2009	strm.a500.evap.squairin	880	kg/hr	0.6	1.6	809	1	\$75,245	\$75,750	\$121,199	1	9	\$121,19
M-507	Pressure Filter Drying Compr	Atlas-Copco	4000 SCFM, 130 psig (ea)	700 hp ea.		2	\$405,000	2009	strm.a500.evap.557	31223	kg/hr	0.6	1.6	12105	0.99	\$402,453	\$405,152	\$648,243	1	2	\$324,12
P-515	Scrubber Bottoms Pump	Goulds	108 GPM, 104 FT TDH		316SS	1	\$6,300	2009	strm.551	72452	kg/hr	0.8	2.3	27197	1.11	\$6,843	\$6,889	\$15,844	1	44	\$15,8
P-530	Filtrate Tank Discharge Pump	Sulzer	590 GPM, 100 FT TDH SIZE 4X3-13		SS	1	\$13,040	2010	strm.a500.evap.571	53181	kg/hr	0.8	2.3	36538	1.15	\$14,567	\$13,928	\$32,035	1	35	\$32,0
P-531	Feed Pump	Warman	1014 GPM 230 FT TDH SIZE 8X6-15	100 hp	SS	1	\$18,173	2010	strm.a500.evap.571	53181	kg/hr	0.8	2.3	36538	1.15	\$20,301	\$19,411	\$44,645	1	45	\$44,6
P-532	Manifold Flush Pump	Warman		100 hp	SS	1	\$17,057	2010	strm.a500.evap.571	53181	kg/hr	0.8	2.3	36538	1.15	\$19,054	\$18,219	\$41,903	1	03	\$41,9
P-533	Cloth Wash Pump	Warman		150 hp	SS	1	\$29,154	2010	strm.a500.evap.571	53181	kg/hr	0.8	2.3	36538	1.15	\$32,568	\$31,140	\$71,621	1	21	\$71,6
P-581	Filtrate Discharge Pump	Sulzer	590 GPM, 100 FT TDH SIZE 4X3-13	75 hp	SS	1	\$13,040	2010	strm.a500.evap.571	53181	kg/hr	0.8	2.3	36538	1.15	\$14,567	\$13,928	\$32,035	1	35	\$32,0
S-505	Pressure Filter	Larox	384 sq. m filtration area ea incl packing		SS316	2	\$3,294,700	2010	strm.a500.evap.571	53181	kg/hr	0.8	1.7	36538	1.15	\$3,680,519	\$3,519,098	\$5,982,467	1	34	\$2,991,2
T-512	Vent Scrubber	Envitech	Inlet Gas: 9681 acfm, 91°F, 1.97 mass% Ethanol		SS304/PP	1	\$215,000	2009	strm.a500.523	82260	kg/hr	0.6	2.4	21759	0.96	\$210,121	\$211,530	\$507,673	1	3	\$507,67
T-530	Filtrate Tank		13,750 gal 14' dia x 12' H		SS	1	\$103,000	2010	strm.a500.evap.571	53181	kg/hr	0.7	2	36538	1.15	\$113,480	\$108,503	\$217,006	1	6	\$217,00
T-531	Feed Tank		20,300 gal 14' dia x 18' H		SS	1	\$174,800	2010	strm.a500.evap.571	53181	kg/hr	0.7	2	36538	1.15	\$192,585	\$184,139	\$368,278	1	8	\$368,27
T-532	Recycled Water Tank	Harrington Plastic	4000 gal.		HDPE	1	\$1,520	2010	strm.a500.evap.571	53181	kg/hr	0.7	3	36538	1.15	\$1,675	\$1,601	\$4,804	1	4	\$4,80

T-533	Pressing Air Compressor Receiver		1350 gal., 300 psig design		CS	1	\$8,000	2010	strm.a500.evap.571	53181	kg/hr	0.7	3.1	36538	1.15	4	\$8,81	\$8,427	125	\$26,	1	25	\$26,1
T-534	Drying Air Compressor Receiver		9,000 gal., 150 psig design		CS	2	\$17,000	2010	strm.a500.evap.571	53181	kg/hr	0.7	3.1	36538	1.15	30	\$18,7	\$17,90	516	\$55,	1	58	\$27,7
									Area 500 Totals							\$11,302,300	\$11,145,318	\$22,343,314		\$19,000,203			
Mechanical Equipment List									Scaled Installed Costs														
EQPT NO	EQUIPMENT TITLE	VENDOR	DESCRIPTION	HP	MATERIAL	NUM REQD	\$	Year of Quote	Scaling Variable	Scaling Val	Units	Scaling Exp	Inst Factor	New Val	Size Ratio	Scaled Purch Cost	Purch Cost in Proj year	Inst Cost in Proj year					
B-608	Aerobic Digester Blower	ADI	14,000 SCFM @ 10.3 psig	1.000		8	\$1,933,750	2010	strm.a600.601	393100	kg/hr	0.6	1	411178	1.05	\$1,986,627	\$1,899,498	\$1,899,498	4	9	\$949,74		
C-614	Aerobic Sludge Screw				CS	1	\$25,000	2010	strm.a600.601	393100	kg/hr	0.6	1	411178	1.05	\$25,684	\$24,557	\$24,557	1	57	\$24,5		
H-602	Anaerobic Digester Feed Cooler	ALFA LAVAL	Wide gap plate & frame 2.5 mgd		SS316; CS	1	\$83,863	2010	strm.a600.601	393100	kg/hr	0.6	1	411178	1.05	\$86,156	\$82,378	\$82,378	1	78	\$82,3		
M-606	Biogas Emergency Flare	ADI				4	\$32,955	2010	strm.a600.601	393100	kg/hr	0.6	1	411178	1.05	\$33,856	\$32,371	\$32,371	2	86	\$16,1		
M-630	Polymer Addition System	ADI	11.4 gph neat polymer	10		1	\$9,300	2010	strm.a600.601	393100	kg/hr	0.6	1	411178	1.05	\$9,554	\$9,135	\$9,135	1	5	\$9,13		
M-632	Caustic Feed System	ADI	0-300 gph Aerobic Digesters #1-#3	1.5		3	\$22,800	2010	strm.a600.601	393100	kg/hr	0.6	1	411178	1.05	\$23,423	\$22,396	\$22,396	2	31	\$14,9		
M-640	Evaporator System						\$3,801,095	2010	strm.a600.601	393100	kg/hr	0.6	1	411178	1.05	\$3,905,034	\$3,733,767	\$3,733,767			\$3,733,767		
P-602	Anaerobic Reactor Feed Pump	ADI	2500 gpm submersible rail mounted	50	CS	4	\$231,488	2010	strm.a600.601	393100	kg/hr	0.6	1	411178	1.05	\$237,818	\$227,388	\$227,388	2	4	\$113,69		
P-607	Waste Anaerobic Sludge Pump	ADI	10 gpm	3		6	\$93,300	2010	strm.a600.601	393100	kg/hr	0.6	1	411178	1.05	\$95,851	\$91,647	\$91,647	3	24	\$45,8		
P-608	Aeration Basin Feed Pump	ADI		15		4	\$84,000	2010	strm.a600.601	393100	kg/hr	0.6	1	411178	1.05	\$86,297	\$82,512	\$82,512	2	56	\$41,2		
P-609	Return Activated Sludge Pump	ADI		40		6	\$177,300	2010	strm.a600.601	393100	kg/hr	0.6	1	411178	1.05	\$182,148	\$174,160	\$174,160	3		\$87,080		

P-611	Centrifuge Feed Pump	ADI		10		2	\$61,200	2010	strm.a600.601	393100	kg/hr	0.6	1	411178	1.05	\$62,873	\$60,116	\$60,	1	58	\$30,0
P-612	Centrate Pump	ADI		15		2	\$70,800	2010	strm.a600.601	393100	kg/hr	0.6	1	411178	1.05	\$72,736	\$69,546	\$69,	1	73	\$34,7
R-609	Membrane Bioreactor	ADI	Includes membrane CIP and Scour system			3	\$5,248,750	2010	strm.a600.601	393100	kg/hr	0.6	1	411178	1.05	\$5,392,274	\$5,155,780	\$5,155,	2	87	\$3,437,1
S-610	Reverse Osmosis System	ADI				1	\$2,210,979	2010	strm.a600.601	393100	kg/hr	0.6	1	411178	1.05	\$2,271,437	\$2,171,816	\$2,171,	1	16	\$2,171,8
S-611	Centrifuge					3	\$6,493,500	2010	strm.a600.601	393100	kg/hr	0.6	1	411178	1.05	\$6,671,062	\$6,378,482	\$6,378,	2	21	\$4,252,3
T-606	Anaerobic Basin	ADI	31 Million gallonwith cover		CONCRET E	4	\$27,000,000	2010	strm.a600.601	393100	kg/hr	0.6	1	411178	1.05	\$27,738,302	\$26,521,754	\$26,521,7	2	7	\$13,260,87
T-608	Aeration Digester	ADI	25 ft H x 115 ft x 344 ft 2 ft floor/wall thickness		CONCRET E	3	\$2,700,000	2010	strm.a600.601	393100	kg/hr	0.6	1	411178	1.05	\$2,773,830	\$2,652,175	\$2,652,	2	17	\$1,768,1
									Area 600 Totals							\$51,654,964	\$49,389,478	\$49,389,478			\$30,073,704
A-701	Denaturant In-line Mixer		4 inch		SS304	1	\$3,850	2009	strm.703	23154	kg/hr	0.5	1	22273	0.96	\$3,776	\$3,801	\$3,801	1	1	\$3,80
A-720	CSL Storage Tank Agitator	Lotus		10 hp	SS304	1	\$21,200	2009	strm.735	1393	kg/hr	0.5	1.5	1323	0.95	\$20,660	\$20,798	\$31,	1	98	\$31,1
A-760	DAP Make-up Tank Agitator	Lotus		5.5 hp	SS304	1	\$9,800	2009	strm.755	163	kg/hr	0.5	1.5	142	0.87	\$9,152	\$9,214	\$13,	1	20	\$13,8
C-755	DAP Bulk Bag Unloader	Flexicon	Super sack unloader			1	\$30,000	2009	strm.755	163	kg/hr	0.6	1.7	142	0.87	\$27,636	\$27,822	\$47,	1	97	\$47,2
P-701	Ethanol Product Pump	Goulds	150 GPM, 112 FT TDH	5	CS	2	\$9,200	2009	strm.a500.515	22681	kg/hr	0.8	3.1	21808	0.96	\$8,916	\$8,975	\$27,	1	12	\$13,9
P-703	Sulfuric Acid Pump	Goulds	5 GPM, 150 FT TDH SIZE 2X1-10	0.5	SS316	1	\$7,493	2010	strm.710	1981	kg/hr	0.8	2.3	1981	1	\$7,492	\$7,163	\$16,	1	75	\$16,4
P-704	Firewater Pump	Goulds	2500 GPM, 150 FT TDH	125	CS	1	\$15,000	2009	strm.a700.713	8343	kg/hr	0.8	3.1	8021	0.96	\$14,536	\$14,633	\$45,	1	62	\$45,3
P-710	Gasoline Pump	Goulds	4 GPM, 60 FT	0.5	CS	1	\$3,000	2009	strm.a700.701	473	kg/hr	0.8	3.1	465	0.98	\$2,959	\$2,979	\$9,2	1	4	\$9,23
P-720	CSL Pump	Goulds	8 GPM, 80 FT TDH	0.5	CS	1	\$3,000	2009	strm.735	1393	kg/hr	0.8	3.1	1323	0.95	\$2,879	\$2,898	\$8,9	1	4	\$8,98

P-760	DAP Pump	Goulds	2 GPM, 100 FT TDH	0.5	CS	1	\$3,000	2009	strm.755	316	kg/hr	0.8	3.1	142	0.87	\$2,689	\$2,707	\$8,392	1	2	\$8,39
T-701	Ethanol Product Storage Tank	Mueller	750,000 gal., 7 day storage, Floating roof		A285C	2	\$1,340,000	2009	strm.a500.515	22681	kg/hr	0.7	1.7	21808	0.96	\$1,303,683	\$1,312,426	\$2,231,125	1	63	\$1,115,5
T-703	Sulfuric Acid Storage Tank		12,600 gal, 12' dia x15' H		SS	1	\$96,000	2010	strm.710	1981	kg/hr	0.7	1.5	198	1	\$95,987	\$91,777	\$137,666	1	6	\$137,66
T-704	Firewater Storage Tank		600,000 gal - 4 hrs @ 2500 gpm		Glass lined	1	\$803,000	2009	strm.a700.713	8343	kg/hr	0.7	1.7	802	0.96	\$781,201	\$786,440	\$1,336,948	1	48	\$1,336,9
T-706	Ammonia Storage Tank	Chemithon	28,000 gal		SA- 516-70	2	\$196,000	2010	strm.717	1171	kg/hr	0.7	2	116	1	\$195,389	\$186,820	\$373,639	1	0	\$186,82
T-710	Gasoline Storage Tank		65,000 gal., floating roof		CS	1	\$200,000	2009	strm.a700.701	473	kg/hr	0.7	1.7	465	0.98	\$197,602	\$198,927	\$338,176	1	6	\$338,17
T-720	CSL Storage Tank		70,000 gal		Glass lined CS	1	\$70,000	2009	strm.735	1393	kg/hr	0.7	2.6	132	0.95	\$67,516	\$67,969	\$176,720	1	0	\$176,72
T-760	DAP Make-up Tank		12,800 gal		SS304	1	\$102,000	2009	strm.717	1615	kg/hr	0.7	1.8	116	0.72	\$81,192	\$81,737	\$147,126	1	6	\$147,12
									Area 700 Totals							\$2,823,265	\$2,827,086	\$4,953,786		\$3,637,493	
Mechanical Equipment List									Scaled Installed Costs												93
EQPT NO	EQUIPMENT TITLE	VENDOR	DESCRIPTION	HP	MATERIAL	NUM REQD	\$	Year of Quote	Scaling Variable	Scaling Val	Units	Scaling Exp	Inst Factor	New Val	Size Ratio	Scaled Purch Cost	Purch Cost in Proj year	Inst Cost in Proj year	NUM REQD	Inst Cost in Proj year	
H-812	Pretreatment/BFW heat recovery	Mueller	9.4 MM Btu/hr		SS304	1	\$41,000	2009	heat.QH812	-2	Gcal/hr	0.7	2.2	-2	0.93	\$38,856	\$39,117	\$86,057	1	57	\$86,0
M-803	Boiler	Babcock & Wilcox	525,000 lb/hr @ 900 psig	2752 kW	CS	1	\$28,550,000	2010	strm.a800.a810.812	238686	kg/hr	0.6	1.8	234784	0.98	\$28,269,041	\$27,029,216	\$48,652,589	1	9	\$48,652,58
M-811	Turbine/Generator	Siemens	23.6 kW, 2 extractions			1	\$9,500,000	2010	work.wtotal	-42200	kW	0.6	1.8	-41324	0.98	\$9,381,215	\$8,969,773	\$16,145,591	1	1	\$16,145,59
M-820	Hot Process Water Softener System	Proctor Sales				1	\$78,000	2010	strm.a800.a810.812	235803	kg/hr	0.6	1.8	234784	1	\$77,798	\$74,386	\$133,894	1	4	\$133,89
M-830	Amine Addition Pkg.	Proctor Sales				1	\$40,000	2010	strm.a800.a810.812	235803	kg/hr	0	1.8	234784	1	\$40,000	\$38,246	\$68,842	1	42	\$68,8

T-826	Deaerator	Proctor Sales	Tray type		CS;SS316	1	\$305,000	2010	strm.a800.a810.812	235803	kg/hr	0.6	3	234784	1	\$304,209	\$290,867	\$872,600	1	\$872,600
									Area 800 Totals							\$38,111.18	\$36,441.604	\$65,959,573		\$65,959,573
M-902	Cooling Tower System	Marley SPX	44,200 gpm	750 hp	FIBERGLASS	1	\$1,375,000	2010	strm.a900.945	10037820	kg/hr	0.6	1.5	11923904	1.19	\$1,524,650	\$1,457,782	\$2,186,673	1	\$2,186,673
M-904	Plant Air Compressor	Rogers Machinery	400 SCFM@ 125 psig	150 hp		1	\$28,000	2010	DRY101	83333	kg/hr	0.6	1.6	83333	1	\$28,000	\$26,772	\$42,835	1	\$42,835
M-908	Chilled Water Package	Trane	2 x 2350 tons (14.2 MM kcal/hr)	3400 hp		1	\$1,275,750	2010	heat.a900.qch wop	14	Gcal/hr	0.6	1.6	13	0.95	\$1,234,354	\$1,180,217	\$1,888,348	1	\$1,888,348
M-910	CIP System		100,000 GAL		SS304/SS316	1	\$421,000	2009	strm.a900.914	63	kg/hr	0.6	1.8	145	2.3	\$694,222	\$698,878	\$1,257,980	1	\$1,257,980
P-902	Cooling Water Pump	Goulds	16,120 GPM, 100 FT TDH SIZE 20X20-28	500	CS	3	\$283,671	2010	strm.a900.945	10982556	kg/hr	0.8	3.1	11923904	1.09	\$302,961	\$289,674	\$897,989	2	\$598,659
P-912	Make-up Water Pump	Goulds	685 GPM, 75 FT TDH SIZE 6X4-13	20	CS	1	\$6,864	2010	strm.a900.904	155564	kg/hr	0.8	3.1	147140	0.95	\$6,565	\$6,277	\$19,459	1	\$19,459
P-914	Process Water Circulating Pump	Goulds	2285 GPM, 75 FT TDH SIZE 8X6-13	75	CS	1	\$15,292	2010	strm.a900.905	518924	kg/hr	0.8	3.1	523463	1.01	\$15,399	\$14,724	\$45,643	1	\$45,643
S-904	Instrument Air Dryer	Zeks	670 SCFM - CYCLING TYPE		CS	1	\$15,000	2009	DRY101	83333	kg/hr	0.6	1.8	83333	1	\$15,000	\$15,101	\$27,181	1	\$27,181
T-904	Plant Air Receiver	Rogers Machinery	3800 gal - 72" x 228" vertical		CS	1	\$16,000	2009	DRY101	83333	kg/hr	0.6	3.1	83333	1	\$16,000	\$16,107	\$49,933	1	\$49,933
T-914	Process Water Tank No. 1		250,000 gal		CS	1	\$250,000	2009	strm.a900.905	451555	kg/hr	0.7	1.7	523463	1.16	\$277,245	\$279,104	\$474,476	1	\$474,476
									Area 900 Totals							\$4,114,396	\$3,984,635	\$6,890,517		\$6,591,187

Mechanical Equipment List								Scaled Installed Costs										
EQUIP NO	EQUIPMENT TITLE	VENDOR	DESCRIPTION	HP	MATERIAL	NUM REQD	\$	Year of Quote	Scaling Variable	Scaling Val	Units	Scaling Exp	Inst Factor	New Val	Size Ratio	Scaled Purch Cost	Purch Cost In Proj year	Inst Cost In Proj year
C- 101	Transfer Conveyor	Dearborn Midwest	160 MTPH ea., enclosed, 60 in. x 55 ft. long	20 hp ea.	CS	2	\$5,397,000	2009	STRM.101	94697	kg/hr	0.60	1.7	104167	1.10	\$5,714,628	\$5,752,952	\$9,780,018
C- 102	High Angle Transfer Conveyor	Dearborn Midwest	160 MTPH ea., enclosed, 72 in. wide	50 hp ea.	CS	2	INCLUDED											
C- 103	Reversing Load-In Conveyor	Dearborn Midwest	320 MT / hr, enclosed, 84 in. wide	20 hp	CS	1	INCLUDED											
C- 104	Dome Reclaim System	Cambelt	100 MTPH ea.	45 kw ea.	CS	2	\$3,046,000	2009	STRM.101	94697	kg/hr	0.60	1.7	104167	1.10	\$3,225,265	\$3,246,895	\$5,519,721
C- 105	Reclaim Conveyor	Dearborn Midwest	100 MTPH ea., enclosed, 48 in. x 125 ft. long	10 hp ea.	CS	2	INCLUDED											
C- 106	High Angle Transfer Conveyor	Dearborn Midwest	100 MTPH, enclosed, 72 in. wide	20 hp	CS	1	INCLUDED											
C- 107	Elevated Transfer Conveyor	Dearborn Midwest	100 MTPH, enclosed, 48 in. x 200 ft. long	10 hp	CS	1	INCLUDED											
C- 108	Process Feed Conveyor	Dearborn Midwest	70 MTPH ea., enclosed, 42 in. x 25 ft. long	5 hp ea.	CS	1	INCLUDED											
M-101	Truck Scale	St. Louis Scale	10' x 70', 200,000 lb		CONCRETE	2	\$110,000	2009	STRM.101	94697	kg/hr	0.60	1.7	104167	1.10	\$116,474	\$117,255	\$199,333
M-102	Truck Dumper	Jeffrey Rader	70' x 55 ton x 63 degree	2 x 50 hp	CS	2	\$484,000	2009	STRM.101	94697	kg/hr	0.60	1.7	104167	1.10	\$512,485	\$515,922	\$877,067
M-103	Truck Dumper Hopper	Jeffrey Rader	3500 cu.ft. hopper w/ drag chain conveyor	50 hp ea.	CS	2	\$502,000	2009	STRM.101	94697	kg/hr	0.60	1.7	104167	1.10	\$531,544	\$535,109	\$909,685
M-104	Concrete Feedstock Storage Dome	Domtec	98 ft. dia., 160 ft. high., 4000 MT		CONCRETE	2	\$3,500,000	2009	STRM.101	94697	kg/hr	0.60	1.7	104167	1.10	\$3,705,984	\$3,730,838	\$6,342,424
M-105	Belt Scale	Tecweigh	Scale plus processor		CS	2	\$10,790	2009	STRM.101	94697	kg/hr	0.60	1.7	104167	1.10	\$11,425	\$11,502	\$19,553
M-106	Dust Collection System	Siy	8500 ACFM	25 hp ea.	CS	6	\$279,900	2009	STRM.101	94697	kg/hr	0.60	1.7	104167	1.10	\$296,373	\$296,360	\$507,213
Area 100 Totals																\$14,114,178	\$14,208,831	\$24,155,013