Woody Biomass in Humboldt County

Select Alternative Uses

Jameson Catlett
Benjamin Goldberg
Roger Turlington
Riley Whipkey

Prepared for: Redwood Coast Energy Authority
Capstone - Spring 2020
Environmental Resources Engineering
Humboldt State University
May 12, 2020

Alternative Uses for Woody Biomass in Humboldt County - Team Jamo

Jameson Catlett, Benjamin Goldberg, Roger Turlington, Riley Whipkey

Executive Summary

A large portion (23%) of the Redwood Coast Energy Authority's (RCEA) electricity portfolio for Humboldt County is sourced from two local biomass incineration plants, using local logging and mill waste as feedstock. Because the biomass that is sourced for incineration meets California's sustainable forestry requirements, the biomass plants are considered GHG neutral, renewable power sources to the state. Despite this, the community has mixed opinions on the local air quality impact and actual climate change contribution resulting from the biomass plants. As a result, RCEA has commissioned the authors to provide a technical, economic, and environmental assessment of alternative uses of biomass feedstock in Humboldt County.

The team developed four alternative use cases for the biomass feedstock, subject to the following constraints:

1. The alternative must meet or exceed all federal, state, and local water and air pollutant standards concerning criteria pollutants and CO_2.
2. The alternative must not create a demand for imported biomass or use a non-waste source of biomass.

Alternative One proposed the creation of a composting facility to convert the woody biomass into a valuable organic soil amendment. Alternative Two used the woody biomass as raw material for the production of particleboard. Alternative Three consisted of a gasification and refining facility that would produce a substitute natural gas for local residential gas customers. Alternative Four proposed the construction of a 500 thousand ton per year wood pellet facility, creating a valuable export product from the waste biomass.

The four proposed alternatives were evaluated against nine different criteria, themselves separated into four categories: Economic, Environmental, Technical, and Social. Each criterion was given a weight from 1-10, based on recommendations from RCEA. The sole Economic criteria was the payback period of the project, in years. The Environmental criteria included the net GHG emission difference between implementation of the alternative and the current baseline. The Technical criteria examined included system robustness, technological maturity, and overall operator skill level required. The Social criteria considered consisted of the amount of new criteria air and water pollutants, and number of jobs provided by the alternative proposal.

The preferred alternative was determined using the Delphi matrix method, and a Wood Pellet manufacturing facility was chosen. This alternative would use all of the available biomass currently being used by the two biomass power plants in Humboldt. The facility is proposed to be sited at the Redwood Marine Terminal 2, the site of a former pulp mill, with access to a dock for loading finished pellets onto cargo ships, shown in Figure 1. The recommendation of the report is an optimized production line with an output capacity of 72 tons of pellets per hour. The economic analysis performed indicated a payback period of 2.4 years for this proposed facility.

The emissions, including criteria and GHG pollutants, were calculated for each of the power generation facilities, the manufacturing of pellets, and the combustion of the pellets. Figure 2 represents the proportionate effect of each process in respect to criteria pollutant emissions, including

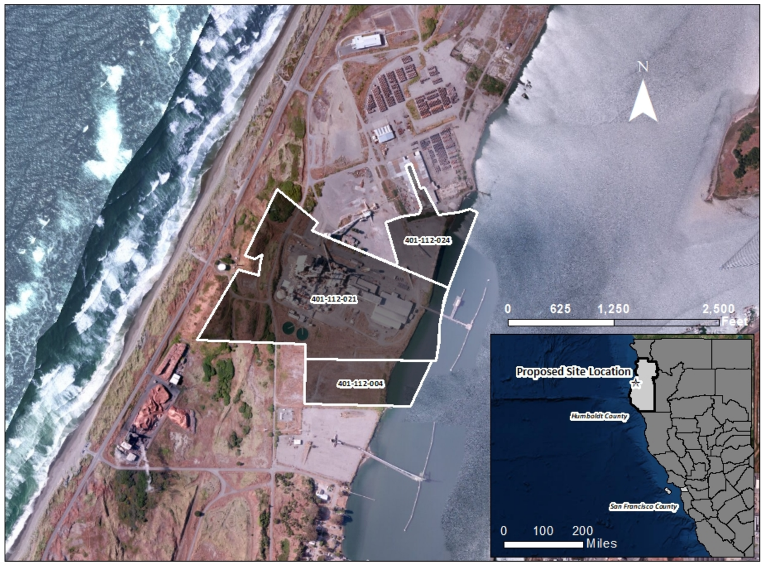

Fig. 1. Location of Redwood Marine Terminal 2 and surrounding parcels for proposed site (California Air Resources Board 2020a; Reed et al. 2012; California Air Resources Board 2020b)

the combined effect of the two power generation facilities. The manufacturing of pellets does not produce any carbon monoxide (CO) or particulate matter (PM). Furthermore, emissions from the pellet manufacturing is lower than the two power generations combined, especially in regards to CO. The combustion of pellets, however, appears to significantly increase all emissions, resulting in significantly higher emission values.

Carbon dioxide (CO_2) emissions can be seen in Table 1. Pellet manufacturing, when compared to the combined power generation facilities, is estimated to produces approximately 82% less CO_2 emissions. If including the combustion of pellets, the amount of CO_2 produced is roughly 44% higher than that of the combined power generation facilities. However, because it has the same "renewable" source material, pellets made from the biomass are considered to be carbon neutral to the state of CA. Depending on which governmental jurisdiction the pellets are combusted in, the emissions could be ruled carbon neutral, a GHG source, or even a carbon credit.

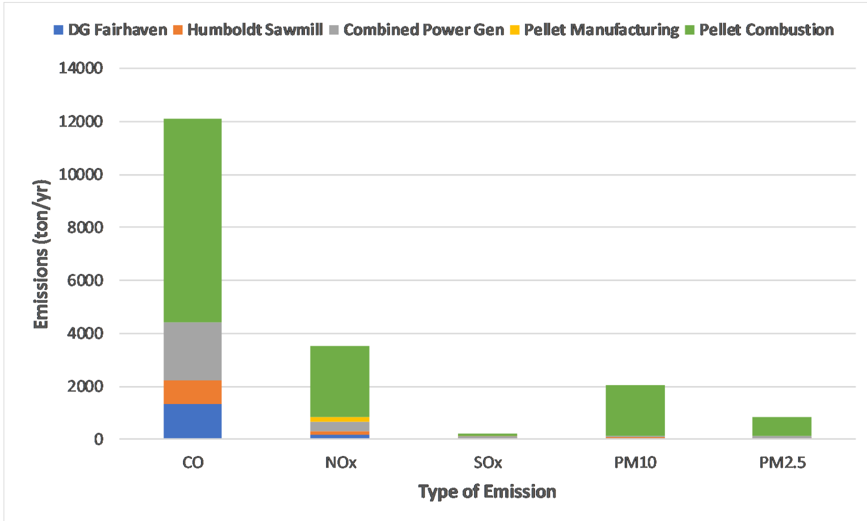

Fig. 2. A stacked chart of criteria pollutants and GHG emissions associated with DG Fairhaven, Humboldt Sawmill Company, pellet manufacturing, and pellet combustion (United States Environmental Protection Agency 1996; California Air Resources Board 2020a; Reed et al. 2012).

TABLE 1. Carbon dioxide emissions for the power generation facilities, pellet manufacturing, and pellet combustion.

Source of CO_2 Emission	Emissions (kton/yr)
DG Fairhaven	200
Humboldt Sawmill Company	218
Combined Power Generation	419
Pellet Manufacturing	77
Combustion of Pellets	666

A sensitivity analysis was performed on several economic inputs to determine the effect on the payback period for the facility. The operation costs, transportation costs, and capital costs of the facility all had a significant effect on the payback period, but the most significant change was caused by reducing the sale price of the finished pellets. A 35% reduction in the pellet price results in more than a 1000% increase in the payback period, and a reduction of more than 40% in price results in a negative yearly net profit. Sensitivity was also performed on the amount of pellets sold annually, which had a slightly weaker effect on the payback period, and is compared to the pellet sale price in Figure 3.

Fig. 3. Sensitivity Analysis of sale price of pellets and amount sold.

Further feasibility studies would be required to implement the preferred alternative. Topics of future research would investigate overseas or domestic bulk pellet customers, particularly in states and countries with favorable carbon credit programs. Additionally, rigorous testing would need to be performed to optimize the pelletizing process with the specific biomass material available. More intensive economic analysis is also needed for accurate long-term planning, including feedstock pricing and availability projections, as well as demand and price sensitivity analysis.

Contents

List of Tables

List of Figures

1 INTRODUCTION

The Redwood Coast Energy Authority (RCEA) is a Joint Powers Organization which focuses on the use of sustainable energy throughout Humboldt County. They are currently recognized as the local authority for sourcing and supplying a large portion of electricity to many cities throughout Humboldt County (Redwood Coast Energy Authority 2020b). Under California SB 350, Humboldt County must work towards reaching the statewide goal of using 50% renewable sources for electricity by 2030 (California Energy Commission 2020).

The most significant source of renewable energy in Humboldt County is woody biomass (ie. wood chips, bark, sawdust, etc.) generated by the local forestry and milling industries. Currently, the majority of this biomass is incinerated for electricity generation at two biomass power facilities. The biomass power facilities in Humboldt County currently emit about 320,000 tons of CO_2 annually, among other pollutants, which has sparked concern within the community (Furniss 2020). While carbon emissions created during the combustion of woody biomass are considered "carbon neutral" in California, many communities are still concerned with health effects associated with the large scale combustion of biomass.

As a response to the community concern, RCEA has commissioned the Humboldt State University (HSU) Environmental Resources Engineering (ERE) Spring 2020 Capstone section to analyze alternative uses of woody biomass in Humboldt County. This report serves to analyse feasible alternative uses for the biomass generated in Humboldt County and should not be taken to represent all available technology in the field.

2 OBJECTIVE STATEMENT

The objective of this project is to recommend a feasible alternative use for woody biomass in Humboldt County. The project should consider all stakeholders to be affected by the use of biomass within Humboldt County. The alternatives presented will address all constraints and criteria determined to be of significant relevance to the project. A final design will be recommended based on an analysis of its ability to best meet the specified constraints and criteria.

3 BACKGROUND

3.1 Overview of Client and Project

Redwood Coast Energy Authority (RCEA) is a local Joint Powers Agency (JPA) comprised of the county of Humboldt, the Humboldt Bay Municipal Water District, and the Cities of Trinidad, Rio Dell, Fortuna, Ferndale, Eureka, Blue Lake, and Arcata (Redwood Coast Energy Authority 2020b). By entering a JPA, the public agencies can now share their resources, finance public works, collaborate on solutions to regional goals, and assist the community to locate grants (California State Legislature Senate Local Government Committe 2007). According to their mission statement, the purpose of RCEA is to "develop and implement sustainable energy initiatives that reduce energy demand, increase energy efficiency, and advance the use of clean, efficient and renewable resources available in the region for the benefit of the Member agencies and their constituents" (Redwood Coast Energy Authority 2020b). Furthermore, through the administration of their Community Choice Program, RCEA purchases local, renewable electricity and allows the community to decide where their energy is derived from (Redwood Coast Energy Authority 2020a).

Of all the power produced in Humboldt County, approximately 32% is generated via biomass conversion (Vergara and Yacob, Lecture Notes, 2020). The woody biomass used to generate power in Humboldt County primarily consists of mill waste and by-products from forestry operations (Redwood Coast Energy Authority 2020c). To generate power using woody biomass, the chemical energy within the wood source must be combusted to generate electricity (US Energy Information Administration 2018). The combustion of woody biomass generates greenhouse gas (GHG) emissions and air pollutants, so members of the community are concerned about health risks due to air pollution (Redwood Coast Energy Authority 2020c). Therefore, RCEA is searching for different methods to utilize biomass which pose less risk to public and environmental health.

3.2 Biomass as a Resource

The term "biomass" can be defined in a number of different ways. The practice of using natural material for energy has been used for over a million years and is one of the first known energy sources to humankind (Scott 2018; Turgeon and Morse 2012). Beginning when early humans used feces and wood to fuel fires for warmth and cooking, the use of common and often renewable materials for energy has been an attractive option for some time. Today, biomass is the blanket term for organic matter which has not been fossilized (World Energy Council 2016). Biomass is a product of plant and animal wastes, and is considered to be an organic resource, which can be both renewable and non-renewable (Turgeon and Morse 2012). In a global context, sources of biomass are forests and agriculture, with woody biomass supplying over 10% of the world's annual energy use (World Energy Council 2016). Most biomass being recovered today is converted to energy through a variety of different methods.

As defined by the California Energy Commission, biomass power in California comes from four main categories: biomass, digester gas, landfill gas, and municipal solid waste (California Energy Commission 2019). These energy resources contributed 5,847 GWh (or 2.99% of CA total) of energy to California's electrical grid in 2018 (California Energy Commission 2019). While digester gas, landfill gas, and municipal solid waste contribute a large amount of energy for use throughout California, this report focuses on the use of woody biomass material generated in Humboldt County. Biomass in California typically comes from industries like agriculture and forestry, which produce a large amount of energy rich by-products (Williams et al. 2008).

A major industry in Humboldt County is forestry and natural resource management (Engel and Singh, In-class lecture 2020). A byproduct of logging trees to produce useful lumber is a large amount of residual woody material, such as bark, sawdust, wood chips, and chunks of dimensional lumber (Engel and Singh, In-class lecture 2020). According to work done by Robert Williams for the California Energy Commission, Humboldt County is the largest producer of forest biomass in the state of California, followed by Mendocino and Siskiyou Counties (Williams et al. 2008). Gross forest biomass produced in Humboldt County between 2007-2020 totaled 2,812,800 bone-dry tons per year (BDT/yr) (Williams et al. 2008). Due to the large amount of forestry and forest derived byproducts, Humboldt County is one of the main contributors of biomass energy in California (Williams et al. 2008). Forest derived biomass in Humboldt County accounted for 3.4% of California's total biomass energy production in 2007 (Williams et al. 2008).

California is on the forefront of climate change action. The California State Assembly Bill 32, enacted in 2006, mandated that greenhouse gas (GHG) emissions in the state be reduced "... to 1990 levels by 2020" (California Air Resources Board (CARB) 2014). In 2016, California reached the target of reducing GHG emissions and saw a reduction in carbon emissions of 13% to below 1990 levels (California Air Resources Board (CARB) 2018). That same year, Senate Bill 32 was enacted which required GHG emissions to be lowered by an additional 40% by 2030 (California Air Resources Board (CARB) 2018). Senate Bill 350, which was also enacted in 2016, sets the goal of having 50% renewable energy in California by 2030 (California Energy Commission 2020). By enacting these bills, California has created opportunities for new developments in renewable energies such as biomass, solar and wind.

3.3 History of Biomass Production, Use, and Disposal in Humboldt County

The history of large scale biomass generation in Humboldt County began in the 1850's as the gold rush and subsequent population boom created a high demand for new timber. This demand led to the development of new timber mills around Humboldt Bay, harvesting the local redwoods and creating large amounts of chips, bark, and sawdust (THA 2020).

Once timber production began to exponentially grow, the problem of disposing of this biomass grew. Larger operations abandoned open pit and field burning, as well as local dump storage for fire safety. Instead, the biomass was burned in furnaces on site at the mill, but were still not very effective. It had been observed that furnaces were designed to retain heat, not release it, leading to inefficient burning rate of material and dangerously high temperatures (Doty 1917).

In 1916, a conical, air-cooled burner was marketed by Colby Engineering company, a design that would incinerate Humboldt's biomass until the Clean Air Act enforcement in the 1980's (Doty 1917). The conical burners were a marked improvement on biomass disposal rates, but at a cost to the environmental health of the area. Because the conical burners were ubiquitous, constantly running, and contained no air quality control equipment of any kind, areas nearby the burners suffered from high particulate matter in the air (Kalt 2016). In addition, the former sites where these burners were located usually have severe soil pollutants, particularly toxic dioxin. The conical burners were a fact of life in Arcata and Eureka for nearly 60 years, as shown in Figure 4.

Fig. 4. A conical burner, bottom left, sends a plume of smoke over Arcata High School, June, 1947 (Schuster 1947)

After the enforcement of the Clean Air Act shut down the conical burners, new methods of disposal were needed. At the same time, an energy crisis led California to push for more renewable energy in its electricity portfolio, and biomass was an answer in many timber communities such as Humboldt. The 18 MW DG Fairhaven plant in Samoa came online in 1987, and the 28 MW Scotia plant followed in 1988. Both plants are equipped to meet the EPA's emission limits, and provide a much cleaner disposal of waste than the prior conical burners. Both of these plants have been offline for various short periods of time between electricity contracts, but are currently both operational and contribute a large portion of RCEA's renewable energy portfolio. (RCEA 2016)

3.4 Potential Biomass Technologies and Uses

There are many technologies which take advantage of the multiple uses of biomass. A large portion of these technologies focus on the conversion of biomass to energy. Due to the high energy content of woody biomass, it is an attractive alternative energy source in place of traditional energy sources such as natural gas and coal (Carreras-Sospedra et al. 2015). The woody biomass generated in Humboldt County is primarily used for power generation at the Scotia and Fairhaven power plants, but the wood waste has many potential uses in various fields. This review presents a variety of biomass uses and technologies found in use today, and should not be considered as an all encompassing guide to the field.

3.4.1 Biomass Conversion to Energy

Incineration Currently, the primary method to recover energy from woody biomass is through incineration in a biomass power plant. Biomass power plants delivered 2.4% of California's total energy demand in 2010 (Carreras-Sospedra et al. 2015). The energy obtained when incinerating biomass can either be used directly for heat, or converted to electricity. Of the energy produced by biomass resources globally, wood products accounted for 68%, and can attain an efficiency of 80% when used for heat and electricity combined (World Energy Council 2016). In a biomass power plant, feedstock is usually moved with conveyor belts to a boiler, where it is incinerated to create steam, which drives a turbine to create energy (California Air Resources Board (CARB) 2013). The most common types of boilers found in biomass power plants are stoker, and fluidized bed boilers (Carreras-Sospedra et al. 2015).

A key difference between traditional biomass use (i.e. wood fires and stoves) and current biomass to energy technologies is that current technologies seek to lessen the environmental impacts of biomass incineration (World Energy Council 2016). Figure 5, as shown by the Placer County Air Pollution Control District, compares the emissions of select criteria air pollutants between the open burning and conversion to energy of woody biomass. It can be seen that when woody biomass is openly burned, it creates far more emissions than when converted to energy in a licensed facility. When burned in a biomass power plant as opposed to in the open, carbon monoxide (CO) and volatile organic compound (VOC) emissions are reduced by 99%, PM10 emissions are reduced by 97%, and NOx emissions are reduced by 60% (Christofk 2012). In Humboldt County, woody biomass is diverted mainly to two biomass incineration plants which produce a combined total of 650,000 MWh per year (Engel and Singh, In-class lecture 2020). Table 2, obtained from Williams et al. shows the higher heating values (HHV) of different woody materials. It can be seen that woody biomass has an average of about 20 MJ per kg of dry material.

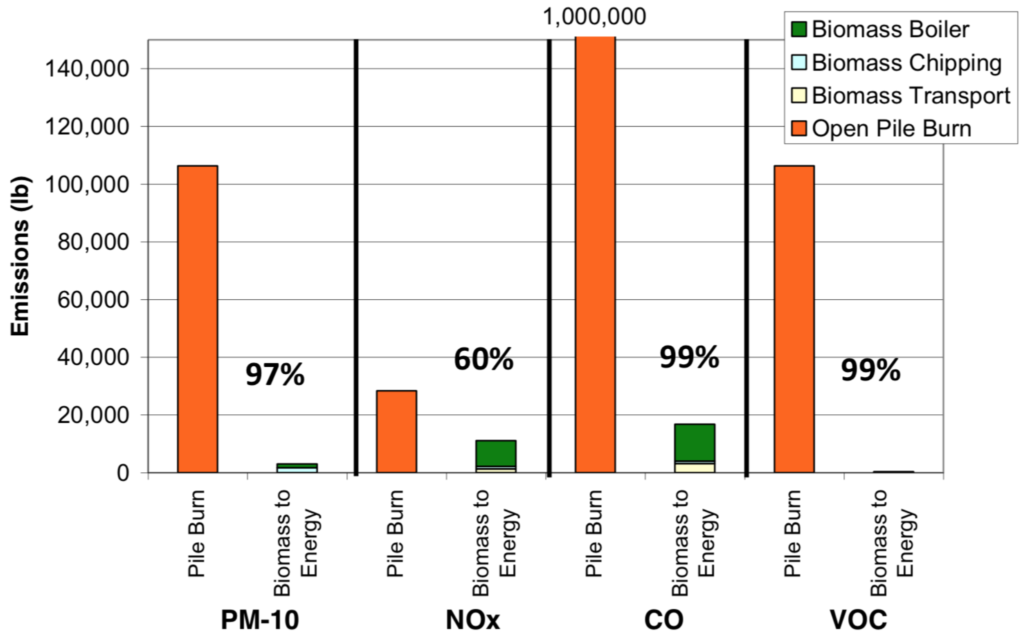

Fig. 5. Compared emissions from the open burning of woody biomass versus conversion to energy including percent reduction of pollutant when converting to energy. (Christofk 2012)

TABLE 2. The higher heating values (HHV) of different woody biomass material, common in Humboldt County. Source: Williams et al. 2008.

Forestry and Dedicated Crops	Higher Heating Value MJ/kg dry	BTU/lb dry
Forest Thinnings and Slash	21	9027
Forest Other	20	8597
Chaparral	18.61	8000
Mill Residue	20	8597
Dedicated Biomass Crops	19	8168

Gasification Another technology which utilizes biomass to create energy is gasification. The gasification process involves a small amount of oxygen, unlike other energy conversion processes, like pyrolysis which involves no oxygen, in order to produce a mix of gases that can be used for energy from a carbon rich material (EERE nd). The mix of gases will often contain Hydrogen gas, Carbon dioxide and monoxide, and methane, which are collectively referred to as syngas (Molino et al. 2016). Pyrolysis is one of the steps of the gasification process, coming after a drying step, which comes after the initial oxidation step, which imparts energy to the biomass for later steps, and the process is finalized by a reduction step, which yields of the final syngas mix (Molino et al. 2016). Moisture content is important in determining the result of the gasification process of biomass, since higher moisture contents in woody mass result in lower energy densities and heating values, and can make the drying step more cumbersome (Molino et al. 2016). The lower heating values (LHV) for syngas vary based on the quality of the feedstock biomass, and are typically in the range of 4-13 mega joules per normal cubic meter, while the char byproducts from the process can have LHV's in the range of 25 to 30 mega joules per kilogram (Molino et al. 2016).

Pyrolysis Another source of energy derived from biomass is biofuels. These fuels are highly concentrated liquids which contain the energy found in the biomass feedstock (Tsita and Pilavachi 2013). Biofuels take advantage of sugar or ethanol rich feedstock to create energy rich fuels; some can even contain enough energy for a transatlantic jet trip (World Energy Council 2016). A common method of producing biofuels is pyrolysis. Pyrolysis refers to the incomplete combustion of biomass in high temperatures with a restricted oxygen supply (Mohan et al. 2006). Pyrolysis is a highly chemically active process and results vary based on temperature, retention time and feedstock (Wijayapala et al. 2017). The constituents of wood which play an important role during pyrolysis are cellulose, hemicellulose, and lignin (Mohan et al. 2006). During pyrolysis, these components are broken down and altered through chemical reactions, which take place in high temperatures. Conventional pyrolysis (or slow pyrolysis) typically produces a charcoal, whereas fast pyrolysis, which uses extreme temperatures, decomposes feedstock into liquid, gas and solid components (Mohan et al. 2006).

Anaerobic Digestion Anaerobic digestion uses bacteria and chemical decomposition in an oxygen void environment to convert nutrient rich feedstock to gas that has between 50-80% methane content (Yunqin et al. 2014; Carreras-Sospedra et al. 2015). Examples of biomass feedstock commonly used in anaerobic digestion are wastes from animal products, mushroom production, and municipal solid waste (MSW) (Carreras-Sospedra et al. 2015). Anaerobic digestion is best done using feedstock with less than 15% solid content (ie. wet feedstock), thus it is not an ideal method for the use of woody biomass (Carreras-Sospedra et al. 2015). Recent work by Torri et al. in 2019 combined pyrolysis with anaerobic digestion in the Py-AD method to create “pyrobiogas” (Torri et al. 2020). The pyrobiogas is a fuel rich in methane and biochar which has an energy content lower than that achieved by traditional pyrolysis methods. The work done by Torri et al. shows that there are new developments for the conversion of biomass into energy containing fuels; however more traditional methods continue to have higher efficiencies.

Torrefaction Torrefaction is one method of processing biomass feedstock to create a more flexible, efficient fuel to burn for energy. The end result of torrefaction is a coal-like char product that can be directly used as fuel and handled more easily than the original biomass feedstock. (Bates and Ghoniem 2012)

The torrefaction process is essentially a controlled Malliard reaction - the same reaction that occurs on seared steak, fried foods, and carmelized onions. Inside a torrefaction reactor, the biomass is heated to 200-300°C in an unpressurized, low oxygen environment. Instead of combusting, the biomass material undergoes Malliard reactions, gasifying the moisture and volatiles of the feedstock, while starting to decompose the biological polymers cellulose, hemicellulose, and lignin. The volatiles released from these reactions can also be used as an energy source. Once the process is complete, the biomass exits the reactor as a brittle, coal-like substance. (Bates and Ghoniem 2012).

This "biocoal" is a much preferable fuel product than the raw biomass, justifying the cost and energy needed to convert it. One advantage the biocoal has over raw biomass is its weight and moisture content, providing a 30% reduction in weight with only a 10% loss in potential energy. This means that torrefied has a better energy density, and costs less to transport than raw biomass. The torrefied product is brittle, and easier to densify into briquettes or pellets. This, combined with biocoal’s hydrophobic properties, make the fuel easier to store with regards to moisture introduction.

Another storage advantage of the char product is the cessation of biological activity; stockpiles of torrefied biomass present no threat of spontaneous heating or combustion due to microbial activity. Finally, the torrefied product is much more homogenous than raw biomass feedstock. Most biocoal has similar sizes, moisture contents, and heating values, with the only large difference is in the ash produced. A comparison of the raw biomass and the torrefied product is shown in Figure 6. (Shankar Tumuluru et al. 2011)

(a) Raw biomass feedstock from DG Fairhaven (Catlett 2020)

(b) Biochar (van de Beld 2019)

Fig. 6. The torrefaction process converts raw woody biomass into a charcoal-like substance with superior fuel properties (Shankar Tumuluru et al. 2011)

Torrefied biomass can be useful in several ways in Humboldt County. For example, torrefaction facilities at the sawmills that produce the biomass could convert it before shipping to the biomass plant in Fairhaven. Even if only a portion of the fuel stream is converted, the biocoal can be used to improve performance of the plant during wetter winter months. If economically feasible, torrefied biomass can even become an export product for other biomass or co-gen electricity plants. (Lottes 2014)

3.4.2 Composting

Biomass, whether primarily comprised of woody material or otherwise, has a place for use in composting. Woody material does not break down as quickly as other organics, and may impede the composting process due to a high carbon to nitrogen ratio (Kreith and Tchobanoglous 2002).

However, woody biomass has been used in composting processes to add structure for increased porosity of the compost pile and in order to aid aeration (Vandecasteele et al. 2016). In addition to the raw biomass material, biomass that is already being used for energy conversion produces ash byproducts that have found uses in enhancing nutrient contents and managing the pH of soil amendments (Asquer et al. 2019).

In the U.S. in 2018, woody biomass made up 30% of all energy generated from biomass sources (Mayes 2019). While the peak U.S. production of energy through biomass was in 2014, it had seen increases during the previous decade (Mayes 2019). Combustion of biomass creates ash byproducts, which can be utilized by composting facilities to enrich the resulting soil amendment by adding nutrients like calcium and potassium (Asquer et al. 2019). In addition to this, a study has shown that incorporating biomass ash in the composting process may significantly reduce the levels of common polycyclic aromatic hydrocarbons that are commonly present in combustion ash through a bioremediation effect (Košnář et al. 2019).

Wood chips have also been used for composting of biological waste. In New York, the static pile composting, where compost piles are left for months without turning or active aeration, utilize woody biomass to aid in composting roadkill (Bonhotal et al. 2007). This static composting process is helped by the increased aeration that occurs naturally when using wood chips as a substrate (Bonhotal et al. 2007).

3.4.3 Consumer Products

Engineered Wood Products According to the State of California (2020), a more desirable option for recycling wood waste is to use it as a feedstock for engineered wood products. Two such products, particleboard and fiberboard, have similar manufacturing processes where wood waste is hot pressed along with resin adhesives (Forest Plywood 2020). Fiberboard generally utilizes wood waste that has been made into individual fibers while particleboard uses small pieces, shavings, and sawdust (Ryczkowski 2020b). The difference between the two can be seen in Figure 7; the top represents the fiberboard which is made of finer particles, and the bottom shows the particleboard made of small pieces. Particleboard is generally less expensive than fiberboard and is used for projects which do not require an elegant finish (Forest Plywood 2020).

Fig. 7. A side view of fiberboard (top) and particleboard (bottom) (Ace Kitchen and Baths, Inc. 2020)

Laminated wood, which usually implies gluing of material to the wood, is generally used for flooring but can also be applied to veneers and furniture (Shaddy 2019). The European Producers of Laminate Flooring (2016) claim laminate flooring to have a positive ecological impact due to enhanced production procedures, as well as the fact that the wood used in manufacturing can be sourced from wood waste. Wood waste can be used in the core layer of the laminate flooring which generally consists of fiberboard underlain with backer paper and overlain with decorative finish and a wear layer (Swiss Krono 2019).

Construction structural panels, such as the stacks of plywood and oriented strand board (OSB) shown in Figure 8, are two more uses for biomass. Plywood is manufactured by placing thin sheets of wooden layers with their grains perpendicular to each other bonded together using adhesive resin (Mou 2020). OSB is manufactured using small, rectangular wood chips which are bonded using heat-cured adhesives (Gromicko 2020). According to the Wood Recyclers Association, OSB and plywood were some of the first implementations of wood waste in the UK (Wood Recyclers

Association 2017).

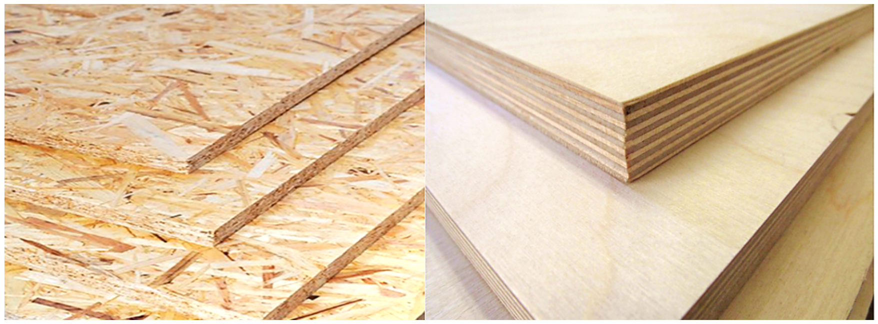

Fig. 8. Sheets of OSB board (left) and plywood (right) (Total Wood Store 2020; Shouguang Qihang Wood Co,. LTD 2020)

Wood Pellets An alternative use of woody biomass is the manufacturing of wood pellets. Pellets can be created from woody biomass by drying, crushing, and compressing the material into pellets that are then cooled and bagged (Reed et al. 2012). The wood pellets can then be purchased and used for residential heating. Due to their source, wood pellets are considered as a form of renewable energy and used for creating electricity in Europe (Drouin 2015). By using high heat and pressure, the biomass is compressed together and the natural plant characteristics bind the pellet without the use of adhesives (European Pellet Council 2018). These pellets, which burn at very high temperatures, allows for a cleaner and more efficient combustion of the biomass when compared to standard fireplace stoves (US EPA 2014).

Mulch Feedstock Wood chips may be useful for a feedstock to mulch. Dr. Chalker-Scott of Washington State University outlines the various benefits of using wood chips as mulch for the soil and claims that where trees are predominant wood chips are the best choice for trees and shrubs (Chalker-Scott 2007). Utilizing wood chips as a use for wood waste would not require any additional manufacturing or processing.

Pulp Pulp, which can be made by either mechanical grinding or chemical treatment of wood chips, is a standard source of fiber used for papermaking (American Forest & Paper Association 2019).

The USDA also invented a method which uses biological processes to selectively degrade lignin to create pulp (USDA 2002a). Using either of these methods could be a source of use for wood chip biomass.

Miscellaneous Uses Other successful approaches for biomass use include animal bedding and landfill cover (USDA 2002b). The University of Massachusetts Amherst outlines how wood shavings, wood chips, and sawdust can all be used to provide animal bedding that is suitable in terms of comfort, moisture content, cleanliness, inertness, and particle size (University of Massachussets Amherst 2020). Landfills must be covered with 6 inches of soil or alternative daily cover materials (ADCM), which includes the use of wood waste (EPA 1992). A study conducted by (Whittaker et al. 2017) on CO2 emissions generated by heaps of wood chips suggests a peak emission of 20,000 to 70,000 ppm of CO_2 at approximately 20-23 days and a significant reduction in emissions thereafter.

3.4.4 Restoration Ecology

Woody biomass can be a valuable resource in the environmental restoration of wetlands, forests, and other important ecological systems. Used this way, wood chips or other woody biomass is amended into the soil of restoration sites, improving drainage and aeration as well as supplying organic carbon for new growth (Daniels 2005). In addition, heavy layers of woody biomass on and in the soil restrict the growth of nonnative or invasive plants, allowing native flora a chance to dominate the site (Eldridge et al. 2012). Figure 9 shows the application of wood chips to restore cleared forest land. The wood chips act as a replacement for the forest floor that hydrologically degraded after clearing (CLT 2019).

There are many types of restoration sites that can benefit from the amendment of woody biomass. One way this has been applied is in the restoration of disturbed mine soils, combined with municipal biosolids and biochar, showing a marked improvement in plant cover over non-amended soils (Page-Dumroese et al. 2018).

More applicable to Humboldt County, woody biomass can be critical in improving restoration wetlands soils. Restoration experiments have shown that biomass reduces compaction of wetland

Fig. 9. Plots of wood chips serve as the new forest floor for this restoration project (CLT 2019).

soils and increases phenolics levels, aiding quicker plant growth that is needed to progress the site back to a natural wetland state (Wolf et al. 2019).

3.4.5 Mycoremediation

A potential use for woody biomass, particularly sawdust and wood chips, is as substrate for growing fungi in mycoremediation projects. Mycoremediation is the use of fungal biological processes to improve the ecological quality of water and/or soil. It is similar to conventional bioremediation and phytoremediation, but differs in that the main organism degrading or sequestering targeted contaminants is not plants or bacteria, but the cultivated mycelium of a specific fungus strain. Mycelium is the fibrous, root like structure that forms the majority of the fungus organism (Figure 10. This mycelium consumes the substrate as it grows in it, and can eventually produce fruiting bodies (mushrooms) that can be harvested. (Singh 2006)

The mycelium of wood-consuming fungi excretes unique enzymes for degrading woody plant material such as cellulose and lignin (Singh 2006). These same enzymes can degrade and deteriorate complex organic molecules, such as those that make up most organic polymers, such as polyaromatic

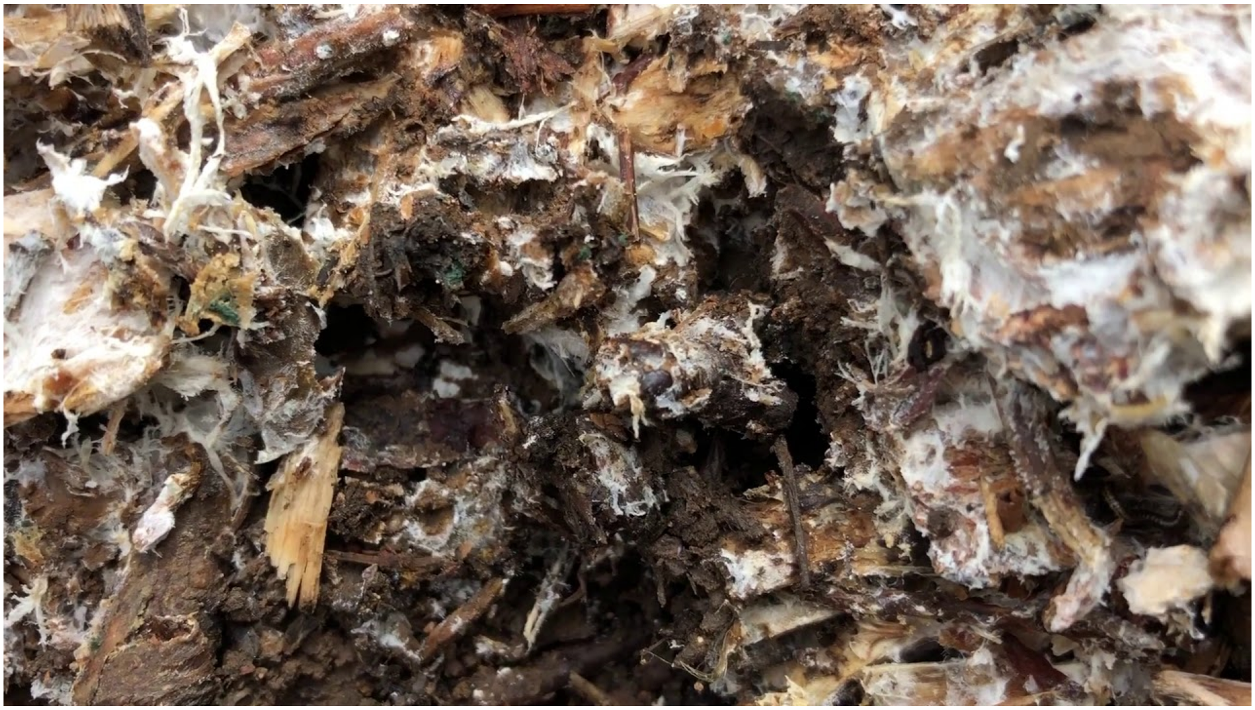

Fig. 10. Fungus mycelia decomposing wood chip substrate (Durr 2016)

hydrocarbons (Young et al. 2015). In addition, the fungus can uptake and sequester heavy metals, treat industrial wastewaters, and filter pathogens from water such as *E. Coli* (Taylor et al. 2015).

The growth of mycelium for mycoremediation can use the woody biomass produced in Humboldt as a substrate. This provides both a food source for necessary cometabolism and a matrix for the mycelium to spawn and inoculate (Singh 2006). The substrate can be layered with soil for *in-situ* treatment, used as media for trickling filters, or used to create packed and fluidized bed reactors (Singh 2006).

A local example of mycoremediation was performed by Fungaia Farm, a mushroom company located in Eureka, CA. The Mid Klamath Watershed Counsel hired the company to remediate a diesel spill behind their offices in Orleans, CA, receiving a Brownsfield grant from the county to fund it. The Fungaia Farm team created a bioreactor to treat the soil by first removing it and then layered it with straw substrate and inoculated burlap material, as shown in Figure 11. After three years of treatment, diesel concentrations in the soil were reduced by 93%, and motor oil concentrations by 83%. (Durr 2016)

Fig. 11. Soil mycoremediation bed designed and constructed by Fungaia Farms (Durr 2016)

Similar contaminated sites are common in Humboldt County, as diesel generators are ubiquitous in the area's current and former rural cannabis cultivation sites. A prospective use of Humboldt-derived biomass would be as substrate for multiple soil or water mycoremediation projects in the County, possibly funded by Brownfield or similar public grants.

3.5 Regulations and Permitting

U.S. air pollutant emissions criteria are compiled in the AP 42 document provided by the Environmental Protection Agency (EPA 2016). While emissions from burning woody biomass differ depending on the quality of the feedstock, the EPA is primarily focused on controlling the emissions of particulate matter and NOx emissions (EPA 2016). The EPA rates emissions from generating facilities based on a letter grade system, from A to E (EPA 2016).

DG Fairhaven Power, a power plant which generates electricity from local biomass, must obtain a Title V Federal Operating Permit of the Federal Clean Air Act (North Coast Unified AQMD 2015). This operating permit is a legally enforceable document which clearly states the responsibilities and actions of the facility relative to controlling air pollution (EPA 2017). Other guidelines outlined by the permit include, but are not limited to, the following: emission limitations, permit duration, noncompliance and violations information, and payment information (California Air Resources Board 2020c). Emission limitations set forth by the operating permit regulate particulate matter, carbon monoxide, nitrogen oxides, and a variety of release point pollutants. The permit summarizes the pollutant thresholds of the combustion boiler shown in Table 3 (North Coast Unified AQMD 2019).

TABLE 3. Combustion boiler emission limits for DG Fairhaven Power LLC. Source: North Coast Unified AQMD 2019

Pollutant Emitted	lbs/hr	tons/year
PM_{10}	12.6	55.4
$PM_{2.5}$	12.6	55.4
NO_X	154.8	236.0
VOC	5.37	23.5
CO	1,264.0	3,316
SO_X	7.9	34.6

Water Quality The DG Fairhaven Biomass plant also has three discharge points where they emit wastewater from the facility, point 001, 010, and 020 (NCRWQCB 2018). These discharge points all allow wastewater from the plant to flow into the ocean, and are subject to water quality standards as governed locally by the North Coast Regional Water Quality Control Board (NCRWQCB 2018). The effluent limitations imposed on the facility are different for each discharge point, with the only common limitation being the limitation on the high and low for the instantaneous pH level of the outflowing water, where the water pH cannot exceed 9.0 and cannot fall below 6.0 at any time (NCRWQCB 2018). These limits can be seen in Table 4.

TABLE 4. Wastewater Discharge Limits for DG Fairhaven Power LLC. Source: NCRWQCB 2018

Pollutant	Units	Maximum Daily Limit	Discharge Point
Copper, Total Recoverable	μg/l	1200	001
Total Suspended Solids	mg/l	100	010
Oil and Grease	mg/l	20	010
Chromium, Total Recoverable	mg/l	0.2	020
Zinc, Total Recoverable	mg/l	1.0	020

Although they are not listed as limits specific to the Fairhaven facility's discharge points, for ocean discharge, there are other limitations when it comes to wastewater, primarily there is a limit for total and fecal coliform densities, that may be relevant to other biomass processing facilities (NCRWQCB 2018).

Soil Amendments There are regulations and rules that apply to soil amendments, which are important when planning on using combustion byproducts like boiler or fly ash as a soil amendment. The EPA suggests that fly ash may be regulated as a soil amendment because it may be considered a caustic or hazardous waste, depending on the results of screening tests which may be required in certain states (EPA 2007). The California Department of Food and Agriculture has specific labeling requirements for commercial soil amendments, and the department considers fly ash and combustion byproducts to fall under Packaged Agricultural Minerals (CDFA 2017). One of the labeling requirements that might apply to using combustion byproducts as soil amendments is the rule for amendments containing heavy metals, which must include a label that points the user to a phone number to find out specific information about the levels and types of heavy metals present in the amendment (CDFA 2017). Thus, laboratory testing would need to be completed before sending any incineration byproducts to be used as a commercial soil amendment.

4 CONSTRAINTS & CRITERIA

In order to narrow the spectrum of available options for the use of woody biomass in Humboldt County, specific constraints and criteria were developed for the project. The constraints represent parameters which any proposed alternative must strictly adhere to. Criteria are proposed in order to gauge each proposed alternatives performance in important categories.

4.1 Constraints

The constraints shown in Table 5 were implemented to ensure all alternatives meet minimum qualifications deemed important and to narrow the scope of the proposed solutions. The first constraint simply states that alternatives will comply with all requisite water and air quality across local, state, and national standards, with no planned periods of violation.

The second and final constraint requires that the alternatives use only the current Humboldt County mill waste stream for biomass. Because of the community's general mistrust of biomass power generation and sustainable forestry, it was decided that directly or indirectly increasing the harvesting of trees that become woody biomass would be unacceptable. In the same spirit, no alternative shall import woody biomass from outside the Humboldt County waste stream.

TABLE 5. Chosen project constraints and their descriptions.

Constraint	Description
Meets Local and Federal Water and Air Quality Standards	The alternative must meet or exceed all federal, state, and local water and air pollutant standards concerning criteria pollutants and CO_2.
Utilizes Current Humboldt Woody Biomass	The alternative must not create a demand for imported biomass or use a non-waste source of biomass.

TABLE 6. Project criteria and their associated indicators, weight, and category.

Criteria	Quantifiable Indicator	Weight
	Economic	
Payback Period	Years until break-even	10
	Environmental	
GHG Emissions	CO_2e emissions kg/yr	7
Biomass Diversion	% of biomass used	6
	Technical	
System Robustness	% downtime	6
Operator Skill Needed	% skilled employees	5
Maturity & Availability	Years of reliable industrial use	5
	Social	
Public Health Impact	# of non-GHG pollutants	5
Public Benefit	# of jobs created	3

4.2 Criteria

In order to analytically compare the merits of the various alternatives, eight criteria were formed across four categories: Economic, Environmental, Technical, and Social. As shown in Table 6, each criterion will receive a weight from one to ten, with ten being the most important and one the least. Each alternative will be scored on the criteria and directly compared and the optimal alternative will be recommended via the Delphi method.

4.2.1 Economic

Each of the possible alternatives are analyzed by comparing their payback periods, see Table 6. The payback period combines a number of economic factors to produce a break-even point in years, which represents the time it would take for a capital investment to be paid off. Examples of factors used to calculate payback period are the capital cost, operation and maintenance (O&M)

costs, and the return on investment. Capital cost includes expenses incurred to purchase fixed assets such as property, equipment, and permits. O&M costs are incurred from activities associated with the continual operation such as utilities, rent, employee pay, and needed repairs.

4.2.2 Environmental

Each alternative was also compared according to the following environmental criteria: environmental impact, and the diversion of wood waste (Table 6). The net GHG emissions in CO_2 equivalent units (CO_2e) were used to determine an alternatives general environmental impact. The following environmental criteria compares alternatives on the quantity of wood waste that each consumes. Because almost all biomass not used by the proposed alternatives will be incinerated or landfilled out of Humboldt county, alternatives that use *more* of the biomass waste stream will be scored higher than those that use less. Alternatives shall include a description of the fate of all woody biomass produced if the alternative is implemented.

4.2.3 Technical

The three criteria in the Technical category are intended to evaluate the difficulty of implementing each alternative. The technical criteria shall include the alternatives' system robustness, required operator skill, and the maturity and availability of the technologies implemented.

System robustness will evaluate alternatives based on expected outages and failure rates, in percentage of downtime.

The experience, education, training, and number of operators for a system will also be compared for each alternative. This is an effect beyond just the economic burden of hiring highly skilled workers. A system that requires highly specialized operators will routinely need to be sourcing talent statewide, nationally, and globally throughout its design lifetime. Following this logic, a system that can source and train operators locally would score higher in this criteria,

Mature technologies are easier to implement, with more available qualified operators, vendors, repair procedures, and general design knowledge. This criteria will balance cutting edge technologies with high theoretical efficiencies with the ease of implementing conventional solutions.

4.2.4 Social

The Social criteria category primarily considers the impact of the proposed alternatives on the public stakeholders of the project. This category comprises of two criteria: public heath impact, and public benefit.

The alternatives were evaluated for their effect on public health, since public concerns about air quality is one of the driving motivations for this project. This goes above and beyond the air and water quality standards enforced by various agencies and governmental bodies, and can be quantified by the number of pollutants other than GHGs that are emitted by an alternative.

The public benefit criterion was used to evaluate alternatives based on the tangible benefits such as job creation as a positive addition to the local community.

5 ALTERNATIVES

Based on the project background research and the determined constraints and criteria, four possible alternative uses for the waste woody biomass generated in Humboldt county were analyzed: (1) production of particleboard wood products, (2) manufacture of wood pellets for use as heating fuel, (3) biofuel conversion via gasification, and (4) composting applications.

Besides a general description of the alternative, each subsection will include the inputs and outputs of the system, the primary processes and reactions involved, the proposed scale of the alternative operation, and performance in terms of the determined criteria.

5.1 Particleboard Production

The conversion of wood into building products has been common practice for some time. Today, lumber is harvested for useful products such as dimensional lumber, plywood and other sheet boards, and furniture. These wood harvesting operations also create large amounts of wood waste. However, this waste can actually be used to create useful material for applications such as building and furniture (Lewis 1971; Mirski and Dziurka 2011; Merrild and Christensen 2009). Particleboard (PB) is made by hot pressing small pieces of wood such as as saw dust and small chips into a compacted board (Ryczkowski 2020a).

5.1.1 *Inputs and Outputs*

The PB manufacturing process relies on a number of inputs, the most important of which is a wood source used to create the product. Additional inputs to the PB production process are resins and chemicals which apply the necessary bonding of the particles and pieces of wood (Santos et al. 2014; Batiancela et al. 2014). A significant amount of water and energy are also required at a PB manufacturing facility (Santos et al. 2014).

The particleboard manufacturing process outputs a useful woody material which can be used for a variety of furniture and non-structural building purposes. Outputs from the process also come in the form of air and water pollutants such as CO, HC, PM, NOx, VOC, and a large number of other chemicals listed in section 10.6-2 of AP-42 by the U.S. EPA (Santos et al. 2014; United States Environmental Protection Agency 2002).

5.1.2 *Primary Processes*

Wood chips used in the production of particleboard must first be dried to remove moisture, which is an extremely energy intensive process (Merrild and Christensen 2009). Energy consumption during this step depends on the moisture content of the feedstock. Average moisture content of the feedstock generated in Humboldt County converted to energy at the DG Fairhaven Biomass power plant is currently 56% (Marino Lecture 2020). Common moisture content of virgin wood is between 40-60% (Merrild and Christensen 2009). Thus, it can be assumed that woody biomass feedstock in Humboldt County contains a 50% moisture content. It is estimated that each kg of water that must be dried out of woody feedstock consumes about 0.12 kg of fuel oil (Merrild and Christensen 2009). Thus, drying the feedstock will use a considerable amount of energy.

The process then uses resin and pressing in high temperatures to compress the dried wood chips and pieces into a board (Mirski and Dziurka 2011; United States Environmental Protection Agency 2002; de Carvalho Araújo et al. 2019). During this process resins like Melamine–urea–phenol–formaldehyde (MUPF), and urea-formaldehyde are used to bond the wood together along with ammonium sulfate as a common catalyst (Mirski and Dziurka 2011; Santos et al. 2014). In order to thwart water absorption in the finished product, additives like paraffin emulsion are added as well (Santos et al.

2014). The material is then formed for thickness and desired density and sent to pre-pressing and cutting, where it is given its initial shape. The sheets are then subject to a hot press with high temperatures and pressures. The boards are then trimmed, cut and sanded and either layered with a veneer coat, or put directly into storage until sale and/or shipment to market. This process is outlined in Figure 12.

5.1.3 Proposed Scale

The manufacturing of PB and MDF can be done at a variety of scales. A smaller scale operation may be achieved, however large-scale operations may have a better return on investment. Thus, it is recommended that the alternative be designed with the goal of diverting all of the available woody biomass in Humboldt County.

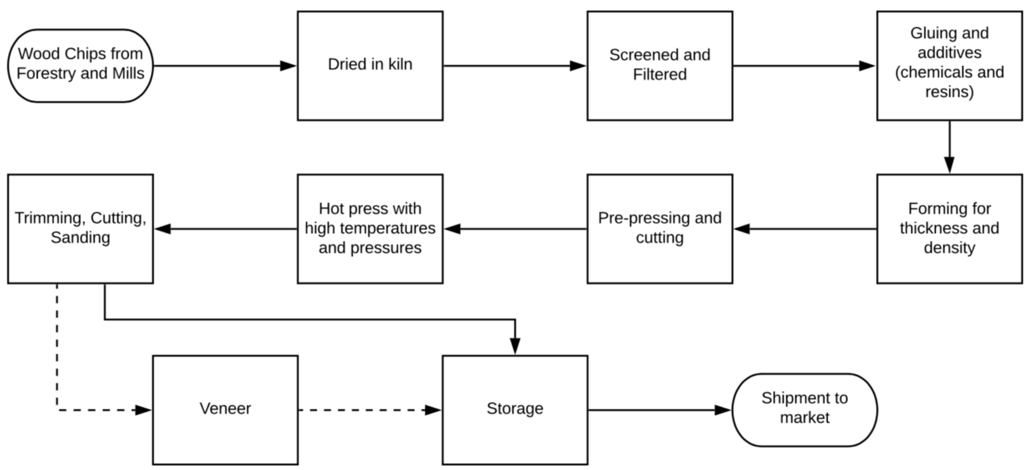

Fig. 12. Generalized process flow chart for PB and MDF production.

5.1.4 Relation to Constraints and Criteria

Constraints Any PB manufacturing facility must adhere to any applicable federal, state, and local laws. There are emission factors outlined in AP-42 by the EPA, sections 10.6-2 and 10.6-3, which help govern the emissions from facilities which produce particle boards and medium density fiber boards (United States Environmental Protection Agency 2002).

The proposed facility would intake only woody biomass produced as a byproduct of the forestry and milling operations in Humboldt County. The facility will be sized to optimally handle the current generation of woody biomass byproducts. As a result, it will not increase the need for raw material feedstock within the county.

Economic Criteria There is a large worldwide industry which produces PB, as well as global and regional markets for finished product (Research and Markets 2019). The system used for the utilization of woody biomass in Humboldt County must be analyzed for its performance in an estimated payback period analysis determined by analyzing capital and O&M costs, as well as return of investment.

Environmental Criteria The manufacturing of PB and MDF is a heavily controlled industry in the U.S. (United States Environmental Protection Agency 2002). According to dos Santos et al., the production of PB made from wood shavings can emit 0.6 grams of formaldehyde, 0.12 g of CO, 0.01 g of total particulate matter ($PM_{2.5}$ and PM_{10}), and 0.3 g of NOx per square meter (m^2) of PB produced (Santos et al. 2014).

The system would be sized appropriately in order to accommodate the amount of wood waste currently being generated in Humboldt County.

Technical Criteria Due to the age of PB manufacturing technology, the available systems today are operationally reliable. The manufacturing process relies heavily on many chemicals and resins and thus outside sources are necessary for operation. This means that if not managed properly, or an external factor stops the delivery of necessary chemicals to the factory, production could be halted. In terms of fuel flexibility, the production of PB uses a standard feedstock of chipped woods. Incoming wood chips and pieces would need to be chipped further and dried to create a uniform feedstock and a number of additives would need to be kept on hand at all times.

Operational skill required to run the process of manufacturing PB varies based on position. A supervisory position will require more expertise and industry knowledge than a machine operator. Entry level employment in a PB production facility requires at least a high school education or GED, light industrial experience, and strong computer skills (Aracuco 2020). Thus, aside from higher level managerial positions, machine operator positions can be filled with relative ease.

As mentioned previously, the technology to produce PB has been widely available since the 1960's and 70's (Lewis 1971). This makes the technology today mature and widely available for commercial purchase and use.

Social Criteria There are a number of pollutants associated with the production of PB (Santos et al. 2014). Emissions are heavily controlled for both air and water quality standards. However, it may be difficult for the public to accept a facility which generates a number of toxic chemical pollutants.

The proposed facility could prospectively add jobs to the community, resulting in a benefit to the local population. The facility would become a new source of manufacturing in Humboldt County, which would promote trade in and outside of the county. It will also stimulate the economy by creating jobs during the construction and operation of the facility, assuming it can maintain an operating profit margin.

5.2 Wood Pellet Manufacturing

5.2.1 Inputs/Outputs and Process

The typical process to manufacture wood pellets from woody biomass, which can be seen in Figure 13, consists of six steps: (1) collection of raw material, (2) drying, (3) crushing, (4) pelleting, (5) cooling, and (6) bagging (Reed et al. 2012). The manufacturing processes are summarized by the following descriptions.

1.) Collection of the raw material consists of acquiring material from the various producers of wood waste. The collection process also includes the trucking required to deliver the biomass and the on-site handling of the material. It is important that the raw material is stored within a dry facility on-site (Reed et al. 2012).

2.) The raw material then must be dried before it can be processed. A study regarding moisture content in pellets suggests an appropriate range of moisture content between 11 and 13 percent for excellent pellet quality (Samuelsson et al. 2012). There are different methods to dry the biomass, but

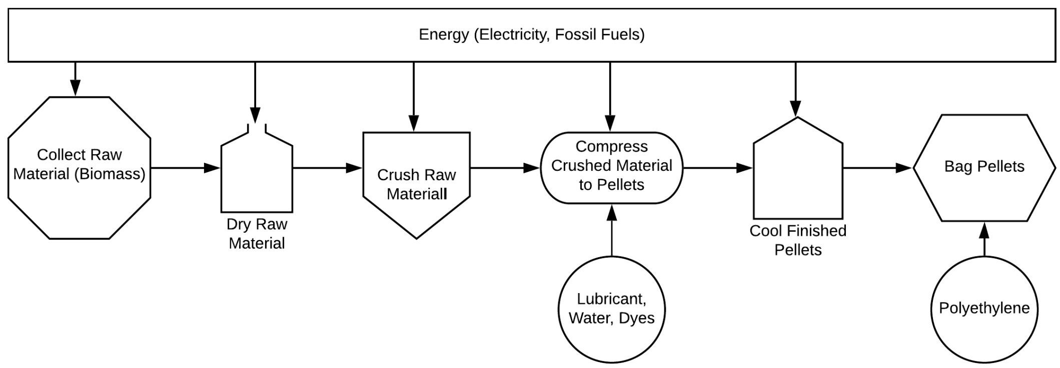

Fig. 13. Flow chart of wood pellet manufacturing using woody biomass as raw material (Reed et al. 2012; Katers et al. 2012)

the main processes include rotary dryers, flash dryers, and super-heated steam dryers (Amos 1999).

3.) Crushing of the material is a process which uses machinery to break down the dried biomass into a fine, compressible material. This can be done by using a device such as a hammer mill, which uniformly reduces the size of the material to approximately 2 mm (Reed et al. 2012).

4.) After leaving the hammer mill, the product is then pelletized. This process includes the use of high pressure and temperature to soften the lignin and bind the particles without the use of adhesives (Reed et al. 2012). Although the pellet formation does not require adhesives, small amounts of lubricants and dies are used to enhance the process (Jones et al. 2007).

5.) The pellets exit the pelletization process between 200 and 250 degrees Fahrenheit and are very soft (woodpellets.com LLC 2020), so they must be cooled to reduce the temperature and harden the pellet. Depending on the scale of the pellet manufacturing, various methods can be used to cool the pellets. Various cooling methods exist and can be categorized into horizontal, vertical, and counter flow coolers (Renewable Energy World 2016).

6.) Pelletization has now created a finished product, so the pellets are bagged for delivery or storage. To accomplish this, the pellets are generally transported via conveyors and into 40-lb plastic bags (Reed et al. 2012).

Each of these processes require energy to accomplish. For instance, the collection of the material requires fossil fuels for transportation and electricity for on-site collection and conveyance methods. Crushing, compressing, cooling, and bagging of the material requires electricity while drying of the material may require either fossil fuels or electricity (depending on the chosen method).

5.2.2 Proposed Scale

The process of creating wood pellets can range in scale from small, home use to industrial sized manufacturing. Figure 14 shows a typical home pelletizer (left) and an industrial sized pelletizer (right). This particular home pelletizer can produce approximately 50 to 80 kg/hr and needs approximately 3 KW of power to operate (Victor Pellet Mill 2017). The larger pelletizer on the right has a processing power of 1000 to 2000 kg/hr and requires 30 KW of power to create pellets (Victor Pellet Mill 2019). Given the amount of biomass received at the power plant, a larger scale operation would be required to utilize the biomass appropriately.

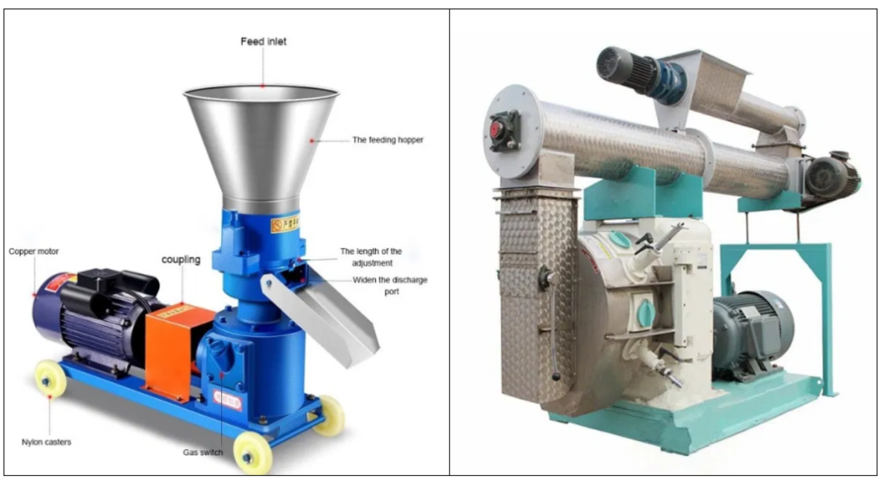

Fig. 14. A small scale pelletizer (left) and a large scale pelletizer (right) (Victor Pellet Mill 2019; Victor Pellet Mill 2017)

5.2.3 Relation to Constraints and Criteria

Constraints To justify that wood pellets are a viable option, the alternative should meet all constraints. The manufacturing of the pellets must not violate any local water or air quality regulations to continue operating. The facility would not require much water (small amounts during pelletization), but would need to abide by any discharge regulations. The pellet operation would have much lower emission rates than the existing power plant, but any facility which emits pollutants must obtain an operating permit from the local air quality management district (AQMD) (California Air Resources Board 2019).

Manufacturing wood pellets can utilize a large percentage of the current biomass received at the plant, because most of the material can be used. The bark of the biomass could not be used to make pellets, so there would be some waste involved. This bark could be used for other purposes such as mulch or landscaping, eliminating a waste stream from the process. To ensure there is no need for imported biomass, the scale of the facility must remain to a level which does not require more biomass than what is in Humboldt County.

If the biomass was used for pelletization rather than in the power plant, there would not be any combustion occurring, possibly reducing carbon emissions. It is also possible to ensure the entire process is powered by electricity, reducing the emissions to zero, but the carbon footprint of the facility should be analyzed to ensure emissions are not higher than that of the power plant.

Economic Criteria From an economic standpoint, pellets are generally considered a less expensive source of fuel (Jones et al. 2007). The capital investment to construct the facility would have to be considered because all of the needed equipment is different technology than is existing at the site. As for the return on investment, there is an existing wood pellet market, and some sources say that the pellet market is expected to grow in the upcoming future (Kram 2020; MarketWatch 2020).

Environmental Criteria The GHGs resulting from the process should be evaluated to determine its environmental impact. The life cycle impact can give insight into the fuel and electricity use contribution to GHG emissions. If the facility was powered by solely electricity, the GHG emissions could also be reduced by eliminating the combustion of fossil fuels.

Technical Criteria This type of facility would need some technically skilled workers who understand the mechanisms involved in pelletization. Routine operation and maintenance is required and would therefore need employees to understand how to repair the facility when needed. The system is dependant on energy sources from either electricity or both electricity and fuels. Pellet manufacturing has basically been around since the 1970's (Spelter and Toth 2009); therefore an abundance of industry knowledge which can be used to develop and operate the facility is available.

Social Criteria By generating pellets rather than using the biomass for creating energy, this alternative would not contribute to RCEA's renewable energy goal. As for the health of the public, the biomass is still being combusted but instead in people's homes. It must be considered that people will continue to heat there homes regardless, so it is not necessarily contributing to a new source of pollution.

5.3 Thermal Gasification

Rather than direct incineration, the energy in the woody biomass can be accessed via gasification, a thermal process that volatilizes the material into a fuel gas mixture. This alternative describes a system that will convert the woody biomass waste produced in Humboldt County into biogas, which can be further refined into substitute natural gas (SNG).

The initial product, biogas, could be cofired in biomass power plants to improve incinerator performance during the wet season, and replace natural gas currently used for power plant operations (Basu 2010). The refined SNG is technically practical in all natural gas applications, including supplying the local natural gas grid and power plant (Hamad et al. 2017). Proposed gasification facilities would most likely be sited at one of the current biomass plants in Fairhaven and Scotia.

An important case study application for this alternatives is the GoBiGas, a 20 MW demonstration plant built as a combined gasification and SNG refinery (Thunman et al. 2019). A similar configuration will be used in the alternative for efficient production of SNG.

5.3.1 Inputs and Outputs

The main inputs of the system are air, woody biomass, electricity, various methanation catalysts activated carbon adsorbent, and a small amount of natural gas for initial firing. The principle outputs of the system include raw biogas (a mix of methane, hydrogen, CO, CO_2, and water vapor), a SNG refined from the biogas, CO_2, tars, inert slag, and biochar. (Basu 2010)

5.3.2 *Primary Processes and Reactions*

There are two separate processes in the alternative operation: the gasification of woody biomass into raw biogas, and the refining of the biogas into substitute natural gas (SNG).

The biomass is fed into a gasifier reactor (Figure 15), where it is processed in a few general stages, beginning by drying at the top of the reactor. As the biomass flows down, it enters the pyrolysis zone, where the temperature is between 200 and 300°C, volatilizing much of the fuel mass into methane and other organics and creating char. After pyrolysis, air or oxygen gas is introduced to create limited combustion, which in turn decomposes even more volatilized gas into hydrogen and carbon dioxide. In the following gasification zone, the char reacts with water to produce hydrogen gas and CO, and the char's reaction with CO_2 produces more CO. The resulting biochar falls to the bottom of the gasifier, while the biogas is captured. (Basu 2010)

The captured biogas is next processed into a more refined SNG that is compatible with the local gas grid. This is performed largely through methanation catalyst reactions, converting both CO and CO_2 with H_2 into methane and water vapor. The gas is further purified with CO_2 scrubbers and dryers to create a product gas that is comparable and compatible with natural gas. (Thunman et al. 2019)

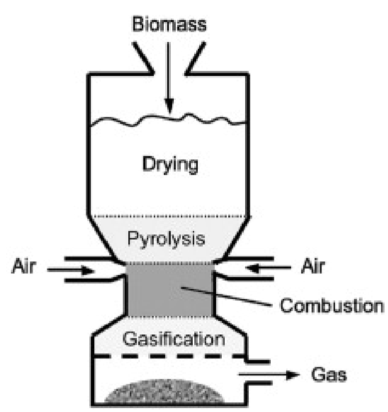

Fig. 15. Diagram of a simple downdraft gasifier. (Richardson 2020)

A flow chart generally describing the proposed system is shown in Figure 16.

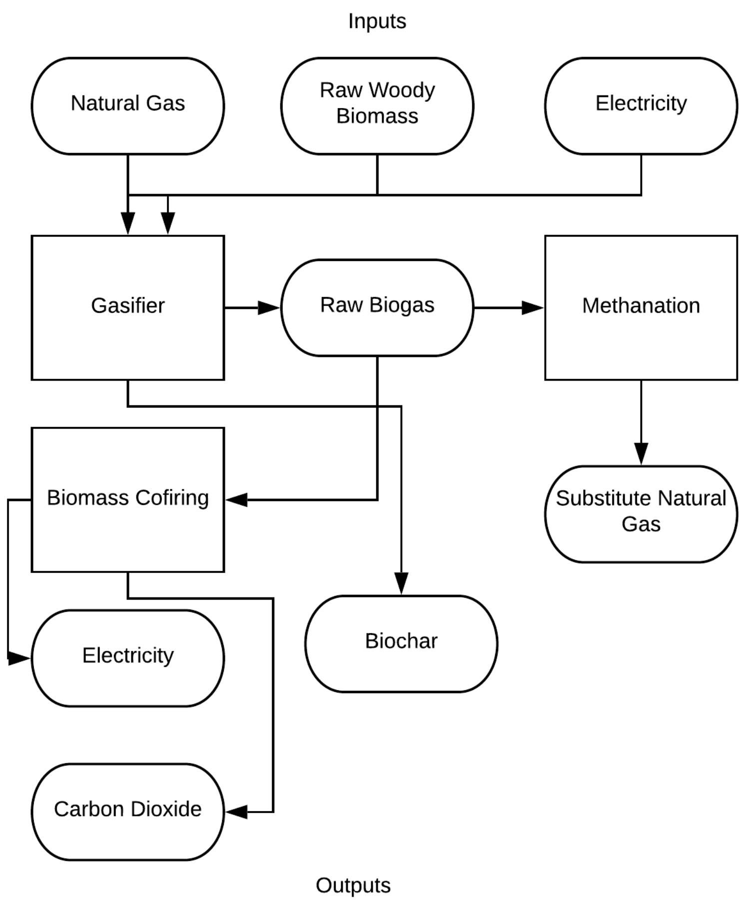

Fig. 16. Generalized process flow chart for the gasification and refining scheme

5.3.3 Proposed Scale

The proposed scale of this alternative will match that of the GobiGas demonstration plant with an output of 20 MW of SNG production (Thunman et al. 2019). This size was chosen largely because it roughly matches the total capacity of the 18 MW Fairhaven plant.

5.3.4 Relation to Criteria and Constraint

Constraints The proposed alternative satisfies all project constraints. The system can be sized to not require additional feedstock beyond the current Humboldt sawmill supply, and the use of even raw biogas cofiring in a power plant incinerator should improve combustion characteristics, lowering emissions for criteria pollutants as well as GHG. (Basu 2010)

Economic Criteria The installation and operation of the proposed facility requires significant capital and O&M costs ranging in the millions of US dollars. Because of low natural gas prices and abundant supply, SNG created by the process may not represent a profitable venture selling to the public gas grid. (Thunman et al. 2019)

Environmental Criteria The fuels created via the gasification process would still be considered carbon neutral, as is the raw biomass. GHG emissions could be lowered by replacing natural gas, a GHG-positive fuel, in energy production with SNG. Another avenue of GHG reduction includes using SNG to power the trucks that transport the biomass out of and around the county.

Technical Criteria Gasification technology is typically very robust, having a wide range of fuel sizes and associated moisture levels that can be accommodated. The gasifier technology has been mature for over 30 years, being used in the coal industry prior. For this reason, many types and brands of gasifier should be available for purchase or construction. However, the methanation technology requires a high level of fuel refinery expertise, and there are few examples of plants automating both processes simultaneously. It is expected that operators and managers will need to be highly educated, experienced, trained, and paid. (Basu 2010)

Social Criteria This alternative can increase RCEA's renewable energy portfolio, mainly by displacing natural gas with the refined SNG. If the fuel is used to improve combustion in the power plants, the local air quality should see an improvement, providing a public benefit. Such a complex process would be unlikely to draw additional public ire, as it will be difficult for the public to differentiate this technology and current biomass power generation. A positive public reception could be achieved by marketing the production of SNG as an important replacement for natural gas.

5.4 Composting Facility

Composting can use woody biomass in combination with other materials to create marketable soil amendments. These soil amendments can be used in many agricultural practices and also for landfill cover (Kreith and Tchobanoglous 2002). Woody biomass can be beneficial for the composting process, as it adds structure and thus increases the porosity and air circulation in a compost pile, which is important to the process of breaking down the raw material (Kreith and Tchobanoglous 2002).

5.4.1 Inputs/Outputs and Processes

The process of composting requires many types of micro-organisms to participate in aerobic decomposition, taking in oxygen and organic material and producing heat and CO_2 (NRCS 2000). In the active phase of composting, thermophilic and mesophilic bacteria speed up the natural decomposition process and raise the temperature in the compost enough to kill certain pathogens and other unwanted organisms in the pile (NRCS 2000). The curing phase slows down the bacterial activity to finish the compost, creating a stable soil amendment. An important factor for producing quality compost is the carbon to nitrogen ratio, with a target weight to weight ratio between twenty-five to one and thirty to one (Kreith and Tchobanoglous 2002). Carbon to nitrogen ratios for sawdust are anywhere from two-hundred to one up to seven-hundred and fifty to one (Kreith and Tchobanoglous 2002). The woody material must then be mixed with more nitrogen rich material to ensure for good composting. There are several options that can be used in Humboldt County that have lower ratios, including cattle manure from local dairy farms, food and yard waste collected by the Humboldt Waste Management Authority (HWMA), and processed sewage sludge from a Wastewater Treatment Plant (WWTP). Table 7 shows the typical carbon to nitrogen values of these other materials (Kreith and Tchobanoglous 2002).

The process of composting this material would require several inputs of energy. The first step to implementing this alternative would be to transport the raw materials from each of the sources to a

TABLE 7. Typical carbon to nitrogen ratios (Kreith and Tchobanoglous 2002)

Material	C:N (weight to weight)
Sawdust	200-750
Food Waste	14-16
Sewage Sludge	5-16
Cattle Manure	11-30

composting facility, requiring trucking from at least two different locations. These raw materials would be stored at the site where composting occurs, and would need to be mixed and, if necessary, chipped to achieve the proper particle size prior to being added to a pile (Kreith and Tchobanoglous 2002). This would require machinery for preprocessing and screening. During composting, energy input would be required for aeration. The amount of energy would be dependent on the selected method of composting, with turned windrow composting requiring a mechanical turning every few days, and static pile composting requiring a piped aeration system to ensure proper airflow (Kreith and Tchobanoglous 2002). Figure 17 shows the process from material collection to sale of the composting alternative.

5.4.2 Proposed Scale

The scale of this alternative is heavily dependent on the availability of the nitrogen rich material described above, since that material would make up a large portion of the compost material's mass. The market for compost in the county would also influence the scale of the operation, since the preference would be to use the soil amendment locally before exporting to other parts of the state and increasing the transportation costs and emissions created by the alternative.

5.4.3 Relation to Constraints and Criteria

The composting alternative can be assessed on its ability to meet the constraints of the project. Composting does not require an extremely large energy input to create a product. However, because of the range of possible material resources used, it could possibly increase the carbon emissions through increased transportation miles. Although it depends on the scale of the alternative, because a minimal amount of woody biomass is needed for the composting mix, it is unlikely that this

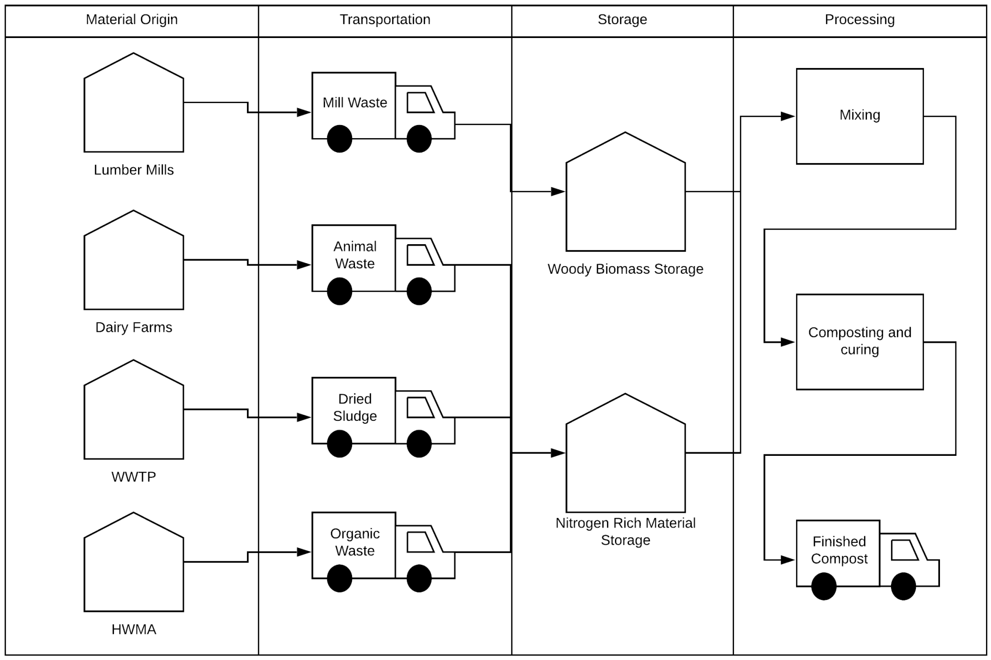

Fig. 17. Flow chart of composting alternative

alternative would increase the demand for woody biomass in the county.

This alternative's performance in the economic payback period criterion is depended on the marketability of the product produced in the county. The initial costs for a static pile composting system with active aeration would likely be dominated by the cost of purchasing a site of proper size to store and compost all of the input material.

This alternative will perform well in the technical criteria. Composting is a well-established and documented technology which does not require much in the way of specific skills to maintain. Some knowledge of the ideal composting conditions must be known for monitoring of the pile, but if static pile composting is implemented, there is little machinery operation required that would need to employ specific skills.

Social is another criteria category that a composting alternative could excel in. This alternative would not contribute to RCEA's energy goal, but a severe impact on public health is unlikely.

6 ALTERNATIVE ANALYSIS

Figure 18, from the report titled "Biomass Power in Humboldt County" by Michael J. Furniss for RCEA, shows the number of trucks transporting woody biomass to the two biomass power plants in Humboldt County. The figure shows that a total of 85 truckloads per day of biomass are transported to the facilities. According to Bob Marino, General Manager of the DG Fairhaven Power facility, each truck load carries 25 US tons of wood waste per trip (Marino 2020). As previously stated, the biomass is assumed to have a moisture content of 50%, and literature values obtained describe a density range between 180-380 kg/m^3 for this type of biomass (Batiancela et al. 2014; Gendek et al. 2016). The average value of 280 kg/m^3 was determined and assumed to be the density of incoming woody biomass for the scope of this project.

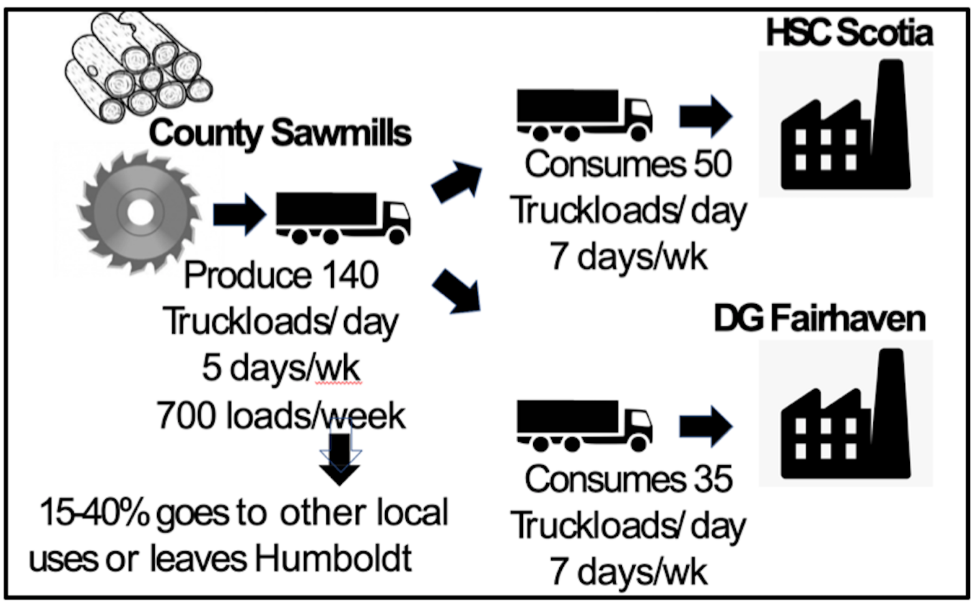

Fig. 18. Woody biomass flow from mills to power plants. (Furniss 2020)

.

Based on the aforementioned assumptions and parameters, the total annual weight of woody biomass transported to the two power facilities was determined to be 702 million kg (702 Gg), which correlates to a volume of 2.507 million m^3/yr.

6.1 Particleboard Production

Based on an assumed density of 600 kg/m^3 for the produced PB, the maximum PB output volume of a plant utilizing all of the available biomass would be 585,000 m^3/yr (Mirski and Dziurka 2011). This means that for every cubic meter of PB produced, approximately 4.3 cubic meters of woody biomass is used. This ratio is consistent with that obtained at Koskisen Oy, a PB manufacturing plant in Finland, which uses 4.5 m^3 of wood chip fuel for every cubic meter of PB produced (Hughes 2016).

6.1.1 Economic Criteria

The three major costs associated with PB production are wood, resin, and labor (Spelter 1994). Initial cost for this alternative is reduced due to the fact that the PB production facility will not need to purchase or process virgin woody material (Solt et al. 2019). The total woody biomass waste currently being generated into electricity totals 2.5 million m^3 per year, which could have the capacity to create a maximum of 585,000 m^3/year of particle board. The average particle board plant capacity in the United States is 258,700 m^3/year, thus a plant which produces 585,000 m^3/year would be about 2.26 times larger than the national average (Wood Based Panels International 2017). In addition to volume, area is another metric often used to analyze the capacity of PB plants. Based on a 3/4 inch (0.019 m) board, a PB plant producing 585,000 m^3/year would produce 30,700,000 m^2/year (330,500,000 ft^2/yr) of board area. Based on data regarding multiple recent PB plant sales documented by the association Wood Based Panels International, the purchase of an existing PB plant of this size could be expected to cost no less than $100 million (Wood Based Panels International 2017). According to Henry Spelter of the US Forest Service in 1994, the average PB plant in the United States had an estimated capital cost of $500 per thousand ft^2 of production (Spelter 1994). Adjusting these costs to 2019 dollars, a capital cost of $870 per thousand ft^2, or 0.87 $/ft^2, was determined. Using these assumptions, a PB plant utilizing all the available woody biomass was determined to have an estimated capital cost of $287,600,000. Operation and Maintenance costs, as well as profits, were determined by scaling costs and revenues for PB plants found by Spelter et al. in 2008 up by a factor of 4.13 (Spelter et al. 2008). Using this method, production costs and revenues of $74,400,000 and $99,200,000 per year were determined, respectively. Using these costs and revenue, an annual net profit of $24,800,000 was determined. Using the projected capital and production costs, and revenue, a simple payback period was determined to be 11.6 years.

6.1.2 Environmental Criteria

Due to the number of additives and chemicals present in the PB manufacturing process, there are a variety of emissions associated with its production, including VOCs and greenhouse gasses (Wilson 2008). Using an emissions inventory for PB production by James Wilson in 2008, emission factors for a large number of VOCs and common pollutants were determined (Table 24, Appendix A). By multiplying each GHG pollutant by its global warming potential (GWP), a total mass of CO_2e was able to be determined to analyze the prospective facility's effect on the environment (Brander 2012). The total annual GHG emissions in carbon dioxide equivalent (CO_2e) for the facility were determined to be 2.29×10^8 kg per year (Table 8).

TABLE 8. GHG emissions associated with the production of PB.

Greehhouse Gasses				
Pollutant	Emission Factor (kg/m^3)	Maximum Scale Emissions (kg/yr)	GWP	Maximum CO_2e (kg/yr)
Carbon dioxide, fossil (GHG)	3.68E+02	2.15E+08	1	2.15E+08
N_2O (GHG)	2.12E-03	1.24E+03	298	3.70E+05
Methane (GHG)	8.70E-01	5.09E+05	25	1.27E+07
Methane, biogenic (GHG)	2.69E-04	1.57E+02	25	3.93E+03
Methane, fossil (GHG)	7.33E-02	4.29E+04	25	1.07E+06
Total CO_2e				2.29E+08

A unique aspect of PB and many consumer wood products is that they contain what is known as a "carbon store". Carbon storage - or carbon sequestration - is the act of absorbing CO_2 from the atmosphere. In the case of consumer wood products, the carbon stored in the wood used to create the product was absorbed from the atmosphere during the trees life. Thus, this can be viewed as essentially having absorbed the amount of carbon stored within the wood from the atmosphere throughout the product's lifespan. According to James Wilson in 2010, the carbon store for PB is -1290 kg/m^3 of board (Wilson 2010). This means that for every cubic meter of PB produced, that

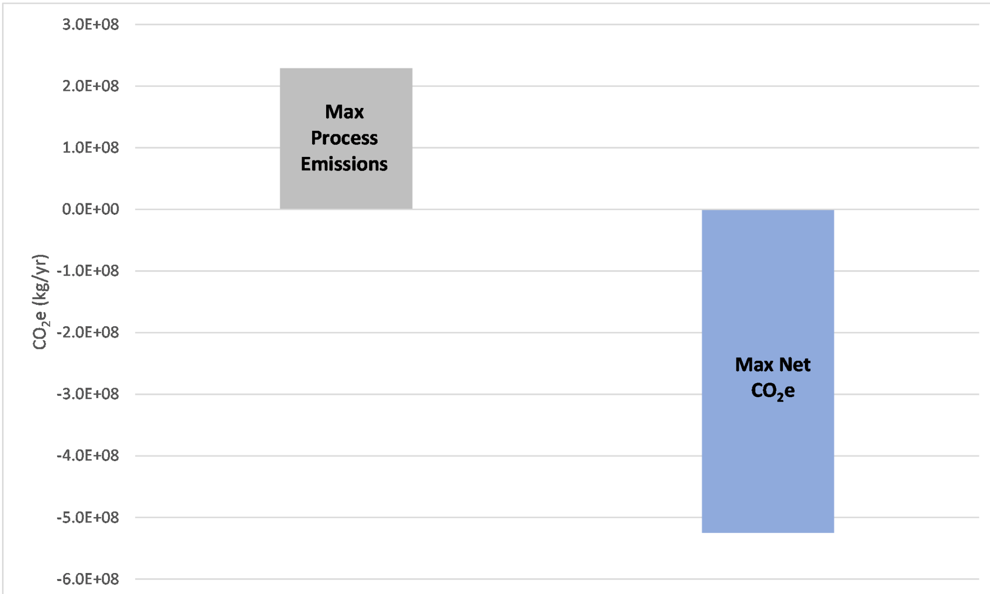

Fig. 19. Estimated net CO_2e emissions from prospective particleboard manufacturing facility

.

1290 kg of carbon is sequestered, or removed, from the atmosphere. As seen in Figure 19, using the idea of carbon sequestration, the prospective PB production facility would actually result in a net reduction in atmospheric GHG concentrations of $5.25x10^8$ kg/yr. A comprehensive list of VOC and chemical emissions can be found in Table 24, Appendix A.

6.1.3 Technical Criteria

Particleboard manufacturing has been present in the building industry since 1947, and since its invention it has become a commonplace item in furniture and facade construction (Spelter 1994). The age and prevalence of this technology ensures that there are a variety of different methods and available machines to manufacture PB. According a study done by the United Nations Food and Agriculture Organization in 1990, the average downtime due to mechanical failures in a PB production facility is estimated to be between 10-20% (United Nations Food and Agriculture Organization 1990).

An analysis by Spelter et al. in 2008, which outlined the capital expenditures in a PB plant, shows the breakdown of wages and employee types for a typical PB plant. Based on the analysis, it was determined that 40% of the employees at the prospective PB plant would be "skilled employees"

(Spelter et al. 2008). Meaning they would require training beyond what can be accomplished on the job site (ie. technical degree or certificate), and would receive a wage higher than the standard worker.

6.1.4 Social Criteria

Using a breakdown of capital expenditures in a PB plant analyzed by Spelter et al. in 2008, and the scaling method outlined in the economic section above, the plant was determined to have the capacity to create 289 jobs in both production and technical labor roles (Spelter et al. 2008). These jobs would provide members of the community with full-time employment at the PB manufacturing facility. The construction phase of this project would also create a number of temporary jobs, the quantity of which was not analyzed for the scope of this project.

Unfortunately, a PB facility also has a number of often unwanted air pollutants. According to emissions data by James Wilson in 2008, in addition to GHGs, there are 50 additional hazardous pollutants associated with the production of PB (Wilson 2008). Adverse human side effects associated with exposure to VOCs present in the PB manufacturing process "include: eye and respiratory irritation (including asthma), irritability, inability to concentrate, and sleepiness" (Baumann et al. 1999). These side effects are likely to cause community concern due to the relative harm these pollutants can cause to the population.

6.2 Wood Pellet Manufacturing

A quantitative analysis of using biomass for wood pellet manufacturing was conducted to compare the alternative to the specified design criteria. This analysis assumed that 100% of the available biomass (approximately 702 million kg) was used to manufacture wood pellets. To use all of the biomass, the operation would require a facility that could process roughly 70 tons per hour. An output of this size would require a substantial amount of machinery. For instance, the larger of industrial size pellet mills appear to have an output capacity which ranges between 4 and 20 tons per hour (abc Machinery 2020; Amisy Wood Pellet Mill 2018). Each of these pellet mills must have other machinery involved in manufacturing (dryers, hammer mills, conveyors, loaders, coolers, etc.) that would be able to sustain a similar output. Many plants of this size are manufactured in modular designed plants which run with parallel systems (Figure 20) and may have multiple pellet mills per system (Visser et al. 2020).

Fig. 20. A pellet manufacturing facility which utilizes multiple pellet mills in a parallel system (Index Journal 2020)

6.2.1 Economic Criteria

Payback Period Economic factors included in the payback period analysis are capital costs, operation and maintenance (O&M) costs, and the post-manufacturing transportation costs. After reviewing various sources for cost estimates, it appears as though the various costs associated with pellet manufacturing differ quite dramatically. For example, an LCA conducted on pellet manufacturing claims that costs of capital and operational expenditures are found to vary by a factor of five when compared (Visser et al. 2020). Therefore, multiple estimates were used when available in an attempt to capture the cost variability.

Two estimates were used to derive a capital cost for the 70 ton per hour facility. The first includes an estimate for a smaller facility which was then scaled up to meet the operational capacity. This estimate, which was conducted by NREL for a 1.2 ton per hour facility, includes costs for engineering, construction, buildings, machinery, and other operational needs (Hunsberger and Mosey 2014). The scaling of the plant was assumed to follow an economy of scale. Economies of scale, which exist in large-scale systems, states that the mean cost decreases as the output increases (Willis and Finney

2004). Therefore, rather than scaling the operation linearly, an equation presented by Hoefnagels et.al (2014) which utilizes the power law function was used (Eq. 1). The scaling factor of 0.7 is used because the system can be set up as a parallel system rather than one large system (Pirraglia et al. 2010) By using this formula along with NREL's baseline capital estimate, a capital cost of $26 million was established.

$$Inv = (Inv_{ref})(P/P_{ref})^{0.7} \tag{1}$$

Where:

$$Inv = \text{capital investment of pellet plant}$$

$$Inv_{ref} = \text{capital investment of NREL estimate}$$

$$P_{ref} = \text{ size of NREL pellet plant (ton/yr)}$$

$$P = \text{size of pellet plant (ton/yr)}$$

The other estimate, which was given by an expert in bioenergy and biomass energy systems, states that capital costs should range between $70,000 and $250,000 per ton per hour capacity (Ciolkosz 2009). To remain conservative, the upper end of this estimate was used in the analysis. Given the needed operational capacity (89 tons per hour) to use 100% of the incoming biomass, a secondary estimate for the capital costs was calculated at roughly $22 million. The geometric mean was then taken of these values, resulting in a final capital cost estimate of $24 million.

The operation costs were developed using the estimates shown in Table 9 (S. Mani et al. 2006). These values were determined through analysis of a 6 ton per hour facility; therefore, due to economy of scale, they may be rather conservative estimates. Nevertheless, after summing the costs and multiplying by the total biomass in tonnes, operational costs were determined as $31 million per year. An economic analysis of wood pellet manufacturing suggests that maintenance costs can be estimated at 2 to 10 percent of the purchase costs depending on the type of machinery and other operational characteristics (Hoque et al. 2006). The maintenance was assumed to be 10% of the purchase costs, and a yearly operational cost of approximately $1.9 million was calculated.

TABLE 9. Operational cost estimates for production of pellets from woody biomass (Reed et al. 2012)

Operational Process	Cost ($/tonne)
Drying	19.39
Hammer Mill	7.84
Pellet Mill	1.88
Pellet Cooler	0.21
Packaging	1.37
Screening	0.05
Personnel	12.74
Equipment	0.33
Land Use/Building	0.05

Transportation costs post-manufacturing were considered to provide a more accurate cost estimate. This transportation represents the travel of the product to its final destination. According to Hoefnagels et al. (2014) and their LCA analysis regarding biomass chains, a large plant has an estimated cost of 11.7 Euros per tonne for pellet transporation. This equates to approximately $11.93 when using an exchange rate of 1.02 USD to 1 Euro. Utilizing this estimate gives a calculated cost of roughly $4.3 million per year.

The payback period was calculated by deducting annual loan, interest, O&M, and transportation costs from yearly revenue. The loan time was then adjusted until the manufacturing plant was able to repay the loan and all costs while maintaining a yearly positive budget. The capital cost was amortized by using the capital recovery factor (CRF). The CRF is used to distribute a large, flat fee into equivalent costs over a particular time period (Willis and Finney 2004). To calculate the CRF, Equation 2 was used (Homer Pro 2020), and a real discount rate of 2.4% was used in the calculation. Using this method yields a payback period of only two years.

$$CRF(i,n) = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{2}$$

Where:

$$i = \text{real discount rate}$$

$$n = \text{number of years}$$

6.2.2 Environmental Criteria

Diversion of Wood Waste The analysis to determine how much wood waste could be diverted from waste was done by comparing operational capacities of pellet mills in the Western United States (U.S. Energy Information Administration 2020). The average capacity in the Western US was calculated as 784,000 tons per year by using recorded operational capacities of pellet manufacturing facilities in this area. This amount slightly surpasses the amount of biomass available (approximately 775,625 tons); therefore, it is assumed that 100% of the available biomass can be used to create wood pellets.

Net GHG Emissions Processing wood waste to create pellets requires energy input from nonrenewable sources and also emits GHGs. For instance, if considering the cradle to gate net GHG emissions from using 100% of the biomass to manufacture pellets, it is estimated that 768 million kg of CO_2e are emitted, even with consideration of carbon uptake by the renewable feedstock (Katers et al. 2012). The boundary in this analysis does not include any processes before receiving the biomass, so any GHG emissions which occur before receiving the wood waste was not considered in this analysis. An LCA conducted by Reed et al. (2012), which uses a system boundary from receiving the product to the final manufacturing stage, indicates a net GHG emission of -0.0183 kg CO_2e /ton of manufacture pellets. This results in a net GHG emission of approximately -246 kg CO_2e . It is apparent that the processes which occur before the manufacturing of the product have a significant impact, for when not considering these impacts, the net GHG is considered negative. For example, an LCA conducted on wood pellet manufacturing claims that feedstock transportation processes is generally considered as the main contributor of energy consumption and GHG emissions (Lu and El Hanandeh 2017). Another factor which was considered is the combustion of the product post-manufacturing. Wood pellets have an emission factor of 1708 g CO_2e /kg wood pellet (Wei et al. 2012). Therefore, if all of the biomass were converted to pellets and then combusted, approximately 1.2 billion kg CO_2e are created.

Inclusion of combustion in the analysis was debated and could possibly be argued. Although natural gas is the primary source of energy for residential heating, about 13 million homes in the US use wood for heating purposes (Reed et al. 2012). Data was not found on the quantity of wood burning stoves in Humboldt County, but according to the NCUAQMD (Guest Lecture, 2020) it is expected that Humboldt County has a large proportion of residences which utilize wood fire stoves. By volume, pellets contain about twice the amount of embodied energy than standard firewood (Katers et al. 2012). Furthermore, according to the EPA, pellet stoves are generally cleaner and more efficient than typical wood burner stoves (EPA 2020). In fact, the NCUAQMD provides incentive programs in Northern California that replaces non certified fire stoves for EPA certified pellet stoves (North Coast Unified AQMD 2020). It could be considered that combustion to heat homes would exist nevertheless, and since pellet burners are more efficient and cleaner, the environmental impact is actually reduced because of these factors.

6.2.3 Technical Criteria

System Robustness Data on specific machinery reliability was not obtained, so it was assumed that one failure per month occurred. The time between failure (TBF) for the drum dryer, hammer mill, pellet mill, and cooler are 25, 15, 10, and 30 hours, respectively (Mobini et al. 2013). Since the operation is assumed to be 24 hours a day and seven days a week, any downtime of the facility is expected to impact manufacturing. By using an assumed failure rate of once per month, the total operational time per year was calculated for each piece of machinery. This was then used to calculate a percentage of operational time per year. The reliability ranges from 95.9% to 98.6% for the specified machinery.

Operator Skill Required By using data for the number of facilities and workers per facility in the United States (U.S. Energy Information Administration 2020), a calculated average of approximately 27 full time employees (FTEs) are needed to run a pellet manufacturing facility. According to an estimate provided by NREL, a plant which has 13 FTEs needs one plant manager and two employees who are skilled in mechanical/electrical applications (Hunsberger and Mosey 2014). Since this estimate is for approximately half of what the average US facility needs to operate, the number of skilled workers was doubled to approximately 6 skilled employees of the 27 FTEs. Therefore, roughly 22% of the FTEs at the pellet facility are assumed to require technical skills.

Maturity and Availability From the research conducted on the pellet manufacturing timeline, it appears as though pelletizing technology has been around for almost a century. For instance, a flat die pellet mill used by farmers for feed was established in the 1900's (Anyang Gemco Energy Machinery 2020). The use of pelletizing wood for stoker fuel in the United States began in the 1930's. During the energy crisis of the 1970's, the wood pellet industry increased mainly in the Pacific Northwest (Spelter and Toth 2009). Since the first residential pellet stove was not created until 1983 (Alliance of Green Heat 2009), pellets were likely not used as a residential heat source. In accordance with this information, and to remain conservative, 35 years of experience is allocated to modern pellet manufacturing.

6.2.4 Social Criteria

Public Health Impact A study conducted on using wood flooring residuals as a biomass feedstock by Reed et al. (2012) outlines the specific pollutants which are created from one ton of pellet manufacturing (Table 10). Other than CO_2 emissions, pellet manufacturing appears to emit a variety of other air pollutants including acrolein, formaldehyde, NO_x, SO_2, SO_x, methane, particulates, and VOCs.

TABLE 10. Air pollutant emissions from manufacturing one ton of wood pellets from biomass (Reed et al. 2012)

Emission	Mass (kg)
CO_2 (fossil)	114
CO_2 (biomass)	65
Acrolein	0.001
Formaldehyde	0.109
NO_x	0.410
SO_2	0.850
SO_x	0.043
Methane	0.329
Particulates	0.120
VOCs	0.060

Public Benefit Pellet manufacturing has the potential to create a local source of employment. The United States has approximately 930 pellet manufacturing facilities and 25,173 FTEs recorded in 2019 (U.S. Energy Information Administration 2020). By using this data, it is estimated that an average US pellet manufacturing facility requires approximately 27 FTEs. Although not quantified, any type of woody residue which is not used for pellets could be distributed to the community for use as mulch or landscaping material.

6.3 Thermal Gasification

The gasification alternative consists of a large facility for the gasification of woody biomass and refining the product gas into substitute natural gas to be supplied to Humboldt's residential gas grid. Because residential customers in Humboldt County use a little over 100 MW of natural gas currently, the gasification plant was sized to 100 MW to entirely meet this demand. The plant would have a target of 8,000 operating hours annually, and a design life of 20 years. Such a facility would be best located nearby the local sawmills, or on a parcel nearby the Fairhaven plant to reduce transportation of the woody biomass.

6.3.1 Economic Criteria

Several assumptions were required to estimate the cost of the plant. The first assumption is that the woody biomass can be acquired and delivered to the facility for no cost. This is a viable assumption because the only alternative for sawmills to dispose of the mill waste would be landfilling outside of Humboldt County at great expense. The second major assumption is that of a very favorable capital interest rate of 2.5%. This is quite low for a private venture, but more in line with a public program such as those offered by the US Department of Energy's LPO programs. Finally, it is assumed that the substitute natural gas produced will be sold at current California residential natural gas prices. True natural gas is much cheaper for power plants, so the gas will be sold residentially to increase financial viability.

To calculate costs for the facility, the economic analysis provided by the GoBiGas project was implemented to estimate the cost for a scaled up 100 MW facility for Humboldt County. Thunman et al. published their estimated scale factors for capital costs using the GoBiGas demonstration plant as a reference. Equation 3was used for capital cost estimations, along with the corresponding scale factors in Table 11. (Thunman et al. 2019)

$$C_i = C_{ref}(\frac{P}{P_{ref}})^{SF_i} \tag{3}$$

Where:

$$C_i = \text{Capital cost for process section } i$$

$$\text{Total Capital Cost} = \Sigma C_i$$

$$C_{ref} = \text{cost for 20 MW reference plant}$$

$$P = \text{facility design capacity, MW}$$

$$P_{ref} = \text{reference plant capacity, MW}$$

$$SF_i = \text{scale factor for process } i$$

TABLE 11. The final costs calculated for each process system, alongside the reference plant cost and associated scale factor.

Process System	Scale Factor	20MW reference estimate 2014 M$	Current Estimate $M
Reactor Systems	0.68	23.8	71
Auxilary Equipment and Project Costs	0.44	95.5	193
Steam cycle, external fuel handling and drying	0.67	18.2	53
Total		137.5	318

Payback Period The gasification and refinery plant would require a relatively high initial capital investment, with an estimated simple payback period of 18 years. With a design life of 20 years, the plant would produce a profit for two years, before being refurbished or taken offline. This indicates that the alternative serves better as a public climate change project rather than a private venture for profit.

6.3.2 Environmental Criteria

Net GHG Emissions Overall, the production and use of substitute natural gas is projected to have zero net greenhouse gas emissions. This is because the biomass-derived gas produces the same amount of CO_2 as the fossil fuel-derived natural gas currently in use. With a full life cycle analysis of the biomass, including the forestry practices implemented, it could be shown that substitute natural gas is carbon-neutral as well. For the purposes of this project, the implementation of this alternative will not produce any more CO_2 than is currently produced.

Diversion of Wood Waste A 100 MW facility would require 700 dry tons of biomass per day, extrapolating the GoBiGas reference plant use of 140 dry tons per day for 20 MW capacity. This makes up 58% of the total biomass waste stream. The plant could have been scaled up further to completely utilize the waste stream, but that production level would far outpace demand for the gas.

6.3.3 Technical Criteria

System Robustness The GoBiGas demonstration plant eventually reached continuous runtimes of 1300 hours before maintenance was required. Given a targeted operating hours of 8000 per year, approximately six shutdowns would occur per year. Assuming each shutdown averages a week, this results in approximately 1,000 hours of downtime per year. This estimation produces an uptime of 87%, falling slightly short of the targeted 8,000 operating hours. (Thunman et al. 2019)

Operator Skill Required It is very likely that all operators of the gasification plant be highly educated, skilled, or experienced. The GoBiGas required significant and frequent process changes and tuning to achieve the desired the results, and spent considerably on engineering at all stages of the project. A larger plant such as the alternative would likely require a similar or greater knowledge base and problem solving skill to keep the plant achieving long runtimes. (Anton Larsson, Ingemar Gunnasrsson, Freddy Tengberg 2014)

Maturity and Availability While gasification of coal and its subsequent refinery is a well established technology, the same process for woody biomass is not. The GoBiGas plant is the first demonstration plant of its size using woody biomass as a feedstock, and a plant the size of the alternative would be the largest current commercial implementation. Overall, the dual gasification and refinery process has less than 5 years of successful production. (Anton Larsson, Ingemar Gunnasrsson, Freddy Tengberg 2014)

6.3.4 Social Criteria

Public Health Impact Because of the nature of gasification and refinery, there are no significant emissions of criteria pollutants. Gas is captured at every step, and contaminants are removed via adsorption beds in the refinery process. During normal operation, it can be expected that no new air or water pollutants will be introduced to the environment. (Anton Larsson, Ingemar Gunnasrsson, Freddy Tengberg 2014)

Public Benefit - Jobs The biomass gasification facility would require about 12 full time employees, three people per shift, three shifts a day. However, the expertise required for these jobs may preclude most locals, making it necessary to import operators from other areas.

6.4 Composting Facility

A quantitative analysis was performed in order to score a composting facility alternative according to the determined criteria for this project. Of the approximately 702 million kg generated per year from mill waste, a small fraction was used in conjunction with several other sources of organic waste in the county. Cow manure from local dairy farms, organics/food waste from waste management facilities, and biosolids from wastewater treatment facilities in the county.

6.4.1 Economic Criteria

Payback Period The costs, as well as potential revenue, for the alternative were taken from a military composting economic analysis for a facility of a similar size and capacity (Naval Facilities Engineering Service Center 2000). The simple payback period calculated for this analysis is dependent on the facility being able to sell most of their produced compost, which was an assumption made for the analysis. The economic analysis numbers used was for a facility that processed 25,000 tons of compost material per year. This alternative utilizes a little more than 28,000 tons of compost material per year, and so the costs and revenues from the analysis were not scaled. Table 12 shows the capital costs, operation costs, and yearly revenues used in a simple payback calculation, as well as the results of that calculation.

TABLE 12. Costs and revenue for a composting facility.

Payback Calculation	
Capital Cost ($)	3000000
O&M ($/yr)	675000
Revenue ($/yr)	750000
Payback Period (yr)	40

6.4.2 Environmental Criteria

For the Environmental Criteria, both the impact of the alternative, judged on net carbon emissions, and the diversion of wood waste achieved by the alternative.

Net GHG Emissions In order to quantify the environmental impact of the alternative, net carbon-equivalent emissions per year was estimated for the composting facility. This includes direct emissions from the compost itself, as well as emissions from transportation of materials and finished compost, balanced against the emissions avoided by using cow manure in compost rather than having it breakdown in a landfill and increased soil sequestration capacity from using the soil amendment. The results of this analysis indicate that the composting alternative would have a negative net carbon-equivalent emissions impact. This is mostly due to the avoided emissions that come from using the cow manure in the compost mix, which is an order of magnitude greater than the amount of direct emissions coming from the compost pile (Vergara and Silver 2019). Table 13 shows the yearly contribution to emissions from direct emissions, transportation, soil sequestration, and using manure in the mix, as well as the total net emissions per year.

TABLE 13. Net GHG emissions from the composting alternative

Source	**Yearly Emissions (MT CO_2e)**
Direct Emissions	161
Transportation	56
Soil Sequestration	-81
Manure Diversion	-3166
Total	**-2957**

Diversion of Wood Waste In order to determine how much wood waste is able to be diverted, the amount of nitrogen-rich organic resources in the county needed to be determined. In order for the composting process to reliably yield good soil amendment, the carbon to nitrogen ratio should be between 25-30:1 and the moisture should be between 40-60% (Kreith and Tchobanoglous 2002). The final mix was determined by adjusting the fraction of total yearly mass available for each of the four feedstock sources until these parameters were met. The available mass of biosolids was based on an estimate of 770 tons per year for the county (EPA nd). The Humboldt Waste Management Agency estimated that it receives 63,000 tons of solid waste per year (Duffy 2018), which an estimated 22.7% of that being food waste (HWMA 2011). The mass of manure that can be harvested from dairy farming was calculated using an estimate of 80 pounds per animal per day, with between 75-80% of that being considered recoverable (NRCS 1995). In order to calculated the mass produced in the county, the mass produced by a single cow in a year was multiplied by an estimate of 19,000 dairy cows in Humboldt County (Humboldt County Department of Community Development Services 2003). The final mix was determined to have a 25:1 carbon to nitrogen ratio and a 51% moisture content by mass. This mix uses only a small fraction of each of the feedstock sources, including only 3.5% of the available yearly wood waste. Table 14 shows the masses of each source used in the mix.

TABLE 14. Feedstock mix of composting alternative

Source	Fraction of Mass Used	Total Available Mass (MT/year)
Biomass	0.035	701565
Biosolids	0.02	770
Food Waste	0.02	14301
Manure	0.02	195441

6.4.3 Technical Criteria

The composting facility was scored highly in the technical criteria, performing best in maturity and availability.

System Robustness An estimate of the downtime for the compost facility was based on the percentage of the time that a studied facility was able to meet its schedule, which was around 90% after proper maintenance schedules were implemented (Zeigenbein 2019). Composting is not particularly prone to outages that affect the end product, since the product typically requires weeks or multiple months to finish.

Operator Skill Required The number of skilled operators required for a compost facility depends on the type of facility. Since the alternative suggests using an aerated static pile facility, no skilled operators are required for windrow turning machines.

Maturity and Availability Composting scores very well for this criterion. Using composted organics as soil amendments has been done by humans for thousands of years (Sidder 2016). Modern, more precise composting techniques were developed in the 1920's (Rao 2015).

6.4.4 Social Criteria

Public Health Impact The majority of emissions from compost are greenhouse gas emissions (which was quantified in the environmental criteria section), but there are some potential pollutants produced in the composting process that affect public health. Composting can release CH_4, NH_3, and N_2O under certain operating conditions (Peigné and Girardin 2004).

Public Benefit For this criterion, the alternatives were scored on how many jobs they would add. Composting facilities employ 6 people per 10,000 tons of raw composting material (Platt and Goldstein 2014). This means that an estimated 17 jobs would be created by the composting alternative.

7 DECISION ANALYSIS

Using data obtained through the methods outlined in the Alternative Analysis section above, each alternative was scored by performance relative to each criterion. By assigning scores to each alternative, they can be compared numerically by adjusting the scores according to weights determined by the client and capstone group.

7.1 Weighting

Input on weighting the criteria was obtained from the client, RCEA, and was considered for the final weights for each of the criteria. The team preparing the report also came up with weights of their own for each of the criteria. The weight used was determined by taking the RCEA weighting, and adjusting it slightly if the team weight was in stark contrast. The weighting for three criteria was the same as requested by RCEA, and no other criterion weight changed by more than two.

7.2 Scoring

In order to assign a score to an alternative's performance based on a particular criterion, a scoring scheme was made based on ranges of quantifiable indicators. Table 16 exhibits the ranges

TABLE 15. Weights assigned to each criterion from the client and weights ultimately used in the decision analysis.

Criteria	RCEA Weight	Used Weight
Payback Period	10	10
Environmental Impact	5	7
Diversion of Wood Waste	5	6
System Robustness	4	6
Operator Skill Required	3	5
Maturity and Availability	3	5
Public Health Impact	3	5
Public Benefit	3	3

for each metric used to determine scores for each alternative. A scale of 10 was used to grade each alternative's performance relative to the criteria, with 10 being "excellent", and 1 being "poor". Scoring brackets were determined by group consensus for quantifiable ranges applicable to the project. The scoring for each criterion can be seen broken down below.

TABLE 16. The ranges and units used to score each alternative relative to the criteria.

		Score				
		1-2	3-4	5-6	7-8	9-10
Criteria	Unit	Poor	Less than Average	Average	Greater than Average	Excellent
Payback Period	Years	>50 yr	25-50 yr	10-25 yr	5-10 yr	<5 yr
Environmental Impact	kg/yr	>750,000,000	250,000,000 to 750,000,000	0 to -250,000	-250,000 to -1,000,000	<-1,000,000
Diversion of Wood Waste	% of wood waste diverted	0-25%	26-45%	46-65%	66-85%	86-100%
System Robustness	% downtime	>40%	39-21%	20-11%	10-5%	<5%
Operator Skill Required	% skilled employees	>80%	60-79%	40-59%	20-39%	<20%
Maturity and Availability	Years	<5 yr	5-15 yr	16-30 yr	31-50 yr	>50 yr
Public Health Impact	# extra pollutants	20+	10-19	5-9	1-4	0
Public Benefit	# Jobs	0-10	10-20	20-50	50-100	100+

Payback Period The payback period for a project is the number of years it takes to regain 100% of the capital investment. A simple payback period is used to determine an estimate of a projects financial viability. The scoring for payback period was determined by assigning score ranges for differing ranges of payback periods. Any payback period of over 50 years was assigned to the "poor" performance category, whereas a payback period of less than 5 years was considered "excellent".

Environmental Impact The index used to create ranges and score Environmental Impact was net annual carbon dioxide equivalent (CO_2e) emissions. Each alternative was analyzed throughout their expected useful lives to determine associated GHG emissions. The CO_2e was calculated by multiplying annual emissions of each GHG by their corresponding global warming potential (GWP). This was then used as a standard metric to compare all alternatives. A metric of over 750,000,000 kg/yr of CO_2e was used to define a "poor" performance in this category, and an "excellent" performance was chosen to be an alternative which had less than -1,000,000 kg/yr of net CO_2e emissions.

Diversion of Wood Waste This criterion deals with the amount of available wood waste each alternative is able to physically divert. The metric used to score this criterion was the percentage of available wood waste diverted. The percentage of available wood waste diverted roughly corresponds to the assigned score. For example, an alternative which uses 100% of the available wood waste would receive a score of 10, and an alternative which uses 20% of the waste wood receive a score of 2.

System Robustness The metric used to define System Robustness for the scope of this analysis was the percentage of average downtime. Downtime, as defined by the Oxford Dictionary, is defined as the "time during which a machine...is out of action or unavailable for use." This metric was used to determine how susceptible each alternative is to system failures, which could adversely effect production and/or productivity. An alternative with over 40% downtime was considered to be "poor", whereas an alternative with an expected downtime of less than 5% would be considered "excellent".

Operator Skill Required Each alternative was scored according to the percent of skilled operators needed to operate the facility. Using this as a measurement gauges how technical the operation is. A more technical operation would be increasingly more difficult and costly as more technical skill is required. For example, skilled employees are more difficult to obtain and generally have higher annual salaries. The scores range from poor being more than 80% to excellent being lower than 20%.

Maturity and Availability The maturity and availability criteria is a measure of how accessible each alternative is. If an alternative does not have much industrial expertise associated with it, it is more difficult to establish and maintain a working operation. A well known alternative may be more successful given that there is history of the process. This was conducted by researching each alternative's history to determine the years of experience each has to offer. An alternative which had less than five years of industrial knowledge was deemed as poor while more than 50 years was scored as excellent.

Public Health Impact Public health impact was scored by evaluating the number of air pollutants other than CO_2 that the alternative emits. As stated in this report, one purpose of this analysis is to address the public's concern regarding air pollution from the current energy generation. Therefore, along with GHG emissions, other pollutant which may cause harm were analyzed. If more than 20 other pollutants were associated with the alternative, the alternative was scored as poor. An excellent score would be if the alternative did not emit any other pollutants.

Public Benefit Benefits to the public was scored by calculating the amount of jobs the alternative would create. Creating jobs in the local area is deemed as a personal benefit because it would provide wages to local residents. A poor alternative would create 0 to 10 jobs while an excellent alternative would create more than 100 jobs.

7.3 Decision Matrix

Each alternative was graded in relation to each criterion, and received a weighted score. The preferred alternative is the biomass pelletization, with the highest combined weighted scores. A breakdown of the decision matrix is shown in Table 17.

TABLE 17. This chart shows the final decision matrix, detailing the criteria grades and weighted scores for each alternative in accordance with the Delphi method. The highest grade(s) and score(s) for each individual criterion is shown in **bold**, and the combined highest scoring alternative, biomass pelletization, is highlighted.

Criteria	Weight	Particleboard Grade	Weighted PB Score	Pellet Grade	Weighted Pellet Score	Compost Grade	Weighted Compost Score	Gasification Grade	Weighted Gasification Grade
Payback Period	10	6	60	**10**	**100**	3	30	7	70
Environmental Impact	7	**10**	**70**	3	21	9	63	5	35
Diversion of Wood Waste	6	**10**	**60**	**10**	**60**	1	6	6	36
System Robustness	6	6	36	**9**	**54**	6	36	5	30
Operator Skill Required	5	5	25	**8**	**40**	**8**	**40**	1	5
Maturity and Availability	5	9	45	8	40	**10**	**50**	3	15
Public Health Impact	5	1	5	5	25	**9**	**45**	**9**	**45**
Public Benefit	3	**10**	**30**	5	15	4	12	4	12
Total Weighted Scores		**331**		**355**		**282**		**248**	

8 PREFERRED ALTERNATIVE

By implementing the Delphi method to score each alternative against the design criteria, pellet manufacturing was deemed as the preferred alternative. The wood pellet alternative was most advantageous in the payback period and diversion of wood waste with a score of 10 in each category. The pellet manufacturing facility also scored well in respect to system robustness because of its low machine downtime.

8.1 Description

The final design considered an incoming wood waste of 619,057 tons/year, and it is assumed that 100% of the biomass will be used. To accomplish this, a facility which can manufacture almost

56 tons/hour is needed. This production rate is based on an operating time of 7,000 hours/year, a production time standard of other pellet manufacturers in the U.S. (Lamers 2017). Therefore, the nameplate capacity of the facility will be roughly 70 tons/hour. At this capacity of wood pellet production, an estimated 37 full time employment and 482 indirect jobs via construction was estimated (U.S. Energy Information Administration 2020; Biomass Magazine 2020)

8.2 Proposed Site Plan and Location

An ideal location for the biomass pelletization plant is at Redwood Marine Terminal 2, a former pulp mill site in Humboldt Bay. The site was attractive because of the presence of an unused deepwater dock, allowing pellets to be loaded directly onto cargo ships after production, maximizing transport efficiency for export. A similar export operation to the proposal is located south of the project site, where Redwood Chip Company transports wood pulp via cargo ships in much the same way. Figure 21 shows the relative location of the site in Humboldt County, as well as highlights the three parcels that may require acquisition.

A proposed rough site plan was composed using measurements of facilities at two similarly sized biomass pelletization plants in Amite, Mississippi, and LaSalle, LA, both owned by Drax Bioenergy. Sizing for the proposed facility is based on measurements of areial footage of the corresponding facilities at these two pellet plants. Because the wood does not need to be debarked or loaded into railcars or trucks, the proposed site was more compact than the reference plants.

The site plan is shown in Figure 22, and the corresponding inventory of facilities is shown in Table 18. A large loading bay for semi trucks and trailers is provided for with a full truck and trailer tipper used to continuously unload shipments. Incoming trucks form a queue, while the tipper dumps the biomass out by lifting both truck and trailer to a 60° angle. This method of directly loading trucks into the shredder hopper is optimal for speed and efficiency of material handling.

The biomass is then shredded and sent to a combination circular stacker-retainer, which manages a stockpile of material to be sent to the dryer. This stockpile management system allows the shredding and pelletization process to be decoupled for operational convenience, as well as homogenizing the material.

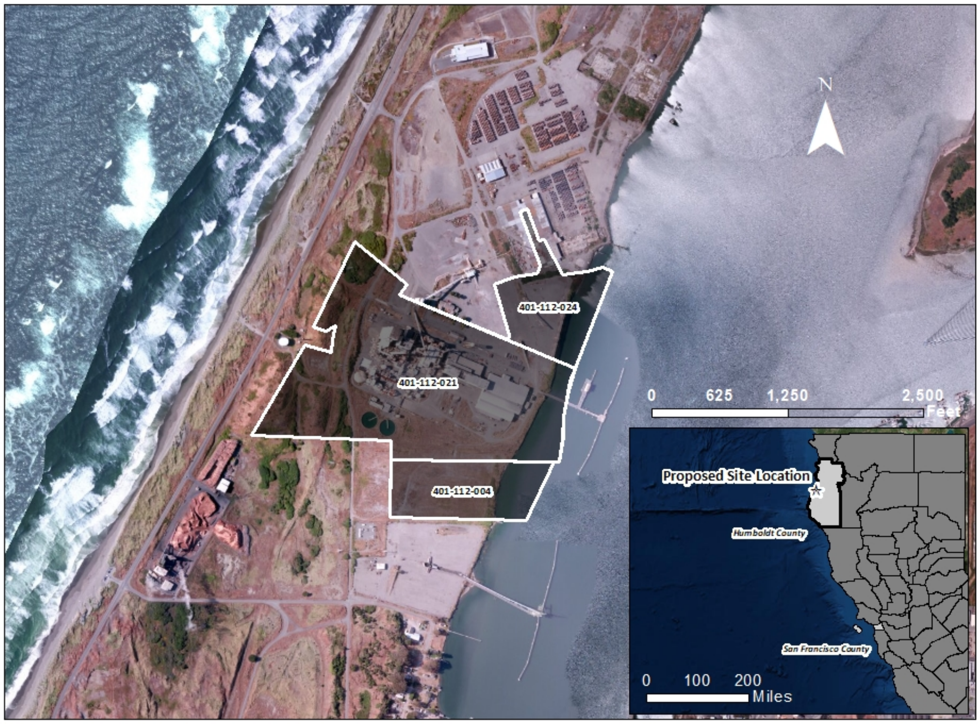

Fig. 21. Location of Redwood Marine Terminal 2 and surrounding parcels for proposed site.

The pelletization process through drying, hammering, pellet milling, and cooling is relatively straightforword. Material conveyors bring cooled pellets either into storage or loaded onto a cargo ship at the dock.

TABLE 18. Inventory of proposed pellet manufacturing plant facilities and processes, for use with the site plan.

Label	Item	Label	Item
A	Truck Staging Bay	**G**	Hammer and Pellet Mills
B	Truck Tipper	**H**	Pellet Coolers and Sifters
C	Biomass Hopper	**I**	Storage Silos
D	Shredder	**J**	Conveyor Runs
E	Stacker-Reclaimer	**K**	Stormwater Basin
F	Dryer	**L**	Extra Shredded Material Storage

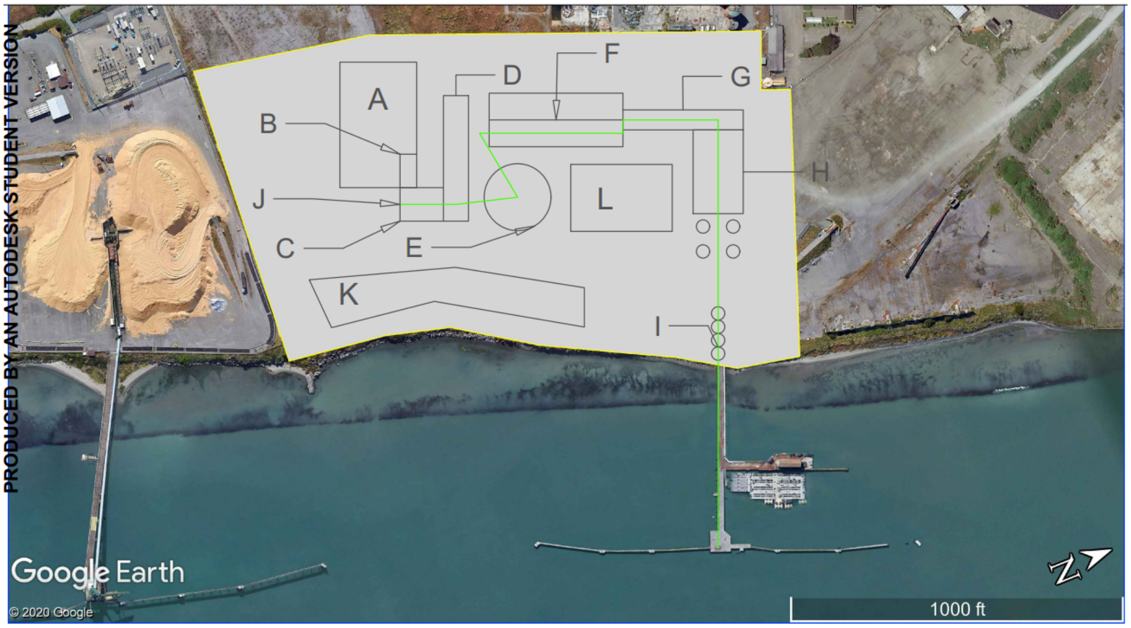

Fig. 22. Rough site plan of the proposed pelletization plant.

8.3 Facility Design

The proposed wood pellet manufacturing facility should be designed to meet a maximum output capacity of 490,000 tons per year, or 70 tons per hour, of pellets. Assuming an average operating capacity of 80% of the nominal capacity, the facility will produce the target production of 390,000 tons per year of pellets. Wood pellet manufacturing facilities are broken down into 8 main processes: unloading feedstock from trucks, shredding the biomass, storage, drying, a hammer mill, pellet mill, cooling, and sifting.

There are a number of different options available when deciding which machinery to use when designing a wood pellet production plant. When determining what type of machines a specific plant will need, it is important to take hourly pellet production, cost, and space into consideration. Table 19 outlines a number of machines which are currently being manufactured which could be used in the prospective pellet plant. Through research of currently used and available technologies in the wood pellet production industry, it became clear that industry leaders are Amisy, Buhler, and Gemco. The wood pellet mill process category offered the most diverse range of available options for mechanics. As seen in Table 19, the maximum output for available machinery varies greatly.

It is imperative to choose machinery which will optimize production at the plant, and do so at a minimal cost. It is important to note that, due to a lack of publicly available pricing and dimensional data, the group reached out to a number of distributors and manufacturers to request price quotes and physical dimensions for the machines presented in Table 19, however none responded.

TABLE 19. List of machinery that could be used in the prospective wood pellet plant (Amisy 2020; Buhler AG 2020b; Gemco Energy 2020a; Whirlston 2020).

Process	Machine	Maximum Output (ton/hr)	# Machines Needed	Cost per unit ($/unit)	Total Cost ($)	Power per unit (kW)	Total Power (kW)
Shredder	Gemco TFS500	0.8	88			11.0	963
	Amisy XP-950	8.0	9			37.0	324
	Amisy XP-1100	10.0	7			37.0	259
	Amisy XP-1210	13.0	6			75.0	404
	Amisy XP-1410	16.0	5			90.0	394
Dryer	Whirlston	5.0	14			87.2	1,220
	Amisy AMS-HG2212	15.0	5			18.5	86
	Amisy AMS-HG2220	20.0	4			30.0	105
	Amisy AMS-HG2420	30.0	3			37.0	86
Wood Pellet Mill	Buhler RWPR-900	9.0	8			328.0	2,549
	Yi Bao Pellet Machine Holz Pellets	1.5	47	9000	420,000	1450.0	67,667
	Gemco BPM-508	2.5	28			113.7	3,184
	Buhler KUBEX-T9	50.0	2			410.0	820
	Buhler KUBEX-T12	80.0	1			585.0	512
	Whirlston MZLH558	2.0	35			162.5	5,688
	CME MILL R150	2.0	35			112.0	3,920
Hammer Mill	Buhler DFZK-1 60 HZ	40.0	2			126.0	252
	Buhler DFZK-2 60 HZ	70.0	2			126.0	252
	Amisy FSP60*60	10.0	7			90.0	630
	Amisy FSP60*75	13.0	5			110.0	592
	Amisy FSP112*40	22.0	3			110.0	350
	Whirlston	3.0	23			45.0	1,050
Cooler	Buhler Coolex	60.0	2				
	Gemco SKLN19	5.0	14			3.0	42
	Gemco SKLN22	8.0	9			3.7	32
Sifter	Gemco SFJH150	8.0	9				
Packaging	Gemco Pellet Packing Machine	22.0	4			n/a	n/a
Full Production Line	Whirlston	10.0	7			556.0 [1]	7,781 [1]
	Amisy	5.0	14			n/a	n/a
Mobile Full Plant	Gemco Biomass Mobile Pellet Plant	0.4	175			41.3	7,219

One option for the prospective plant may be either the Whirlston or Amisy Full Production Lines.

[1]Energy estimate does not take shredder into consideration.

These full production lines incorporate all parts of the manufacturing process from start to finish. The Whirlston production line has a maximum output capacity of 10 tons per hour, which means that to meet the nominal facility capacity of 70 tons per hour, a total of 7 production lines would need to be run in parallel. However, another option would be to choose a combination of machines to use in conjunction with one another to provide the optimal production line.

This report recommends that a production line with a maximum output of 72 tons per hour be made using:

- 6 Amisy XP-1210 shredder units
- 6 Amisy AMS-HG2212 dryer units
- 9 Amisy FSP60*60 hammer mills
- 9 Buhler RWPR-900 wood pellet mills
- 9 Gemco SFJH150 2-layer sifters

(Amisy 2020; Gemco Energy 2020b; Buhler AG 2020a).

Figure 23 shows a flow diagram for wood waste through machinery at the prospective plant using the above outlined production line. This production line utilizes machines with similar outputs to create a streamlined manufacturing process for a high-volume output pellet facility. Using a production line with a number of machines in parallel will provide redundancy which could prove key in keeping production moving in the case of mechanical failures.

8.4 Payback Period

All cost estimates in this analysis were generated using the nameplate capacity of the facility (70 ton/hour). Among the various methods researched to estimate the capital cost, final costs appeared to vary by magnitudes of tens of millions. To determine a capital cost which was representative of this project's scale, a similar plant was referenced to give a better range of a realistic cost. The LaSalle BioEnergy plant, which has a nameplate capacity of 450,000 tonnes, was purchased for 43 million pounds. This capacity is close to the nameplate capacity for the project's proposed facility

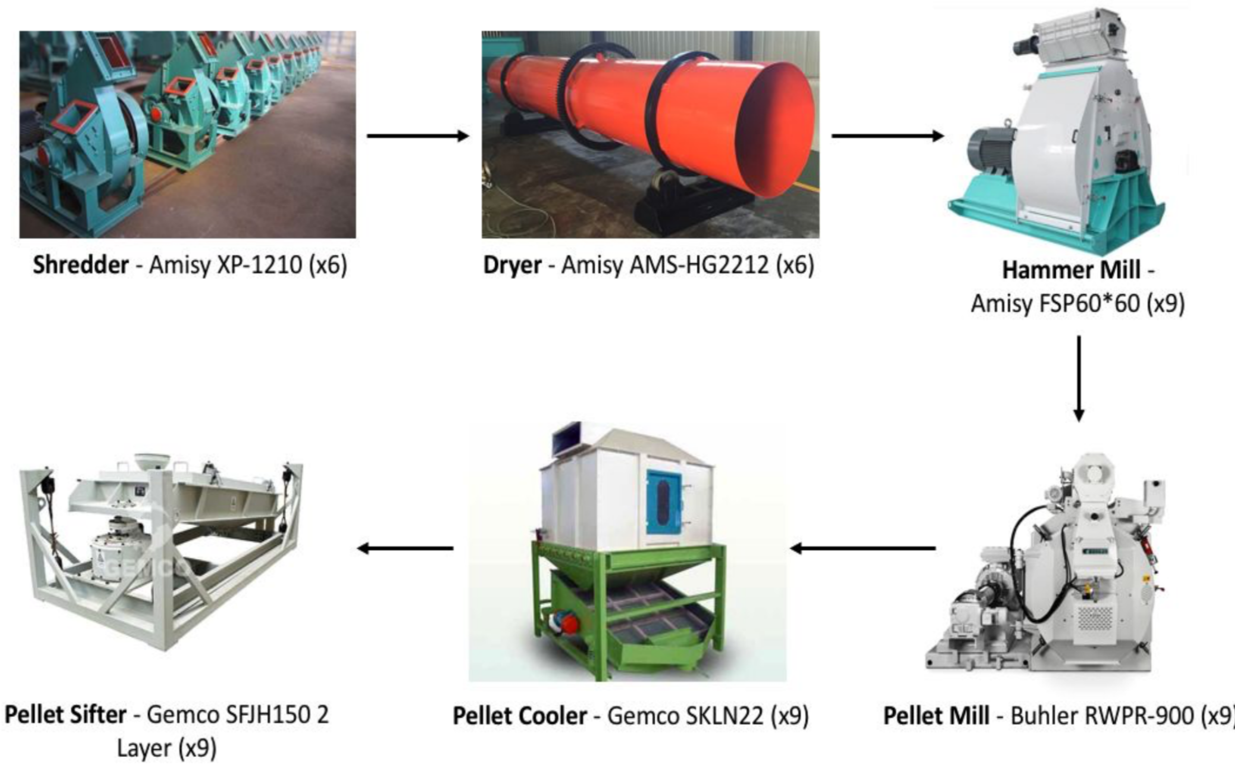

Fig. 23. Proposed 72 ton/hr production line and machinery flow diagram for the facility.

(442,260 tonnes). Using a 1.25:1 Great British Pound to USD conversion, this is approximately $60 million in capital costs. The capital cost estimate used for this project was provided by a large pellet/briquette machine manufacturer at $125 per ton of produced pellets (Gemco Energy 2020c). Therefore, a facility which uses 100% of the biomass has an estimated capital cost of $54.8 million.

The operational costs were estimated using the procedure described in the pellet analysis section of the report. To calculate the operational costs, the parameters in Table 20 were used (S. Mani et al. 2006). These cost estimates assume the biomass is dried from a solid fuel burner which utilizes wood shavings at a 10% moisture content and an electric rotary dryer. The remainder of the manufacturing equipment is powered by electricity. In total, operational cost estimates include heat energy costs for drying, electricity costs, and personnel costs (S. Mani et al. 2006). The operating costs for the facility were estimated at approximately $11.2 million per year when using this approach.

The maintenance costs were estimated by using the procedure discussed in the pellet analysis section of the report and by assuming a 70 ton/hour capacity. By using 6% of the ISBL costs, the

TABLE 20. Operational costs per ton used to develop operational estimate for 70 ton/hour facility.

Process	**Cost ($/ton)**
Drying	7.11
Hammer Mill	0.64
Pellet Mill	1.71
Pellet Cooler	0.19
Packaging	1.24
Screening	0.05
Personell	11.56
Miscallaneous Equipment	0.30
Land Use/Buliding	0.05
Pellet Storage	0.01

maintenance costs were estimated at $2.1 million per year. Since there would not be a sufficient market to sell the pellets in Humboldt County, the pellets are assumed to be shipped to San Francisco. To calculate the cost for required transportation of the product, an estimated $20.24 per-ton-per-mile was used for pellet transport (Hoque et al. 2006). The implementation of this estimate yields a $27.3 million per year transportation cost.

A summary of the annual costs are shown in Table 21, and a five year cost analysis is show in Figure 24. The capital cost was annualized using Equation 2 and a real discount rate of 2.6%. It was assumed that 100% of the pellets can be sold. Furthermore, the selling price was assumed to remain constant at the average US selling price of approximately $166 per ton. Using these estimates, a yearly revenue of $64.6 million is expected. To determine a payback period, the loan period was optimized so that each year had a positive balance after deducting the costs (including the loan payment) from annual revenue. By following this procedure, a payback period of 2.4 years was calculated.

$$CRF(i, n) = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{2}$$

Where:

$$i = \text{real discount rate}$$

$$n = \text{number of years}$$

TABLE 21. Estimated annual costs, including amortized capital costs, for the pellet manufacturing facility.

Source of Cost	Annual Cost ($)
Operation	11.2 Million
Maintenance	2.1 Million
Transportation	27.3 Million
Capital (Year 1-2)	23.8 Million
Capital (Year 3)	7.3 Million

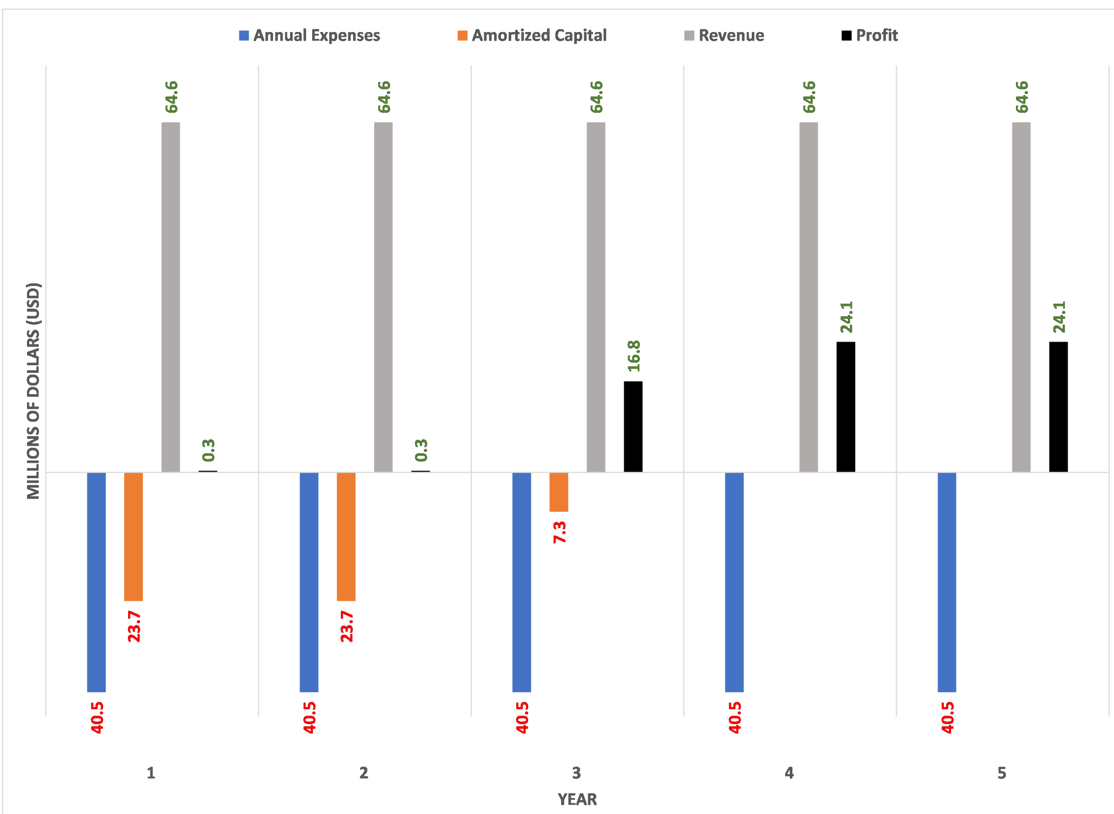

Fig. 24. 5 year cost analysis of the 70 ton/hr pellet manufacturing facility.

8.5 Environmental

The environmental impact of the pellet facility was evaluated and compared to the DG Fairhaven and Humboldt Sawmill Company annual criteria pollutant emissions (Table 22). Data for the two power generation plants were obtained from the California Air Resource Board (CARB) Pollution Mapping Tool for the years of 2011-2017, and the median was then taken for the representative emission value. Emissions generated during the manufacturing of the pellets were developed using the estimates shown in Table 23 (Reed et al. 2012).

TABLE 22. Median of 2011-2017 criteria air pollutants for DG Fairhaven and Humboldt Sawmill Company along with estimates for pellet manufacturing and combustion emissions (United States Environmental Protection Agency 1996; California Air Resources Board 2020a; Reed et al. 2012; California Air Resources Board 2020b)

	Criteria Pollutant & GHG Emissions (tons/yr)					
	CO	**NO_x**	**SO_x**	**PM_{10}**	**$PM_{2.5}$**	**CO_2**
DG Fairhaven	1,341	158	28	31	29	200,466
Humboldt Sawmill Company	876	175	35	37	33	218,130
Pellet Facility (Manufacturing)	-	176	19	<1	<1	76,954
Combustion of Pellets	7,683	2,691	78	1,896	741	666,130

Manufacturing pellets from woody biomass waste does not create any carbon monoxide or particulate matter, both of which degrade local air quality. Moreover, when comparing the facility to the cumulative emissions of NO_x, SO_x, and CO_2 generated from the two power plants, emissions are lower in each category. For instance, the pollutant emissions are roughly 37%, 61%, and 17% less than the combined values for NO_x, SO_x, and CO_2, respectively.

While the combustion of the pellets produced at the proposed facility produces more total criteria pollutants than the current incineration, the environmental effect of the pellets will not be localized to Humboldt County. Moreover, the emissions from pellet combustion would be concentrated more so in the evening and colder months rather than being a 24/7 emission output. Used in residential stoves, pellet combustion pollutants are not a concentrated point source, and often replace less efficient basic woodstoves. If the pellets are exported for use in power generation, the biomass would likely supplant coal or another fossil fuel source.

TABLE 23. Pollutant emissions to air, water, and soil per one ton of pellet manufacturing

Type of Emission	Mass (kg)
Air	
CO_2 (fossil)	114.00
CO_2 (biomass)	65.00
Acrolein	0.00
Formaldehyde	0.11
NO_x	0.41
SO_2	0.85
SO_x	0.04
Methane	0.33
Particulates	0.12
VOCs	0.06
Water	
BOD	0.64
Suspended Solids	0.08
Chemical Oxygen Demand	0.02
Chloride	2.15
Soil	
Wood Ash	0.21

8.6 Sensitivity Analysis

For the preferred alternative, some of the cost estimates were analyzed to determine the effect of the estimates on the overall economic performance of the design. For the maintenance costs, an estimate of 6% of the costs 'inside boundary limits,' which includes the operation costs and annual payment of the capital loan (Shah et al. 2016). This estimate given from (Shah et al. 2016) is listed as the high end of the range, with 3% being the lower end of the range. A sensitivity was performed for these maintenance costs, and was found to only bring the payback period down to 2.3 years at 3% from 2.4 years at 6%. The capital cost estimate was based on a similarly sized pellet manufacturing plant (Gemco Energy 2020c). Adjustments in the capital cost led to the payback period scaling up in a linear relationship. A doubling in the capital cost estimate would result in a payback period of 4.9 years, slightly more than double the base payback period estimate. The operating and transportation costs were also analyzed for their effect on the payback period. Figure 25 shows that adjusting the operating costs does not affect the payback period very much, where an increase of costs by 35% increases the payback period by just over 20%, up to 2.9 years. The transportation costs have a slightly larger impact, where a change in 35% increases the payback period by 62.5%, up to 3.9 years.

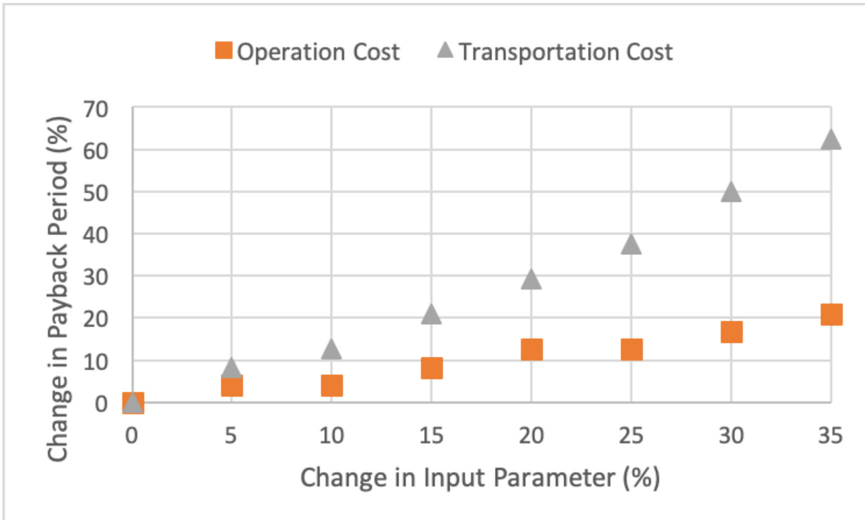

Fig. 25. Sensitivity Analysis of Operating and Transportation Costs

The biggest impact on the payback period for this design is the sale price of the finished pellets. The sale price of the finished product was reduced in 5% increments up to a 35% reduction in sale price. Figure 26 shows that a 35% reduction in price would increase the payback period by over 1000%, resulting in a payback period of 28 years. A reduction of 40% or more resulted in a negative net yearly revenue and an inability to payback the capital loan, regardless of payback period.

The two cost parameters that had the greatest effect on the overall payback period were the capital cost estimate and the pellet sale price. These estimates should be kept in mind for further analysis, since they could potentially double or quadruple the payback period. Throughout the sensitivity analysis, the lowest estimate of payback period was 2.3 years and the highest estimate was 28 years.

9 RECOMMENDATIONS AND CONCLUSIONS

This report focused on alternative uses of biomass generated by forestry and milling operations in Humboldt County, CA. The group proposed four alternative uses to replace the current use of energy

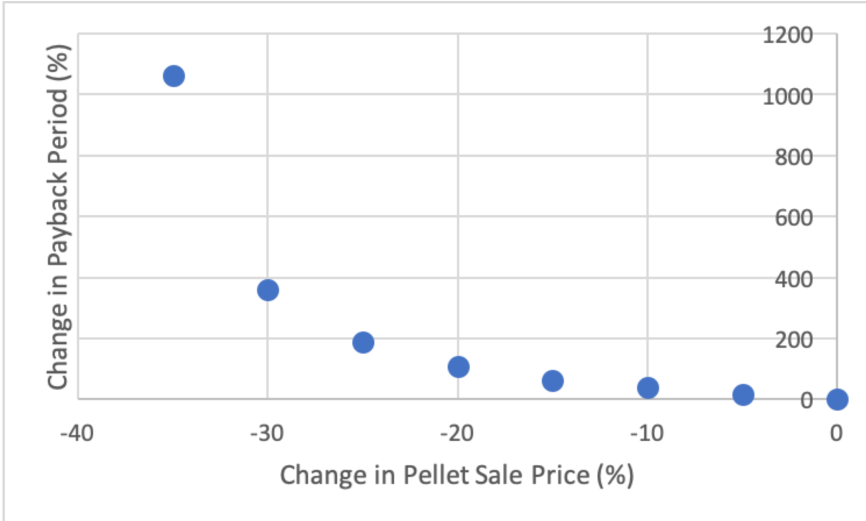

Fig. 26. Sensitivity Analysis of Sale Price of Finished Pellets

production through combustion. These alternative uses were composting, gasification, particleboard production, and wood pellet production. Through a quantitative analysis of these alternatives, a comparison was made using the delphi-matrix method. Upon comparing the alternatives, the wood pellet production facility became the preferred alternative.

An analysis of the preferred alternative was performed in order to determine its feasibility as a project at a specific location in Humboldt County. A production line was designed (Figures 22 and 23) to show how this facility could be implemented on a local site. This should not be meant to represent a final site plan and the recommendation is that further site inspections and feasibility studies take place if the decision is made to move forward with this project.

Sources of error associated with the analyses found in this report can be mainly attributed to assumptions made regarding material properties and flows. When preparing engineering reports and analyses, it is imperative to make assumptions based on credible scientific research. While these assumptions make it possible to perform analyses for emissions, costs, and facility design, they are an important source of error in reports. In order to show the impact of assumptions, a sensitivity analysis was performed on key parameters which were based on assumptions. Two key economic assumptions were shown to have a significant impact on the payback period of this alternative. The parameters that had the greatest effect on the outcome was the assumed sale price of the produced pellets, which was assumed to be $166 per ton, and the capital cost, which was based on the cost of a single, similarly sized facility. A key recommendation is that these values are investigated further, as the sensitivity analysis shows that if the price per ton of pellets drops 40% or more, then the capital loan could not be paid back using the interest and discount rates assumed for the economic analysis.

The report shows that the preferred use of biomass generated in Humboldt County is the production of wood pellets. The wood pellets produced can be used both locally and exported globally as a heat source to be used in place of standard firewood. When considering the energy content of wood pellets, it is shown that pellets contain twice to almost three times the amount of embodied energy (Reed et al. 2012; USDA 2004; Katers et al. 2012). For instance, when using energy estimates given by these sources, it takes roughly 5.8 tons of pellets or 16.5 tons of wood to produce 100 GJ of energy. Applying emission factors to these estimates results in 63.7% less CO_2 emissions when using pellets for heat energy (Wei et al. 2012; EPA 1996). In addition to heating uses, wood pellets can also be used as fuel for electricity generating power plants. Wood pellets are used as a replacement fuel in former coal power plants throughout Europe and in the U.K., where there is a growing export market for biomass pellets (Drouin 2015).

Using the recommended production line, the wood pellet production facility would have a nominal capacity of 72 tons per hour, or 502,000 tons per year, and have a capital cost of $55 million. The payback period was determined to be 2.4 years given a yearly revenue of $65 million. This alternative will not only use all of the biomass currently feeding both the Scotia and DG Fairhaven power plants, but will also create a useful commodity and business opportunity for the local community.

REFERENCES

abc Machinery (2020). "Ring Die Wood Pellet Machine.

Ace Kitchen and Baths, Inc. (2020). "Why Ply?

Alliance of Green Heat (2009). "Chronology of Wood Heat.

American Forest & Paper Association (2019). "Pulp.

Amisy (2020). "Wood Hammer Mill.

Amisy Wood Pellet Mill (2018). "Good Choice Industrial-use Ring Die Wood Pellet Mill for Mass Biomass Pellets Production." *Amisy Wood Pellet Mill* (July).

Amos, W. A. (1999). "Report on Biomass Drying Technology." *Report No. NREL/TP-570-25885, 9548* (January).

Anton Larsson, Ingemar Gunnasrsson, Freddy Tengberg (2014). "The GoBiGas Project: Demonstration of the Production of Biomethane from Biomass via Gasification." *Goeteburg Energy AB*.

Anyang Gemco Energy Machinery (2020). "Pellet Mill Report: A Complete Guide for Pellets Industry Beginners and Pellet Mill Buyers.

Aracuco (2020). "Production Operator (Particleboard Technician) 1.

Asquer, C., Cappai, G., Carucci, A., De Gioannis, G., Muntoni, A., Piredda, M., and Spiga, D. (2019). "Biomass ash characterisation for reuse as additive in composting process." *Biomass and Bioenergy*, 123, 186–194.

Basu, P. (2010). *Biomass Gasification and Pyrolysis: Practical Design and Theory*. Academic Press, Burlington, MA OCLC: ocn502035604.

Bates, R. B. and Ghoniem, A. F. (2012). "Biomass torrefaction: Modeling of volatile and solid product evolution kinetics." *Bioresource Technology*, 124, 460–469.

Batiancela, M. A., Acda, M. N., and Cabangon, R. J. (2014). "Particleboard from waste tea leaves and wood particles." *Journal of Composite Materials*, 48(8), 911–916.

Baumann, M. G., Batterman, S. A., and Zhang, G.-Z. (1999). "Terpene Emissions from Particleboard and Medium-Density Fiberboard Products." *Forest Products Journal*.

Biomass Magazine (2020). “Highland Pellets to build 500,000 ton-per-year plant in Arkansas.

Bonhotal, J., Harrison, E. Z., and Schwarz, M. (2007). “Composting Road Kill.” 12.

Brander, M. (2012). “Greenhouse Gases, CO2, CO2e, and Carbon: What Do All These Terms Mean?.” *Ecometrica*, 3.

Buhler AG (2020a).” *Wood Pelleting Plant / Biomass: RWPR-900*.

Buhler AG (2020b). “Coolex - Pellet Cooler.

California Air Resources Board (2019). “Air Districts (APCD OR AQMD) Operating Permits.

California Air Resources Board (2020a). “CARB Pollution Mapping Tool.

California Air Resources Board (2020b). “Facility Search Engine.

California Air Resources Board (2020c). “FCAA- Title V Overview | California Air Resources Board.

California Air Resources Board (CARB) (2013). “Biomass Conversion.” 10.

California Air Resources Board (CARB) (2014). “Assembly Bill 32 Overview (August).

California Air Resources Board (CARB) (2018). “Climate pollutants fall below 1990 levels for first time (July).

California Energy Commission (2019). “California Biomass and Waste-to-Energy Statistics and Data.” *energy.ca*.

California Energy Commission (2020). “Clean Energy and Pollution Reduction Act – SB 350.

California State Legislature Senate Local Government Committe (2007). “Governments Working Together A Citizen’s Guide to Joint Powers Agreements.

Carreras-Sospedra, M., Dabdub, D., and MacKinnon, M. (2015). “Assessment of the emissions and energy impacts of biomass and biogas use in California.” 131.

CDFA (2017). “Conventional Fertilizing Materials Licensing, Registration, & Labeling Guide.

Chalker-Scott, L. (2007). “Wood chip mulch: Landscape boon or bane?

Christofk, T. (2012). “Air Quality Issues and Opportunities - Placer County Forest Resource Sustainability Initiatives (December).

Ciolkosz, D. (2009). “Manufacturing Fuel Pellets from Biomass.” *Penn State Extension*.

CLT (2019). “Restoring a Forest Using Wood Chips.” *Capital Land Trust*.

Daniels, W. L. (2005). “Using Soil Science Principles for Wetland Mitigation, Voluntary Restoration and Creation.

de Carvalho Araújo, C., Salvador, R., Moro Piekarski, C., Sokulski, C., de Francisco, A., and de Carvalho Araújo Camargo, S. (2019). “Circular Economy Practices on Wood Panels: A Bibliographic Analysis.” *Sustainability*, 11(4), 1057.

Doty, C. (1917). “Meeting of the West Coast Association.” *The Timberman*, 17.

Drouin, R. (2015). “Wood Pellets: Green Energy or New Source of CO2 Emissions?.” *Yale E360*.

Duffy, J. (2018). “Strategic Plan Update 2018.” 17.

Durr, L. (2016). “Mycoremediation Project: Using Mycelium to Clean Up Diesel- Contaminated Soil in Orleans, California.” 12.

EERE (n.d.). “Hydrogen Production: Biomass Gasification.” *Hydrogen Production: Biomass Gasification | Department of Energy*.

Eldridge, J. D., Redente, E. F., and Paschke, M. (2012). “The Use of Seedbed Modifications and Wood Chips to Accelerate Restoration of Well Pad Sites in Western Colorado, U.S.A..” *Restoration Ecology*, 20(4), 524–531.

EPA (1992). “Document Display | NEPIS | US EPA.

EPA (1996). “AP42 Residential Wood Stoves.

EPA (2007). “The Use of Soil Amendments for Remediation, Revitalization, and Reuse.

EPA (2016). “AP-42: Compilation of Air Emissions Factors.” *Air Emissions Factors and Quantification*.

EPA (2017). “Basic Information about Operating Permits | Operating Permits Issued under Title V of the Clean Air Act | US EPA.

EPA (2020). “Pellet Stove Fact Sheet.

EPA (n.d.). “Biosolids Reference Sheet.

European Pellet Council (2018). “A Unique Biomass Fuel.

Forest Plywood (2020). “Medium Density Fiberboard (MDF) vs Particle Board.

Furniss, M. J. (2020). "Furniss_Biomass Humboldt-RCEA-1_19-FINAL.docx.

Gemco Energy (2020a). "Mobile Pellet Plant.

Gemco Energy (2020b). "Pellet Cooler.

Gemco Energy (2020c). "Wood Pellet Plant Cost: A Feasibility Study of Wood Pellet Plant." *GEMCO Energy*.

Gendek, A., Aniszewska, M., and Chwedoruk, K. (2016). "Bulk density of forest energy chips." *Annals of Warsaw University of Life Sciences*, 11.

Gromicko, N. (2020). "OSB vs. Plywood - InterNACHI®.

Hamad, M. A. F., Radwan, A. M., and Amin, A. (2017). "Review of Biomass Thermal Gasification." *Biomass Volume Estimation and Valorization for Energy*, J. S. Tumuluru, ed., InTech.

Homer Pro (2020). "Capital Recovery Factor.

Hoque, M., Sokhansanj, S., Mani, S., Jafari, L., Lim, J., Zaini, P., Melin, S., Sowlati, T., Afzal, M. T., and Alberta, E. (2006). "ECONOMICS OF PELLET PRODUCTION FOR EXPORT MARKET.

Hughes, M. (2016). "Wood and Wood Products: Manufacture of wood-based panels (March).

Humboldt County Department of Community Development Services (2003). "Humboldt 2025 General Plan Update: Agricultural Resources and Policies.

Hunsberger, R. and Mosey, G. (2014). "Pre-Feasibility Analysis of Pellet Manufacturing on the Former Loring Air Force Base Site." *Renewable Energy*, 58.

HWMA (2011). "HWMA Waste Characterization Study Update.

Index Journal (2020). "Maryland-based company buying Colombo plant.

Jones, D., Harper, D., and Taylor, A. (2007). "Wood Pellets - An introduction to their production and use." 3.

Kalt, J. (2016). "Good News and Bad News About New Dioxin Data." *Humboldt Baykeeper*, 1.

Katers, J. F., Snippen, A. J., and Puettmann, M. E. (2012). "Life-Cycle Inventory of Wood Pellet Manufacturing and Utilization in Wisconsin." *Forest Products Journal*, 62(4), 289–295.

Košnář, Z., Wiesnerová, L., Částková, T., Kroulíková, S., Bouček, J., Mercl, F., and Tlustoš, P. (2019). "Bioremediation of polycyclic aromatic hydrocarbons (PAHs) present in biomass fly ash by co-composting and co-vermicomposting." *Journal of Hazardous Materials*, 369, 79–86.

Kram, J. W. (2020). "Wood pellet supply, demand on the rise | Biomassmagazine.com.

Kreith, F. and Tchobanoglous, G. (2002). *Handbook of Solid Waste Management*. Mcgraw-Hill, second edition.

Lamers, P. (2017). "U.S. Pellet Industry Overview." *Report No. INL/EXT–17-41028-Rev000, 1485429*, Idaho National Laboratory (January).

Lewis, W. C. (1971). "BOARD MATERIALS FROM WOOD RESIDUES." 11.

Lottes, A. (2014). "SUPPLY CHAIN AND PROCESS EMISSIONS IMPACT OF TORREFACTION TO ENABLE BIOMASS USE IN LARGE POWER PLANTS VERSUS RAW BIOMASS USE IN SMALL POWER PLANTS." Ph.D. thesis, Humboldt State University, Humboldt State University.

Lu, H. R. and El Hanandeh, A. (2017). "Assessment of bioenergy production from mid-rotation thinning of hardwood plantation: Life cycle assessment and cost analysis." *Clean Technologies and Environmental Policy; Berlin*, 19(8), 2021–2040.

MarketWatch (2020). "Wood Pellet Market Grow at a CAGR of 8.5% During 2018- 2024 - MarketWatch.

Mayes, F. (2019). "Increases in electricity generation from biomass stop after a decade of growth." *Today in Energy - U.S. Energy Information Administration*.

Merrild, H. and Christensen, T. H. (2009). "Recycling of wood for particle board production: Accounting of greenhouse gases and global warming contributions." *Waste Management & Research*, 27(8), 781–788.

Mirski, R. and Dziurka, D. (2011). "The Utilization of Chips from Comminuted Wood Waste as a Substitute for Flakes in the Oriented Strand Board Core." *Forest Products Journal; Madison*, 61(6), 473–477.

Mobini, M., Sowlati, T., and Shahab, S. (2013). "A simulation model for the design and analysis of wood pellet supply chains." *Science Direct*, 111, 1239–1249.

Mohan, D., Pittman, C. U., and Steele, P. H. (2006). "Pyrolysis of Wood/Biomass for Bio-oil: A Critical Review." *Energy & Fuels*, 20(3), 848–889.

Molino, A., Chianese, S., and Musmarra, D. (2016). “Biomass gasification technology: The state of the art overview.” *Journal of Energy Chemistry*, 25(1), 10–25.

Mou, S. U. (2020). “Plywood Manufacturing Process - Step by Step - Civil Engineering.

Naval Facilities Engineering Service Center (2000). “Aerated Static Pile Composting.” *7-II/B-2 AERATED STATIC PILE COMPOSTING*.

NCRWQCB (2018). “Waste Discharge Requirements for DG Fairhaven Power LLC.

North Coast Unified AQMD (2015). “Regulation I Rule 102 - Required Permits.

North Coast Unified AQMD (2019). “Title V Operating Permit & NCUAQMD Permit to Operate NCU 096-12.” *Report no.*

North Coast Unified AQMD (2020). “Woodsmoke Reduction Pilot Program.

NRCS (1995). “Animal Manure Management.

NRCS (2000). “National Engineering Handbook.

Page-Dumroese, D. S., Ott, M. R., Strawn, D. G., and Tirocke, J. M. (2018). “Using Organic Amendments to Restore Soil Physical and Chemical Properties of a Mine Site in Northeastern Oregon, USA.” *Applied Engineering in Agriculture*, 34(1), 43–55.

Peigné, J. and Girardin, P. (2004). “Environmental Impacts of Farm-Scale Composting Practices.” *Water, Air, & Soil Pollution*, 153(1-4), 45–68.

Pirraglia, A., Gonzalez, R., and Saloni, D. (2010). “TECHNO-ECONOMICAL ANALYSIS OF WOOD PELLETS PRODUCTION FOR U.S. MANUFACTURERS.” *BioResources*, 5(4).

Platt, B. and Goldstein, N. (2014). “State of Composting in the U.S..” *Biocycle*.

Rao, D. (2015). “History of Composting.

RCEA (2016). “RCEA Biomass Questionnaire.

Redwood Coast Energy Authority (2020a). “About Community Choice – Redwood Coast Energy Authority.

Redwood Coast Energy Authority (2020b). “About RCEA – Redwood Coast Energy Authority.

Redwood Coast Energy Authority (2020c). “Local Biomass – Redwood Coast Energy Authority.

Reed, D., Bergman, R., Kim, J.-W., Taylor, A., Harper, D., Jones, D., Knowles, C., and Puettmann,

M. E. (2012). "Cradle-to-Gate Life-Cycle Inventory and Impact Assessment of Wood Fuel Pellet Manufacturing from Hardwood Flooring Residues in the Southeastern United States." *Forest Products Journal; Madison*, 62(4), 280–288.

Renewable Energy World (2016). "How To Make Wood Pellets - Wood Pellet Manufacture Steps." *Renewable Energy World*.

Research and Markets (2019). "Worldwide Particle Board Market Outlook to 2024 with Kastamonu, Roseburg, Norbord, Boise Cascade, and Columbia Dominating the Landscape (July).

Richardson, Y. (2020). "Downdraft Gasifiers - an overview | ScienceDirect Topics." *Downdraft Gasifiers*.

Ryczkowski, A. (2020a). "What Is the Difference Between Particleboard & Fiberboard?." *Hunker*.

Ryczkowski, A. (2020b). "What Is the Difference Between Particleboard & Fiberboard? | Hunker.

S. Mani, S. Sokhansanj, X. Bi, and A. Turhollow (2006). "ECONOMICS OF PRODUCING FUEL PELLETS FROM BIOMASS." *Applied Engineering in Agriculture*, 22(3), 421–426.

Samuelsson, R., Larsson, S. H., Thyrel, M., and Lestander, T. A. (2012). "Moisture content and storage time influence the binding mechanisms in biofuel wood pellets." *Applied Energy*, 99, 109–115.

Santos, M. F., Battistelle, R., Bezerra, B., and Varum, H. (2014). "Comparative study of the life cycle assessment of particleboards made of residues from sugarcane bagasse (Saccharum spp.) and pine wood shavings (Pinus elliottii)." *Journal of Cleaner Production*, 64, 345–355.

Schuster (1947). "Photograph Collections - Humboldt Room - HSU Library Special Collections." *Schuster Aerial Photos* (June).

Scott, A. C. (2018). "When Did Humans Discover Fire? The Answer Depends on What You Mean By 'Discover'." *Time.com* (June).

Shaddy, W. (2019). "What Is Laminated Wood? | Hunker.

Shah, A., Baral, N. R., and Manandhar, A. (2016). "Chapter Four - Technoeconomic Analysis and Life Cycle Assessment of Bioenergy Systems." *Advances in Bioenergy*, Y. Li and X. Ge, eds., Vol. 1, Elsevier, 189–247.

Shankar Tumuluru, J., Sokhansanj, S., Hess, J. R., Wright, C. T., and Boardman, R. D. (2011). “REVIEW: A review on biomass torrefaction process and product properties for energy applications.” *Industrial Biotechnology*, 7(5), 384–401.

Shouguang Qihang Wood Co,. LTD (2020). “1220x2440 6-25mm osb/osb sheet/osb board with cheap price Product Photos,1220x2440 6-25mm osb/osb sheet/osb board with cheap price Product pictures - Page1.

Sidder, A. (2016). “The Green, Brown, and Beautiful Story of Compost.” *National Geographic*.

Singh, H. (2006). *Mycoremediation: Fungal Bioremediation*. John Wiley & Sons (November).

Solt, P., Konnerth, J., Gindl-Altmutter, W., Kantner, W., Moser, J., Mitter, R., and van Herwijnen, H. W. (2019). “Technological performance of formaldehyde-free adhesive alternatives for particleboard industry.” *International Journal of Adhesion and Adhesives*, 94, 99–131.

Spelter, H. (1994). “Capacity, production, and manufacturing of woodbased panels in North America.” *Report No. FPL-GTR-82*, U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI.

Spelter, H. and Toth, D. (2009). “North America’s wood pellet sector.” *Report No. FPL-RP-656*, U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI.

Spelter, H., Winandy, J., and Zauche, T. (2008). “ANAEROBICALLY DIGESTED BOVINE BIOFIBER AS A SOURCE OF FIBER FOR PARTICLEBOARD MANUFACTURING: AN ECONOMIC ANALYSIS.” *Report no.*, U.S. Forest Service, Forest Products Laboratory.

Swiss Krono (2019). “What Is Laminate Flooring and How Is It Made? | Swiss Krono USA.

Taylor, A., Flatt, A., Beutel, M., Wolff, M., Brownson, K., and Stamets, P. (2015). “Removal of Escherichia coli from synthetic stormwater using mycofiltration.” *Ecological Engineering*, 78, 79–86.

THA (2020). “Humboldt County History.” *Timber Heritage Association*.

Thunman, H., Gustavsson, C., Larsson, A., Gunnarsson, I., and Tengberg, F. (2019). “Economic assessment of advanced biofuel production via gasification using cost data from the GoBiGas plant.” *Energy Science & Engineering*, 7(1), 217–229.

Torri, C., Pambieri, G., Gualandi, C., Piraccini, M., Rombolà, A. G., and Fabbri, D. (2020). "Evaluation of the potential performance of hyphenated pyrolysis-anaerobic digestion (Py-AD) process for carbon negative fuels from woody biomass." *Renewable Energy*, 148, 1190–1199.

Total Wood Store (2020). "Baltic Birch Marine Plywood Redi-Cuts - Total Wood Store.

Tsita, K. G. and Pilavachi, P. A. (2013). "Evaluation of next generation biomass derived fuels for the transport sector." *Energy Policy*, 62, 443–455.

Turgeon, A. and Morse, E. (2012). "Biomass Energy." *National Geographic* (November).

United Nations Food and Agriculture Organization (1990). "Energy Consercation in the Mechanical Forest Industries." *FAO Forestry Paper 93*, Rome.

United States Environmental Protection Agency (1996). "AP-42: Residential Wood Stoves - Emission Factors (October).

United States Environmental Protection Agency (2002). "EPA AP-42.

University of Massachussets Amherst (2020). "Crops, Dairy, Livestock and Equine: Bedding Options for Livestock and Equine | UMass Center for Agriculture, Food and the Environment.

US Energy Information Administration (2018). "Biomass explained - U.S. Energy Information Administration (EIA).

U.S. Energy Information Administration (2020). "U.S. Energy Information Administration - EIA - Independent Statistics and Analysis.

US EPA (2014). "Biomass Heating and Cooling Technologies." *US EPA* (October).

USDA (2002a). "Biopulping Industrial Wood Waste - US Forest Service Research & Development.

USDA (2002b). "Successful approaches to recycling urban wood waste / Solid ... - Full View | HathiTrust Digital Library | HathiTrust Digital Library.

USDA (2004). "Fuel Value Calculator.

van de Beld, B. (2019). "Torrefaction - Biomass Technology Group BV." *Biomass Technology Group*.

Vandecasteele, B., Boogaerts, C., and Vandaele, E. (2016). "Combining woody biomass for combustion with green waste composting: Effect of removal of woody biomass on compost quality." *Waste Management*, 58, 169–180.

Vergara, S. E. and Silver, W. L. (2019). "Greenhouse gas emissions from windrow composting of organic wastes: Patterns and emissions factors." *Environmental Research Letters*, 14(12), 124027.

Victor Pellet Mill (2017). "Small Pellet Mills For Home Use.Home Pellet Mill for Sale.Featured Price." *Victor Pellet Mill,Pellet Mill Manufacturer,Feed Crusher,Feed Mixer Supplier*.

Victor Pellet Mill (2019). "Industrial pellet mill for sale big capacity machine making livestock feed." *Victor Pellet Mill,Pellet Mill Manufacturer,Feed Crusher,Feed Mixer Supplier*.

Visser, L., Hoefnagels, R., and Junginger, M. (2020). "Wood pellet supply chain costs – A review and cost optimization analysis." 118.

Wei, W., Zhang, W., Hu, D., Ou, L., Tong, Y., Shen, G., Shen, H., and Wang, X. (2012). "Emissions of carbon monoxide and carbon dioxide from uncompressed and pelletized biomass fuel burning in typical household stoves in China." *Atmospheric Environment*, 56, 136–142.

Whirlston (2020). "9-10T/H Sawdust Pellet Production Line.

Whittaker, C., Yates, N. E., Powers, S. J., Donovan, N., Misselbrook, T., and Shield, I. (2017). "Testing the Use of Static Chamber Boxes to Monitor Greenhouse Gas Emissions from Wood Chip Storage Heaps." *Bioenergy Research; New York*, 10(2), 353–362.

Wijayapala, R., Karunanayake, A. G., Proctor, D., Yu, F., Pittman, C. U., and Mlsna, T. E. (2017). "Hydrodeoxygenation (HDO) of Bio-oil Model Compounds with Synthesis Gas Using a Water–Gas Shift Catalyst with a Mo/Co/K Catalyst." 35.

Williams, R. B., Jenkins, B., and Kaffka, S. (2008). "An Assessment of Biomass Resources in California, 2007, 2010 and 2020." *Report no.*, University of California, Davis.

Willis, R. and Finney, B. (2004). *Environmental Systems Engineering Economics*. Kluwer Academic Publishers.

Wilson, J. B. (2008). "Particleboard: A Life-Cycle Inventory of Manufacturing Panels from Resource Through Product." *CORRIM: Phase II Final Report*, 57.

Wilson, J. B. (2010). "LIFE-CYCLE INVENTORY OF PARTICLEBOARD IN TERMS OF RESOURCES, EMISSIONS, ENERGY AND CARBON." *WOOD AND FIBER SCIENCE*, 42, 17.

Wolf, E. C., Rejmánková, E., and Cooper, D. J. (2019). “Wood chip soil amendments in restored wetlands affect plant growth by reducing compaction and increasing dissolved phenolics.” *Restoration Ecology*, 27(5), 1128–1136.

Wood Based Panels International (2017). “Particleboard Growth goes Global - Wood Based Panels (December).

Wood Recyclers Association (2017). “About Waste Wood.” *Wood Recyclers Association*.

woodpellets.com LLC (2020). “How Are Pellets Made?

World Energy Council (2016). “World Energy Resources, 2016.” *Report no.*

Young, D., Rice, J., Martin, R., Lindquist, E., Lipzen, A., Grigoriev, I., and Hibbett, D. (2015). “Degradation of Bunker C Fuel Oil by White-Rot Fungi in Sawdust Cultures Suggests Potential Applications in Bioremediation.” *PLOS ONE*, 10(6), e0130381.

Yunqin, L., Ge, X., and Li, Y. (2014). “Solid-state anaerobic co-digestion of spent mushroom substrate with yard trimmings and wheat straw for biogas production.” *Bioresource Technology*, 169, 468–474.

Zeigenbein, J. (2019). “Compost Facility Maintenance.” *Biocycle*.

APPENDIX A. PARTICLEBOARD SUPPLEMENTAL DATA & ANALYSES

TABLE 24. Emissions associated with the production of particleboard. Emission factors are multiplied by the volume of PB produced to determine maximum emissions. (Wilson 2008).

Pollutant	Emission Factor (kg/m3) [1B]	Maximum Scale Emissions (kg/yr)	GWP [2B]	Maximum CO2e (kg/yr)
Acetaldehyde (HAP)	1.90E-03	1.11E+03	-	-
Acetic acid	5.31E-04	3.11E+02	-	-
Acetone	2.41E-04	1.41E+02	-	-
Acrolein (HAP)	1.48E-04	8.66E+01	-	-
Aldehydes, unspecified	9.88E-03	5.78E+03	-	-
Alpha-pinene	2.48E-03	1.45E+03	-	-
Aluminum	5.00E-04	2.93E+02	-	-
Ammonia	1.81E-01	1.06E+05	-	-
Barium	5.02E-04	2.94E+02	-	-
Benzene	1.01E-03	5.91E+02	-	-
Beta-pinene	9.61E-04	5.62E+02	-	-
Butane	1.04E-03	6.08E+02	-	-
Carbon dioxide	9.27E-02	5.42E+04	-	-
Carbon dioxide, biogenic	2.42E+02	1.42E+08	-	-
Carbon dioxide, fossil (GHG)	3.68E+02	2.15E+08	1	2.15E+08
Carbon disulfide	2.09E-04	1.22E+02	-	-
Carbon monoxide	2.48E+00	1.45E+06	-	-
Carbon monoxide, fossil	1.54E-01	9.01E+04	-	-
Chlorine	9.04E-04	5.29E+02	-	-
Dinitrogen monoxide (GHG)	2.12E-03	1.24E+03	298	3.70E+05
Ethanol	1.54E-04	9.01E+01	-	-
Formaldehyde	6.28E-02	3.67E+04	-	-
HAPS	7.83E-02	4.58E+04	-	-
Hydrocarbons, unspecified	5.69E-03	3.33E+03	-	-
Hydrogen chloride	1.05E-02	6.14E+03	-	-
Hydrogen fluoride	1.43E-03	8.37E+02	-	-
Iron	5.95E-04	3.48E+02	-	-
Lead	1.76E-04	1.03E+02	-	-
Limonene	2.78E-04	1.63E+02	-	-
Manganese	1.04E-03	6.08E+02	-	-
Mercury	4.25E-06	2.49E+00	-	-
Methane (GHG)	8.70E-01	5.09E+05	25	1.27E+07
Methane, biogenic (GHG)	2.69E-04	1.57E+02	25	3.93E+03
Methane, fossil (GHG)	7.33E-02	4.29E+04	25	1.07E+06
Methanol	4.86E-02	2.84E+04	-	-
Naphthalene	2.74E-04	1.60E+02	-	-
Nickel	4.60E-04	2.69E+02	-	-
Nitrogen dioxide	6.69E-04	3.91E+02	-	-
Nitrogen oxides	1.89E+00	1.11E+06	-	-
Organic substances, unspecified	2.07E-03	1.21E+03	-	-
NMVOC, non-methane VOC	1.15E+00	6.73E+05	-	-
NOx	2.63E-04	1.54E+02	-	-
Organic substances, unspecified	1.63E-01	9.54E+04	-	-
Particulates	2.92E-01	1.71E+05	-	-
Particulates, <10 um	4.43E-01	2.59E+05	-	-
Particulates, <2.5 um	6.07E-02	3.55E+04	-	-
Particulates, >10 um	4.73E-02	2.77E+04	-	-
Particulates, >2.5 um, <10um	2.41E-02	1.41E+04	-	-
Particulates, SPM	1.86E-04	1.09E+02	-	-
Particulates, unspecified	1.64E-01	9.59E+04	-	-
Pentane	1.78E-03	1.04E+03	-	-
Phenol (HAP)	9.27E-03	5.42E+03	-	-
Potassium	8.90E-02	5.21E+04	-	-
Propane	3.15E-04	1.84E+02	-	-
SO2	4.13E-04	2.42E+02	-	-
Sodium	2.44E-03	1.43E+03	-	-
Sulfur dioxide	3.86E-02	2.26E+04	-	-
Sulfur oxides	4.17E+00	2.44E+06	-	-
Toluene	3.12E-04	1.83E+02	-	-
Vanadium	1.34E-03	7.84E+02	-	-
VOC	6.02E-01	3.52E+05	-	-
Zinc	5.28E-04	3.09E+02	-	-

Particleboard Plant Calculations	
Total Volume (m^3/yr)	2.507E+06
Annual Mass (kg/yr)	7.02E+08
Annual Mass Dry Wood (kg/yr)	3.51E+08
Annual Mass Water (kg/yr)	3.51E+08
Maximum Volume Plant size (m^3/yr)	585,000
Maximum Volume Plant size (m^2/yr)	30,708,661
Maximum Volume Plant size (ft^2/yr)	330,544,961

Cost Estimates	
Captital Cost (\$/ft^2)	$ 0.87
Capital Cost (\$/m^2)	$ 9.36
Total Production Cost (\$/ft^2)	$ 0.23
Total Projected Profit (\$/ft^2)	$ 0.30

Maximum Plant Economics	
Total Prodcution Cost ($/yr)	$ 74,400,000
Total Capital Cost ($)	$ 287,600,000
Gross Profit ($/yr)	$ 99,200,000
Net Profit ($/yr)	$ 24,800,000
Simple Payback Period (yr)	11.6

Biomass Characteristics

Biomass Data

Property	Value	Unit	
Moisture Content Received at Plant	50	%	**Bob Marino DG Fairhaven**
Density 50% M.C. Low	180	kg/m³	**Batiencela et al. 2014, Gendek A. et al. 2016**
Density 50% M.C. High	380	kg/m³	
Density 50% M.C. Average	280	kg/m³	
Mass of Biomass per Truck	25	Ton/Truck	**Bob Marino DG Fairhaven**
Trucks of Biomass (Scotia + DG)	85	Truck/Day	**Furniss 2020**
Mass Biomass Per Year	775625	ton/year	
	7.04E+08	kg/year	
	7.03635E+05	tonne/year	
Volume Biomass (50% MC)	2512983.4	m³/yr	
Potential Cost/Ton (Sawmill Residuals)	33.5	$	**US Energy Information Administration 2020**
Potential Cost/Ton (Other Residuals)	29.9	$	

Conversions

1 ton pellets	=	17.3	GJ	**Reed et al 2012**
1 ton pellets	=	17300	MJ	
1 ton	=	907.185	kg	
1 lb	=	0.453592	kg	
1 tonne	=	1000	kg	
1 ton	=	1.10E-06	g	
1 tonne	=	1.10231	US ton	
1 ton pellets	=	7	m³ of bulk biomass @ 50-55% MC	**KMEC Engineering 2018**
1 Mg	=	1	tonne	
1 yr	=	8760	hr	
1 mile	=	1.60934	km	
1 ton	=	0.907185	Mg	

Class Data (Used in Preferred Analysis)

Class Wet Biomass Intake (USton/yr)	619057.296		
Density water (kg/m3)			
Pellet output tons/yr	390,006		
Pellet output kg/yr	353807680.6		
Pellet output tons/hr	56		
Target moisture %	0.13		
Initial moisture %	0.5		
Nameplate Capacity us tons/yr	487,508	7000 hrs/yr	**Lamers, P. (2017).**
Nameplate Cap tonnes/yr	442260		
Nameplate Cap tons/yr	70		
Yearly Operating time (hr/yr)	7000		

Maturity/Downtime/Life of Machinery

Life of Pellet Machinery

Machinery Type	Life	Units	
Solid fuel burner	10	yrs	
Rotary drum dryer	15	yrs	
Drying fan	10	yrs	
Multiclone	15	yrs	
Hammer Mill	10	yrs	
Pellet Mill	10	yrs	
Pellet Cooler	15	yrs	**Hoque et al. 2006**
Screen Shaker	10	yrs	
Packaging unit	10	yrs	
Storage bin	20	yrs	
Misc. equipment	10	yrs	
Front end loader	10	yrs	
Fork Lift	10	yrs	
Truck	15	yrs	

Conversions

1 year	=	8760	hours

Failure Estimates

Process	Time Between Failure (hr)	Time to Repair (hr)	
Drum Dryer	25	1	
Hammer Mill	15	0.5	**Mobini et al.**
Pellet Mill	10	1	
Cooler	30	0.5	

Assumptions

Failures/Year	12

Calculations

Drum Dryer	Downtime/year	300
	Operational time/year	8460
	Reliability (%)	96.6
Hammer Mill	Downtime/year	180
	Operational time/year	8580
	Reliability (%)	97.9
Pellet Mill	Downtime/year	120
	Operational time/year	8640
	Reliability (%)	98.6
Cooler	Downtime/year	360
	Operational time/year	8400
	Reliability (%/yr)	95.9

Employment

Direct Employment (Southern US - Larger Capacity)		
Total Capacity	9006334	**US Energy Information Administration 2020**
# of Facilities	35	
Facility Capacity	257323.8286	
Total FTE Employees	1301	**US Energy Information Administration 2020**
FTE Employee/Facility	37.17142857	

Indirect Employment (500K/yr plant)		
Construction	482	**Biomass Magazine (2020)**

Pellet Alternative Analysis Finances

Costs (Pellet Alternative Analysis)			
Capital			
NREL Capital Cost (1.2 Ton/hr)	1281740	$	**Hunsberger & Mosey 2014**
Capacity Needed Full Biomass Use	70	ton/hour	
Capital Cost Using Formula (Full Biomass Use)	2.20.E+07	$	**Hoefnagels R. et al. 2014**
Penn State Capital Estimate Low	70000	$/(ton/hr)	
Penn State Capital Estimate High	250000	$/(ton/hr)	**Ciolkosz 2009**
Penn Statet Capital Average	160000	$/(ton/hr)	
Penn Statet Capital Estimate (1.2 Ton/hr)	192000	$	
Penn Statet Capital Estimate (Full Biomass Use)	1.74E+07	$	
Geometric Mean of Estimates	1.96.E+07		
Operating (Study based on 6 tonne/hr production)			
Drying	19.39	$/tonne	
Hammer Mill	7.84	$/tonne	**Mani et al. 2006**
Pellet Mill	1.88	$/tonne	

Pellet Cooler	0.21	$/tonne	
Packaging	1.37	$/tonne	
Screening	0.05	$/tonne	
Personell	12.74	$/tonne	
Equipment	0.33	$/tonne	
Land Use/Buliding	0.05	$/tonne	
Maintenance			
Low	3% of ISBL Costs		
High	6% of ISBL Costs	*ISBL is equal to all costs	**Shah et al. 2016**
Average	4.5% ISBL Costs	"Inside Boundary Limits"	
Avg. **Pellet Transport Costs Entire Operation**			
Large Plant	11.7	€/tonne	**Visser et al. 2020**
Small Plant	18.8	€/tonne	
Large Plant	12.87	$/tonne	
Small Plant	20.68	$/tonne	
Total Biomass Use Transport	5.02E+06	$/yr	

Total Costs

Operation	1.94E+07	$/yr
Maintenance	1.16E+06	$/yr
Transportation	5.02E+06	$/yr
Capital	1.96.E+07	$

Sales Revenue

Average Selling Price	165.546363	$/ton	**US Energy Information Administration 2020**
Ton Pellets Produced	3.90E+05	ton/yr	
Revenue	6.46E+07	$/yr	

Payback Period		
Loan Repayment Period	0.6	
US Inflation Rate	0.023	**Coinnews Media Group 2020**
Loan Rate	0.0475	**Trading Economics 2020**
Real Discount Rate	0.024	**Willis & Finney 2004**
CRF	1.699	**Willis & Finney 2004**
Annual Payment	33,241,863	
Annual Balance (Net Profit) ($/yr)	5,741,474	

Preferred Analysis Finances

Costs				
		Capital		
Gemco Energy		125	$/ton	**Gemco 2020**
Subtotal Cost		48750762.06	$	
Grinding on Site		4.00E+06	$	**Gemco 2020**
Storage		2.00E+06	$	**Gemco 2020**
	TOTAL	5.48E+07	$	
		Operating (Study based on 6 tonne/hr production)		
Drying		7.84	$/tonne	
Hammer Mill		0.7	$/tonne	
Pellet Mill		1.88	$/tonne	
Pellet Cooler		0.21	$/tonne	
Packaging		1.37	$/tonne	**Mani et al. 2006**
Screening		0.05	$/tonne	
Personell		12.74	$/tonne	
Miscallaneous Equipment		0.33	$/tonne	
Land Use/Buliding		0.05	$/tonne	
Pellet Storage		0.01	$/tonne	
	TOTAL	**25.18**	**$/tonne**	
		1.11E+07	**$/yr**	
		Maintenance		
Low		3% of ISBL Costs		**Shah et al.**
High		6% of ISBL Costs		

	Average	4.5% ISBL Costs	*ISBL is equal to all costs "Inside Boundary Limits"	

Transportation (Study Conducted in Canada)

	Chip Transportation per 50km	13.86	$/tonne	
	Chip Transportation per 100km	30.37	$/tonne	
	Pellet Transportation per 50km	5.17	$/tonne	
	Pellet Transportation per 100km	13.99	$/tonne	**Hoque et al.**
	Distance Samoa to SF	274	miles	**Google**
	Distance Samoa to SF	440.95916	km	
-->100% Ship to SF	Transportation Costs	2.73E+07	$/year	

Monetary Conversion

1 British Pound	=	1.1	$USD

Total Annual Costs

Operation	1.11E+07	$/yr
Maintenance	2.09E+06	$/yr
Transportation	2.73E+07	$/yr
Capital	2.37E+07	$/yr
TOTAL	6.43E+07	$/yr

Sales Revenue

Average Selling Price	165.546363	$/ton	**US Energy Information Administration 2020**
Ton Pellets Produced	390,006.10	ton/yr	
Revenue	64,564,090.82	$/yr	
	55.72	ton/hr	

Payback Period

Loan Repayment Period	2.4	
US Inflation Rate	0.023	https://www.usinflationcalculator.com/inflation/current-inflation-rates/
Loan Rate	0.0475	https://tradingeconomics.com/united-states/bank-lending-rate
Real Discount Rate	0.024	**Willis & Finney 2004**
CRF	0.434	**Willis & Finney 2004**
Annual Payment	23,746,738	
Annual Balance	305,174	

Environmental

Emissions/Ton of Pellets

Type of Emission	Mass (kg)
Air	
CO_2 (fossil)	114.00
CO_2 (biomass)	65.00
Acrolein	0.00
Formaldehyde	0.11
No_x	0.41
SO_2	0.85
So_x	0.04
Methane	0.33
Particulates	0.12
VOCs	0.06
Water	
BOD	0.64
Suspended Solids	0.08
Chemical Oxygen Demand	0.02
Chloride	2.15
Soil	
Wood Ash	0.21

Reed et al. 2012

Emissions DG Fairhaven 2016

Pollutant	Value (tonne)	Unit	
CO_2	85532.00	tonne	**California Air Resources Board (2020)**

CH_4	27.75	tonne
N_2O	3.64	tonne
VOC	8.88	ton
NO_x	74.80	ton
SO_x	12.70	ton
PM10	14.30	ton
PM2.5	13.30	ton
Biomass GHG	81085.00	tonne CO_2e
NonBiomass GHG	6158.00	tonne CO_2e
Total GHG	87243.00	tonne CO_2e

Pellet Burning

PM_{10}	4.00	kg PM_{10}/Mg pellets	**Lu & Hanandeh 2017**
Total PM_{10} All Pellets	1719630.48	kg PM_{10}/yr	
Total PM_{10} All Pellets	1895.57	ton PM_{10}/yr	
PM2.5	1.90	g PM2.5/kg pellet	**Tiegs et al. 1998**
Total PM2.5 All Pellets	2.09439E-06	ton PM2.5/kg pellet	
Total PM2.5 All Pellets	741.0115833	ton PM2.5/yr	
Pellet Burning Emission Factor	1708	g CO_2/kg pellet	**Wei Et al. 2012**
	1.71	ton CO_2/ton pellet	
	666129.8115	ton CO2/yr	**US EPA 1996**
	39.4	lb CO2/ton pellet	
CO	19.7	kg/Mg	**<--Multiply by .5 (US EPA 1996)**
	0.021715527	ton/Mg	
Total CO All Pellets	7683.120101	ton/yr	
NOx	13.8	lb CO2/ton pellet	**US EPA 1996**
	6.9	kg/Mg	**<--Multiply by .5 (US EPA 1996)**
	0.007605946	ton/Mg	
	2691.042066	ton/yr	
SOx	0.4	lb CO2/ton pellet	**US EPA 1996**
	0.2	kg/Mg	**<--Multiply by .5 (US EPA 1996)**
	0.000220462	ton/Mg	
	78.0012193	ton/yr	

Firewood Burning

1649.4	g CO2/kg wood	**Wen Wei et al.2012**
5.8357E+11	g CO2/total kg biomass	
583.5703884	Mg CO2/total kg biomass	

Power Generation Emissions

	California Air Resources Board 2020a, 2020b						
	CO (tons/yr)	**NOx (tons/yr)**	**SOx (tons/yr)**	**PM10 (tons/yr)**	**PM2.5 (tons/yr)**	**CO2 (MT/yr)**	**CO2 (ton/yr)**
DG Fairhaven							
2017	10.90	3.4	0.3	0.3	0.3	1344	1481.50464
2016	616.80	74.8	12.7	14.3	13.3	87243	96168.83133
2015	1341.10	157.7	27.6	30.8	28.7	191541	211137.5597
2014	1466.1	171.6	30.2	33.6	31.3	225237	248280.9975
2013	1359.2	159.7	28.1	31.2	29	181860	200466.0966
2012	1368.9	160	28.2	31.4	29.2	183855	202665.2051
2011	1239.5	144.3	25.6	28.4	26.4	165038	181923.0378
MEDIAN	1341.10	157.70	27.60	30.80	28.70	181860.00	200466.10
Humboldt Sawmill							
2017	890.50	166.8	34.5	35.7	32.9	5435	5991.05485
2016	1421.00	174.8	34.6	37.4	34.5	6132	6759.36492
2015	637.30	144.6	22.9	33.7	31.3	5002	5513.75462
2014	0	0	0	0.1	NO DATA	197884	218129.512
2013	876.1	254.5	34.6	65.9	NO DATA	280630	309341.2553
2012	885	249.9	36.4	38.3	NO DATA	283421	312417.8025
2011	811.8	245	33.4	49.8	NO DATA	265676	292857.3116
MEDIAN	876.10	174.80	34.50	37.40	32.9	197884	218129.512

Emission Totals

	CO	NOx	SOx	PM10	PM2.5	CO2
DG Fairhaven	1341.10	157.70	27.60	30.80	28.70	200466.10
Humboldt Sawmill Company	876.10	174.80	34.50	37.40	32.9	218129.51
Pellet Facility (Manufacturing)	-	176.3	18.5	-	-	76953.5
Combustion of Pellets	7683.1	2691.0	78.0	1895.6	741.0	666129.8

LCA & Emissions Considering Renwable

Property	Value	Unit	
LCA Emission (Electricity Production)	-410.0000	g CO_2e/kWh	**Dabdub et al. 2017**
LCA Fossil Energy Used (Biomass Pellet Manufacturing)	2.3000	GJ/ton	**Reed et al 2012**
	-0.0183	kg CO_2e/MJ	**Reed et al 2012**
Emissions	-0.00002	kg CO_2e/GJ	
	-0.0003	kg CO_2e/Ton of Pellets	
Total Net Emissions (Full Biomass Use System Boundary)	-245.5551188	kg CO_2e/yr	
Total Net Emissions (Full Biomass Use Cradle to Gate)	0.0572	kg/MJ	
Total Net Emissions (Full Biomass Use Cradle to Gate)	7.68E+08	kg CO2e/yr	

Total CO2 Emissions

Process/Statistic	Value	Units	
Power Generation (Both Powerplants)	320000	tons CO_2/yr	**Furniss 2020**
Uncompressed Burning Emission Factor	1649.4	g CO_2/kg wood	**Wei Et al. 2012**
	1.65	ton CO_2/ton wood	
Pellet Burning (Full Biomass Use)	666129.8115	tons CO_2/yr	
Pellet Burning (Full Biomass Use)	604302973.1	kg CO_2/yr	
Total CO2 (Manufacturing and Post Manufacture)	665884.2564	tons CO_2/yr	

Conversions/Constants

1 ton pellets	=	17.3	GJ	**Reed et al 2012**
1 ton	=	907.185	kg	
1 lb	=	0.453592	kg	
1 tonne	=	1000	kg	
1 ton	=	1.10E-06	g	
1 tonne	=	1.10231	ton	
1 hectare	=	2.47105	acres	
1 acre	=	4046.86	m^2	

APPENDIX M. BIOGAS ANALYSIS

Parameters		Source
Biomass Stream		
Truckloads per week	700	RCEA Presentation
cubic yards/truck	120	RCEA Presentation
cubic yards/week	84000	
cubic yards/day	12000	
m3/day	9174.312	
wet density kg/m3	280	Batiancela, M. A., Acda, M. N., and Cabangon, R. J. (2014). "Particleboard from waste tea leaves and wood particles." *Journal of Composite Materials*, 48(8), 911–916.
wet kg/day	2568807	
moisture content	50%	Manager of DG Fairhaven
dry density kg/m3	140	
dry tonnes/day available	1284.404	
Maximum biomethane output (All biomass) MW	171.2538	
		US Energy Information Administration https://www.eia.gov/dnav/ng/ng_pri_sum_a_EPG0_PRS_DMcf_a.htm
Residential Natural gas 2019 $/1000cf	13.32	Abraxas Energy Calculator https://www.abraxasenergy.com/energy-resources/toolbox/conversion-calculators/energy/
Natural gas MWh/1000cf	0.293071	

APPENDIX N. BIOGAS ANALYSIS

Operating hours/yr	8000	

Facility Parameters		**Source**
Biomethane output MW	100	Larsson et al, "The GoBiGas Project" https://www.goteborgenergi.se/Files/Webb20/Kategoriserad%20information/Forskningsprojekt/The%20GoBiGas%20Project%20-%20Demonstration%20of%20the%20Production%20of%20Biomethane%20from%20Biomass%20v%20230507_6_0.pdf?TS=636807191662780982
Heat output MW	25	Larsson et al 2014 25% of Biomethane output
Reference plant Output MW	20	Larsson et al 2014
Reference plant fuel requirements dry tonnes/day	150	
MW per dry tonnes per day	0.133333	
dry tonnes/day per MW	7.5	
dry tonnes/day for targeted output	750	
trucks per week needed	408.75	
MWh /yr	800000	
Revenue $/yr	36359764	Larsson et al 2014
Revenue M$/yr	36.35976	
Operating hours	8000	
$/mwh	45.4497	
% of biomass stream consumed	0.583929	
Exchange Rate		
Dollars/sek	0.1	Humboldt County General Plan https://humboldtgov.org/DocumentCenter/View/58846/Section-317-Energy-Consumption-and-Conservation-Revised-DEIR-PDF

APPENDIX O. BIOGAS ANALYSIS

Natural Gas Demand		Abraxas Energy Calculator https://www.abraxasenergy.com/energy-resources/toolbox/conversion-calculators/energy/
million therms	30	
million mwh/year	0.9	
Operators/20MW	3	Larrson et. Al 2014
Total Operators 100MW	15	
best case		
Gobigas hrs uptime/quarter after 2 years	1850	Larrson et. Al 2014 fig 3.1
Gobigas hrs uptime/yr	7400	
Targeted Operating hours	8000	
Uptime %	93%	

Cost Parameters				
Cost	Scale Factor	20MW reference estimate 2014 MSEK	20MW reference estimate 2014 M$	Current Estimate $M
Initial				
Reactor Systems	0.68	238	23.8	71.10113934
Auxilary Equipment and Project Costs	0.44	955	95.5	193.8876619
Steam cycle, external fuel handling and drying	0.67	182	18.2	53.50338888
Total		1375	137.5	318.4921901
Operation Costs	sek/mwh	$/mwh	$/yr	
20 mw reference	352	35.2	5632000	
100mw reference	166	16.6	13280000	
200mw reference	132	13.2	21120000	
Cost Source:				

APPENDIX P. BIOGAS ANALYSIS

Thunman, H., Gustavsson, C., Larsson, A., Gunnarsson, I., and Tengberg, F. (2019). "Economic assessment of advanced biofuel production via gasification using cost data from the GoBiGas plant." *Energy Science & Engineering*, 7(1), 217–229.	

Annual Analysis		
payback period yrs	18	
interest rate	2.5%	
Capital Recovery Factor	0.069670081	
Capital Cost M$/ year	$ 22.19	
Operating cost M$/yr	$ 13.28	
Total Cost M$/yr	$ 35.47	
Cost $/MWh	$ 44.34	
Revenue $/MWh	$ 45.45	
Revenue M$/yr	$ 36.36	
Design life years	20	Larsson et al 2014
Service years after payback period	2	
Total Facility Profit at 20 year decommissioning $M	$ 46.16	

APPENDIX Q. BIOGAS ANALYSIS

GHG Emissions		
Biomethane		
CO2 lbs/MBTU	117	US energy information administration https://www.eia.gov/tools/faqs/faq.php?id=73&t=11
kg/lb	0.453514739	
CO2 kg/MBTU	53.06122449	
MBTU/MWH	3.412141635	
CO2 kg/MWH	181.0524133	
MWh/yr	800000	
CO2 kg/yr	144841930.6	
Current Natural Gas CO2 kg/yr for 800K MWH		
Same as Biomethane	144841930.6	
Net GHG kg/yr	0	

APPENDIX R. COMPOST ANALYSIS

Woody Biomass	
Mass per Truck (US tons)	25
kg per US ton	907
Mass per Truck (kg)	22675
Truckloads per week[1]	595
Weeks per year	52
Truckloads per year	30940
Mass per year (kg)	701564500
% N[2]	0.11
C:N[2]	500
Moisture (%)	50
N (kg/yr)	771720.95
C (kg/yr)	38586047.5
H_2O (kg/yr)	350782250

Biosolids	
Mass produced (tons)[3]	770
Mass produced (kg/yr)	770000
% N[2]	1.9
C:N[2]	16
Moisture (%)[4]	75
N (kg/yr)	14630
C (kg/yr)	234080
H_2O (kg/yr)	577500

Food Waste	
MSW generated (tons)[5]	63000
Food Waste Fraction (%)[6]	22.7
Food Waste (tons)	14301
Food Waste (kg/yr)	14301000
% N[2]	2.5
C:N[2]	15
Moisture (%)[7]	49
N (kg/yr)	357525
C (kg/yr)	5362875
H_2O (kg/yr)	6978888

APPENDIX S. COMPOST ANALYSIS

Cow Manure	
Mass Produced (lbs/day/cow)[8]	80
Amount Recoverable (%)[8]	77.5
lbs per kg	2.2
Mass Produced (kg/day/cow)	36
Mass Collected (kg/day/cow)	28
# dairy cows in county[9]	19000
Mass collected (kg/day)	535455
Mass Collected (kg/year)	195440909
% N[2]	1.7
C:N[10]	16
Moisture (%)[10]	61
N (kg/yr)	3322495
C (kg/yr)	53159927.27
H_2O (kg/yr)	119218954.5

Mix					
Source	Fraction Used	Mass N (kg)	Mass C (kg)	Mass Water (kg)	Mass Used (kg)
Biomass	0.035	27010	1350512	12277379	24554758
Biosolids	0.02	293	4682	11550	15400
Food Waste	0.02	7151	107258	139578	286020
Manure	0.02	66450	1063199	2384379	3908818
Total:		100903	2525649	14812886	28764996

Mix Stats	
Moisture (%)	51
C:N	25

% of Total Biomass Used:	3.5

Biomass Usage Annotations:
For this analysis, masses of material as well as of nitrogen, carbon, and water content were calculated on a per year basis for each of the materials being mixed together for the compost system. The mass of each material is based on a literature value, and in the 'Mix' section, the fraction of each material is controlled. This means that not all of each material will be used.
In an analysis of the final compost mixture's moisture content and C:N ratio, it was found that if each waste stream is used in equal fractions (except for biomass), then these values fall within the ideal range for composting. In order to calculate the mass per year of nitrogen, the percentage

of nitrogen from the literature was multiplied by the mass of material per year. To get the mass of carbon, the mass of nitrogen was multiplied by the C:N ratio.

For the overall mixture, the moisture content was calculated by summing all of the water content as well as the total mass of the mix, then dividing the total mass of water by the total mass of the mix. For the overall C:N ratio, the sum of the masses of carbon was divided by the sum of the masses of nitrogen. The literature sets the acceptable range of moisture levels to between 40-60%, and the acceptable C:N ratio to between 25-30:1.

In some cases, the literature gives a range of values for a C:N ratio or % N by weight. In these cases an average number was assumed. This is the case for the %N of food wastes, the amount recoverable from cow manure, and the C:N ratio for biomass (which is based on 2 literature ranges).

In other cases, like the moisture content for biosolids, an assumption was made based on the literature. The citation used (reference 4), indicates that biosolid moisture content is no lower than 75% after de-watering. These calculations assume that this lower end moisture biosolid, post de-watering, is what is used.

Biomass Usage References:

1 - Furniss, M. J. (2019). "Biomass Power in Humboldt County." Redwood Coast Energy Authority.
2 - EPA. (n.d.). "Biosolids Reference Sheet." Environmental Protection Agency.
3 - CSWRCB. (2004). "General Waste Discharge Requirements for Biosolids Land Application." California State Water Resources Control Board.
4 - Bellur, S. R., Coronella, C. J., and Vásquez, V. R. (2009). "Analysis of biosolids equilibrium moisture and drying." *Environmental Progress & Sustainable Energy*, 28(2), 291–298.
5 - HWMA. (2018). "HWMA 2013-2023 Strategic Plan Appendix H: Strategic Plan Update 2018." Humboldt Waste Management Authority.
6 - HWMA. (2011). "HWMA Waste Characterization Study Update." Humboldt Waste Management Authority.
7 - Ezeah, C., Fazakerley, J. A., Roberts, C. L., Cigari, M. I., and Ahmadu, M. D. (2015). "Characterisation and Compositional Analyses of Institutional Waste in the United Kingdom: A Case Study of the University of Wolverhampton." *Journal of Multidisciplinary Engineering Science and Technology (JMEST)*, 2(7), 1725–1735.
8 - NRCS. (1995). "Animal Manure Management." <https://www.nrcs.usda.gov/wps/portal/nrcs/detail/null/?cid=nrcs143_014211> (Mar. 5, 2020).
9 - Humboldt County Department of Community Development Services. (2003). "Humboldt 2025 General Plan Update: Agricultural Resources and Policies." Humboldt County.
10 - Hughes, K., and Dusault, A. (2005). "Achieving Economic and Environmental Benefit through Agricultural and Municipal Cooperation in Co-composting Green Waste with Animal Manure." Sustainable Conservation.

APPENDIX U. COMPOST ANALYSIS

Environmental

Direct Emissions from Composting	
Emissions (g CO_2 equivalent per kg of feedstock)[1]	5.6
Yearly mass of feedstock (kg)	28764996
Yearly emissions (g CO_2 equivalent)	161083976
Yearly emissions (kg CO_2 equivalent)	161084

Total emissions per year (kg CO_2 -e)	217112

Transportation							
Source	Distance (miles)	Tons per trip	Tons per year	Trips per year	Miles per year	Ton Miles	g CO_2 equivalent
Biomass	10	25	24555	982	9822	245548	39729598
Biosolids	10	25	15.4	0.62	6	154	24917.2
Food Waste	10	25	286	11	114	2860	462780.36
Manure	25	25	3909	156	3909	97720	15811169.55
						Total (g):	56028465
						Total (kg)	56028

Emissions Avoided				
Source	Mass Utilized (kg per yr)	Emissions (g CO_2 equivalent per kg of feedstock)[1]	Yearly emissions (g CO_2 equivalent)	Yearly emissions (kg CO_2 equivalent)
Sequestration	28764996	-0.28	-8054198.791	-8054
Manure	3908818	-810	-3166142727	-3166143
			Total:	-3174197

Total Net Emissions per year (kg CO2 -e)	-2957084

Environmental Annotation:
For this calculation, I used the direct composting emissions value from the first cited reference to calculate an estimate of the yearly direct emissions. For the transportation emissions, the second cited reference was used for a way to calculate. The average emissions from a truck (per ton-mile) was used from that source, and a few assumptions were made. Sources of feedstock (especially manure sources) might be spread slightly throughout the county. However, since a very small percentage of each material is being utilized by this process, it was assumed that the sources could be found relatively close to the composting site. It was assumed that manure was a further distance traveled per trip on average than the other three sources.

Environtmental References:

APPENDIX V. COMPOST ANALYSIS

1 - Vergara, S. E., and Silver, W. L. (2019). “Greenhouse gas emissions from windrow composting of organic wastes: Patterns and emission factors.” *Environmental Research Letters*, 14(12), 1–10.
2 - Mathers, J. (2015). “Green Freight Math: How to Calculate Emissions for a Truck Move.” *EDF+Business*, <https://business.edf.org/insights/green-freight-math-how-to-calculate-emissions-for-a-truck-move/> (Mar. 12, 2020).

APPENDIX W. COMPOST ANALYSIS

Payback Period

Capital Cost ($)	3000000
O&M ($/yr)	675000
Revenue ($/yr)	750000
Simple Payback	40

Payback Time (years)	40

Economic Annotation:
For the simple payback period, many sources were initially searched for an analyzed. After doing some preliminary calculations, it appeared that these values obtained did not scale well when the operation was scaled up. The resource cited here was found that gave numbers for a facility utilizing a specific amount of wood waste per year. Since this resource gave an idea of the scale of the operation, the proposed alternative was scaled to approximately the same size, and so this resources values were used to give an estimate of cost and payback.

Economic References:
1 - “7-II/B-2 AERATED STATIC PILE COMPOSTING.” (2000). <https://p2infohouse.org/ref/20/19926/P2_Opportunity_Handbook/7_II_B_2.html> (Mar. 12, 2020).

Jobs

Jobs Per 10000 Tons of Raw Materials[1]	6
Tons of Raw Material Per Year	28765
Jobs	17

Jobs Annotation:
For an estimate of the number of jobs that would be required for the proposed facility, the cited reference was used to get an idea of the number of employees needed per amount of material. This resource gave an estimate based on surveying of composting facilities.

Jobs References:
1 - Platt, B., Goldstein, N. (2014). “State Of Composting In The U.S.” *BioCycle*, <https://www.biocycle.net/2014/07/16/state-of-composting-in-the-u-s/> (Mar. 14, 2020).