SUPPLY CHAIN AND PROCESS EMISSIONS IMPACT OF TORREFACTION TO ENABLE BIOMASS USE IN LARGE POWER PLANTS VERSUS RAW BIOMASS USE IN SMALL POWER PLANTS

By

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ABSTRACT

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The purpose of this study is to determine if electricity from torrefied biomass causes fewer greenhouse gas (GHG) emissions than electricity currently produced with raw biomass in Humboldt County. Torrefaction is an emerging woody biomass pre-treatment option that enables replacement of coal in large-scale power plants. This study quantifies emissions per unit energy produced (g CO_2e kWh_e^{-1}) and per unit mass utilized (g CO_2e BDT^{-1}) for two electricity generation pathways, termed raw biomass and torrefied biomass. The raw biomass pathway represents business as usual, to which the torrefied biomass pathway is compared. The biomass fuel for both pathways is timber harvest waste. To estimate total GHG impact, CO_2, CH_4 and N_2O emissions and credits for all processes from waste harvest to power production are calculated for both pathways and compared. Total emissions for the raw biomass pathway are -370 ± 920 g CO_2 e kWh_e^{-1}, versus -240 ± 810 g CO_2e kWh_e^{-1} for the torrefied biomass pathway, with uncertainty expressed as one standard deviation. Because consumption of biomass fuel offsets large alternative disposal emissions, the pathway that consumes more biomass fuel achieves lower net emissions. Emissions per BDT of forestry waste utilized were calculated to be -330,000 ± 180,000 g CO_2 e BDT^{-1} for the raw biomass pathway and -360,000 ± 76,000 g CO_2 e BDT^{-1} for the torrefied biomass pathway. On a per mass basis, combustion

emissions in the torrefied pathway offset less of the savings from avoided emissions than in the raw biomass pathway. The difference between the business-as-usual raw biomass pathway and the prospective torrefied biomass pathway represents an opportunity to develop lower-emission biomass fueled energy systems on a per BDT utilized basis that also emit less than the cleanest current fossil fuel power plants, 290 g CO_2 e kWh^{-1} (Moomaw et al., 2011), on a per kWh basis. Further research on alternative waste disposal practices and emissions is necessary to refine uncertainty estimates for this study. This study recommends that further torrefaction pretreatment research be completed to encourage development of the technology.

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ABBREVIATIONS AND DEFINITIONS

This study synthesizes data from a variety of research disciplines. It is my intention that the information be useful to members from all disciplines. The following list of definitions is grouped by discipline and then alphabetized.

Forestry

Bone Dry Ton (BDT): one short ton of biomass, usually chipped, not including water weight. For example one BDT of biomass that is 35% moisture by weight is 1.43 short tons of green biomass.

Forestry thinnings: small diameter trees and low hanging branches removed as silviculture or fire hazard mitigation operations

Landing site: clearing in a forested area where logging activities are centered

Logging Slash: wood waste generated during commercial timber harvest operations; composed of tops, limbs and bark of harvested trees and some casualty small-diameter trees killed by harvesting equipment.

Mastication: waste disposal method for logging slash or forestry thinnings. A specialized machine shreds the material and disperses in into the field.

Pile and Burn: waste disposal method for logging slash or forestry thinnings. Waste is piled and left to dry out. It is later burned.

Timber harvest waste: logging slash; woody biomass left at a timber harvest landing after timber operations cease.

<u>Greenhouse Gas Life Cycle Assessment</u>

Greenhouse gas (GHG): a gas with the capacity to trap heat in the atmosphere

Global warming potential (GWP): measure of the climate forcing effect of an emission relative to carbon dioxide. .

LCA: Life Cycle Assessment; "Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (ISO, 2006)

System Boundary: "Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (ISO, 2006)

Carbon dioxide equivalent (CO_2e): unit used to express the effect of an absolute quantity of GHG emission as though it were carbon dioxide

Power Plants

Cofire: Use of two fuels, termed primary and secondary, in the same power system.

Shipping

Articulated tug and barge, or articulate tug-barge (ATB): covered, ocean going short distance barge used to transport wood chips between Eureka, CA and Portland, OR

Short Sea Shipping (SSS): maritime shipping occurring along dedicated marine routes; generally domestic and using container or barge ships

Drayage: A term used to refer to shipping logistics. Drayage is a short transport of goods, usually as part of a longer shipping route containing two transport modes.

INTRODUCTION

Renewable energy development is important to ensure continued human prosperity. Renewable energy is created from fuel that can be regenerated through natural processes over a period of time that is useful to humans. Benefits of renewable energy can include reducing environmental impacts such as greenhouse gas pollution, diversifying technologies that provide energy, and expanding geography of and increasing quantity of land suitable for energy production, addressing crises including global warming, utility poverty, resource decline, and decreased self-determination among communities with state dependence.

Biomass fueled energy systems have the potential to address these concerns, particularly in locations with densely forested lands. Biomass is considered renewable because, on most sustainably managed lands, forests can replenish after harvest over a period of 20-60 years. In the United States, many forested areas have an unhealthy stem density and natural events such as fire, disease or insect infestation are more lethal to forest inhabitants, including humans, than they were 150 years ago (North, Stine, O'Hara, Zielinski, & Stephens, 2009; USDA Forest Service, 2011; Magruder, Chhin, & Brian Palik, 2013). Thinning dense, overcrowded forests increases ecosystem health, supplies resources for economic development, and produces a renewable source of fuel that can be substituted for fossil fuels to reduce carbon emissions, among other benefits.

Many states and the Federal Government recognize the value of biomass energy. The Federal Government supports biomass energy production through the Food, Conservation and Energy Act of 2014, known commonly as the Farm Bill, and through several programs at the USDA Forest Service, and the Department of Energy. California, Oregon, and Vermont have specified that a certain percent of their Renewable Portfolio Standard for electricity will be generated from biomass, and California plus fifteen other states host and contribute to an emerging wood energy deployment strategy of searching out and supporting wood energy projects through Statewide Wood Energy Teams.

The fuel may be the same across projects, but conversion systems vary. In the California, most biomass power plants are small-scale (<50MW) plants (California Biomass Energy Alliance, 2014). Small-scale biomass power plants traditionally burn raw waste biomass from sawmills, urban forestry or industrial forest activities. Such plants have a typical efficiency of 23% (Craig, 1999; Wiltsee, 2000).

In other states, many large scale coal power plants co-fire biomass with coal at rates up to 10% to reduce greenhouse gas emissions (2002; Spath M. a., 2001; Sebastián, Cofiring versus biomass-fired power plants: GHG (Greenhouse Gases) emissions savings comparison by means of LCA (Life-cycle Assessment) methodology, 2011; Boman & Turnbull, 1997; Thrakan et al., 2005). This 10% blend of raw biomass is a *de facto* limit, since a higher blend would require separate storage and handling systems, which can be cost prohibitive (Nicholls & Zerbe, 2012). The average efficiency of existing coal plants in the US is 33%,, but can achieve efficiencies as high as 37% (Campbell, 2013).

Biomass pre-treatment options such as pyrolysis, torrefaction and pelletization have expanded the use and efficiency of biomass for thermal and electrical energy production in the Northern United States and in Europe (Lamers, 2012; Yoder, 2011; Bohan, 2010). Pyrolysis and torrefaction allow biomass to be used as fuel for large-scale power plants that were designed to burn coal. Both treatments roast fuel at low temperatures in oxygen free environments to remove moisture and other impurities. The product has handling and combustion characteristics similar to coal, allowing it to be used as the primary fuel, rather than a co-fire additive, for coal-fired power plants without significant system changes (Bergman, 2005). Low moisture content, high energy density and the ability to pulverize to a fine dust are all characteristics of torrefied biomass and are also necessary of primary fuel for coal power plants. Transitioning biomass from fuel for small-scale power plants or co-firing in large-scale power plants to the primary fuel for large scale power plants has the potential to lower emissions. Fully powering a large scale power plant with torrefied biomass can reduce emissions by displacing fossil fuels but also by producing more energy per unit biomass fuel, which results in lower emissions per unit energy. Expanding infrastructure using known, existing technologies is a low-risk way to quickly increase output of biomass energy systems. The purpose of this study is to develop a close analysis of the emissions of these two biomass to power pathways to identify opportunities to reduce greenhouse gas emissions in the production of renewable energy.

Scope of Study

This research investigates greenhouse gas (GHG) emissions savings that can be achieved through burning torrefied biomass in large-scale rather than small-scale power plants. The study uses life cycle assessment (LCA) to measure to an amount of emissions per unit electrical energy and per unit mass of biomass for two electric power production pathways, termed "raw biomass", and "torrefied biomass" after the fuel they consume.

The International Standards Organizations lists LCA as a "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (ISO, 2006). The term "life cycle" refers to all steps in the production, use and disposal process. LCA measurements typically start with raw material development and acquisition and end when those materials begin use as another product or achieve equilibrium in the environment. The system boundaries for this analysis are fuel harvest and electricity production.

Both electricity production pathways utilize waste woody biomass fuel from Humboldt County, California. This waste is a product of timber harvest on private industrial timber lands. Timber harvest waste emits greenhouse gasses without producing economic value if not used to produce a commercial product. This research considers waste utilization to result in avoided emissions compared to the current waste disposal methods, a combination of open pile burning and in field decay.

The raw biomass pathway includes waste harvest, processing, transportation to power plant, handling, combustion, and waste disposal. The torrefied biomass pathway includes the same steps as well as transportation, handling and processing for torrefaction pre-treatment (Figure 1). Ash disposal is the end boundary of both pathways.

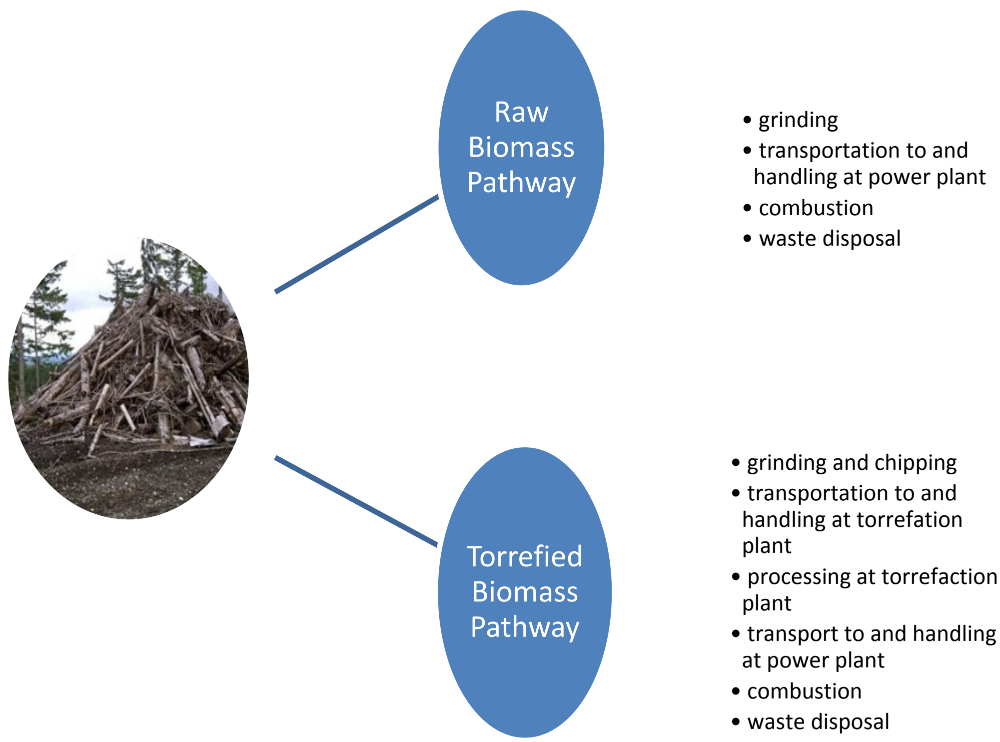

Figure 1. Raw and torrefied biomass pathways both begin with timber harvest waste piles

Emissions that occur during harvest, transport, processing and energy production are summed, and avoided emissions are subtracted for an overview of total emissions. Total emissions are reported per unit electricity produced and per bone dry ton (BDT) of raw biomass waste to form the functional units for each pathway. Functional units are grams of carbon dioxide equivalent per kilowatt hour of electrical energy produced (g CO_2e kWh^{-1}) and grams of carbon dioxide equivalent per BDT harvest waste (g CO_2e BDT^{-1}). Data inputs for this research come from forestry, transport and industrial research, and public data.

Using consistent units allows estimation of the amount of harmful emissions that can be avoided by utilizing large-scale power plants even though additional processing is required.

The downstream boundary for this study is the generation of electrical power. Losses or emissions beyond this boundary, such as transmission losses, are not considered here. Future study is required to assess any difference in these factors between small and large power plants.

This paper further contains a literature review, methods and results of the analysis and discussion. The literature review will provide additional information about biomass fuel and power pathways as applicable to this study. The methods section describes LCA and splits the study into two phases, the fuel collection phase and electricity production phase, each containing a series of processes. The steps of each process are discussed in detail and the equations used to quantify emissions are explained. The results section presents the results by process as well as the total emissions. Following a comparison of carbon emissions for each pathway, identification of emissions sources that contribute most to overall pathway emissions, recommendations for emissions reduction opportunities and areas for further study will be included.

LITERATURE REVIEW

Research for this study covers LCA, greenhouse gas emissions, forestry biomass pretreatment and power generation. Humboldt County has more active private timberland than any other county in California. Three first generation, small scale power plants are currently the main outlet for disposal of timber harvest waste. This literature review explores existing information regarding the opportunity to reduce greenhouse gas emissions by treating biomass and using it to fuel a more efficient power plant.

Life Cycle Assessment

LCA is a method for assessing the environmental impacts of a product over its lifetime. Inputs and outputs occur throughout the lifetime of the product, represented by goods or services (Finnveden, 2009). All inputs must be accounted for, and all outputs, or co-products, are allocated some portion of the emissions. Determining how much of total emissions are allocated to each co-product can happen in a variety of ways. There are four main allocation methods for LCA: system expansion, mass allocation, energy allocation and market value, or economic, allocation (Suh, 2010).

System expansion can be used if a co-product of the main product in the LCA replaces another product produced in an unrelated process. In that case, replacement of the other product will avoid the emissions associated with that product. System expansion involves more comprehensive accounting because emissions of alternative products, or those that would be produced if the product considered were not manufactured, must be considered (Kodera, 2007) System expansion is not utilized in this study because the main product of harvesting timber is timber, and electricity, the focus of this LCA, is the co-product. Still, allocation is needed to justify system boundary in this LCA. Mass and energy allocation assign a percent of total emissions to co-products based on the percent of mass or energy that is contained in the co-product. Mass cannot be used because energy does not have a mass. Energy allocation cannot be used because timber does not have an electrical energy value. In economic allocation, a ratio of emissions are assigned by the ratio of economic value the product has to the co-product (Ardente, 2012). Mass and energy allocation are considered more consistent than economic allocation, which is dependent on variable market factors.

The current biomass market in California is constrained by low demand and high supply, driving value to low or negative values. Land managers often pay to have the waste product biomass burned on site, or when required, assign prices as low at $0.10 per BDT to remove the product through existing markets (Rykoff, 2014). This is so low compared to the value of timber that the ratio of economic value of timber to timber harvest waste is considered to be 0. This research uses economic allocation to assign all of the growth and timber harvest emissions to timber, and none to timber harvest waste.

Other forest waste biomass LCAs have demonstrated a range of emissions reductions over fossil fuel combustion when including carbon sequestered during timber growth and released during timber harvest. Intensive harvest practices and long transport distances result in savings over fossil fuel electricity as low as 7% (Sebastián, 2011), while harvest requiring less machinery and transport, when collected from healthy forests with high soil production and therefore high rates of carbon sequestration, can have savings as high as 130% (Pacific Southwest Research Station, 2009).

Emissions

Greenhouse gas emissions are of concern because of their effect on global climate change. GHGs influence the Earth's heat balance, causing the planet to be warmer than it would otherwise. Many countries and states have made commitments to reduce greenhouse gas emissions and passed regulations on high-emission industries over the past decade. In the electricity sector, renewable fuels including biomass have traditionally been considered carbon-neutral and systems fueled by them are considered no- or low-carbon. This analysis considers emissions of carbon dioxide (CO_2), methane, (CH_4), and nitrous oxide (N_2O). Emissions are reported as CO_2 equivalent (CO_2e). This is calculated by multiplying the mass of the emission type by its global warming potential (GWP) (Table 1).

GWP is a measure of the potential for an emission to affect global climate. It is calculated relative to CO_2, so the GWP of CO_2 is 1. GWP is generally calculated in three categories, 20-year, 100-year and 500-year. The categories represent the effect of an emission as cumulated over an amount of time. For gaseous emissions, this study utilizes the 100-year GWP values in the Intergovernmental Panel on Climate Change (IPCC)

Fifth Assessment Report (AR5) released in 2013 by the United Nations International Panel on Climate Change (Myhre, 2013).

Black carbon is quickly becoming an important topic of study, but until recently has not been widely accepted as a primary climate forcer. Many uncertainties surround estimates of black carbon emissions and the effect of those emissions on the climate (Bond, 2013). Due to the relatively large uncertainty and controversial status of black carbon GWP, this study does not consider black carbon for the main results. Results for this study are reported. For the black carbon comparison in the discussion, this study uses the black carbon emissions factor for open biomass burning, which includes fires that move across space, like a forest fire, rather than concentrated fires. Variables that affect combustion and emissions will be different. Estimates of black carbon emissions from pile and burn will benefit future study in this field. Blodgett Research Station, UC Berkeley Center for Forestry, in conjunction with the Placer County Air Pollution Control District, is in the process of measuring black carbon emissions for pile and burn.

Table 1. Global Warming Potentials of selected emissions.

Common Name	Chemical Formula	100 year Global Warming Potential (GWP ± standard deviation, 95% CI)
Carbon dioxide[1]	CO_2	1
Methane[1]	CH_4	34 ± 11.9
Nitrous oxide[1]	N_2O	298 ± 104
Black Carbon[2]	-	910 -810 or + 910

[1] (Myhre, 2013)
[2] (Bond, 2013)

Bioenergy emissions are well studied in the literature. However, forest waste biomass systems are not well represented and have a different emissions profile than more studied biomass systems fueled by agricultural byproduct or dedicated short rotation woody crops (SRWC). SRWC fueled raw biomass power plant systems are estimated to emit approximately 100 g CO_2 kWh^{-1}in small scale, 15-25 MW_e power plants (Djomo, 2011; Sebastián, Cofiring versus biomass-fired power plants: GHG (Greenhouse Gases) emissions savings comparison by means of LCA (Life-cycle Assessment) methodology, 2011), a very low value by comparison. Large scale, 600 MW natural gas and coal power plants typically release at least five times as many emissions. Typical, natural gas systems emit 500 - 590 g CO_2e kWh^{-1} (Spath, 2000) and coal fired plants emit 750-950 g CO_2 kWh^{-1} (Widder, 2011; Spath, 2004). The most efficient natural gas combined cycle power plants can achieve emissions as low as 290 g CO_2 kWh^{-1} (Moomaw et al., 2011). Emissions per unit energy increase as plant size decreases and efficiency drops. Forestry waste in a small scale system is likely to have higher emissions per unit energy than SRWC in a small scale system because of transport emissions, but not as much as fossil fuel systems.

The historic source of carbon is also important when considering the impact of carbon-based emissions. The difference between biogenic carbon and fossil, or geologic carbon, is debated among environmental, governmental and industry interests (U.S. Environmental Protection Agency, 2011; Erickson, 2014; Gunn, Ganz, & Keeton, 2012). Biogenic carbon is carbon that is part of a living or recently living structure. It has been and will be a part of the carbon cycle within the human timeframe. Fossil or geologic carbon was part of a living structure millennia ago, and has since been stored under geologic structures. It will continue to be stored and kept out of the atmosphere without human interference.

Biomass in Humboldt County

Humboldt County produces more timber and timber harvest waste on an annual basis than any other county in California. This section will consider the volume of biomass available, methods for retrieving timber harvest waste, and current utilization systems.

Resource availability

Statewide analysis of California biomass availability states that Humboldt County will produce 871,000 bone dry tons (BDT) of timber harvest waste, of which 401,800 BDT are technically available each year, for the years 2007-2020 (Williams, 2008). Technically available forest biomass includes that which is accessible by machinery available to the biomass market but not necessary for maintaining ecological function or located on protected land (Sethi, 2005).

Other forms of biomass such as urban waste and arbor trimmings or animal waste are also available for energy production in Humboldt County, but on a much smaller scale (Williams, 2008). They are not considered in this study because collection systems for them do not exist. Woody biomass generated on public lands and made available through forest thinning operations is unreliable as feedstock for biomass power. Public forest management is limited in Humboldt County and thinning operations depend on inconsistent government funding (Becker et al., 2011). Biomass generated through forest thinning practices is not considered because supply is considered inconsistent.

Over 50% of the land in Humboldt County is "Timber Production Zone" (TPZ), and $^{2}/_{3}$ of that land is owned by large timber companies (Humboldt County Planning Commission, 2012). In 2011, Humboldt County companies sold 216,272 million board feet of timber (California Board of Equalization, 2012), or approximately 24 million feet of 20-inch diameter trees. TPZs are areas dedicated to growing and harvesting timber (California State Legislature, 1982) and can be expected to generate timber harvest waste on a regular, predictable schedule.

Timber harvest waste is stripped from cut trees and transported to centralized operation landing sites during timber harvest operations. Timber harvest waste generally consists of tree branches and bark. Environmental and fire hazard laws require that the waste be disposed of as alternative wood product or in mastication or pile-and-burn operations. If the waste is sold as alternative product, the co-product allocation process used here would attribute harvest and decomposition emissions to that product on the basis of its value as a fraction of the total value of the forest products. If it is disposed of in the forest by mastication or pile-and-burn, emissions are generated and society gains no value beyond the lumber, so emissions are allocated solely to the lumber.

Consortium for Research on Renewable Industrial Materials (CORRIM) group has funded timber harvest waste availability research in Eastern Washington. Oneil (2009) determined that traditional estimates of burn pile volume and resulting wood fiber and energy can be underestimated by as much as half depending on the biomass market.

Oneil measured logging slash in 6 forest types including Western Red Cedar. Western Red Cedar ecosystems are considered “wet” forests and are most similar to Humboldt County’s redwood and redwood/Douglas fir mix forests. North Coast forests have 30% more live biomass per acre than drier forests to the east (Valachovic, 2013).

Harvest

Fuel harvest is similar for both utilization pathways in this study, and reflects current timber harvest waste harvesting practices. This section describes the type of harvest system used to measure harvest emissions in Han 2012a.

When forest waste is harvested, it is picked up from a slash pile, processed through a grinder (Figure 2) and loaded into a chip van (Figure 3). The torrefaction process requires relatively small and uniform sized pieces. To transform tree tops and branches into appropriately sized chips for torrefaction, it is estimated that a grinder and a chipper will be needed at the timber harvest landing (Han, 2012b). First, the fuel will pass through a large grinder, then pass to a smaller chipper to create more uniform pieces. The chipper will load the fuel directly into the chip van for transport (Figure 4).

A standard chip van reaches capacity at 25 tons. When chipped for standard purposes, biomass settles to 4.85 m^3 per ton (Kofman, 2010). When chipped to smaller pieces for a torrefaction pathway, biomass will settle to less volume per ton. Standard chip vans are not larger than 120 m^3. Fuel for the raw and torrefied biomass pathways will reach weight limit in a chip van rather than volume limit. Therefore the torrefaction pathway will not reduce haul miles per ton of fuel.

Chips are hauled to the biomass power plant or a stationary torrefaction facility for the raw and torrefied pathways, respectively. Torrefied biomass is a more valuable product than raw biomass, allowing greater hauling distances. As prices that can be paid to transport the product increase, so does the distance it can be profitably transported (Deutmeyer, et al., 2012).

Figure 2. Biomass Grinder (Biomass One, 2014)

Figure 3. Chip Van (Searcy, 2010)

Figure 4. Machine chips forestry waste and deposits into chip van for transport (Searcy, 2010)

Once delivered to the processing facility, a biomass power plant or torrefaction plant in the pathways presented in this paper, the material is unloaded, stored, and processed (Figure 5).

Figure 5. Chip van is unloaded into conveyor system for processing at plant (Searcy, 2010)

<u>Utilization</u>

Humboldt County has three recently operational raw biomass power plants. Woody biomass from industrial private timber harvest and sawmill waste provide sufficient fuel source for the plants. Raw biomass power plants in Humboldt County provide a total of 50 megawatts (MW) of electrical power to the local grid and meet 25-35% of electricity demand in the county (Schatz Energy Research Center, 2013).

Official names of each plant are Humboldt Bay Generating Station Repower, Blue Lake, and Pacific Lumber Company (California Energy Commission, 2014). They are more commonly known by aliases, DG Fairhaven, UltraPower and Scotia Biomass (California Energy Commission, 2014). Respectively, the online capacity of each plant is 15, 11 and 32.5 MW. All three plants were built primarily to handle sawmill or paper pulping waste and first came online in the 1980s. Blue Lake was closed, updated and reopened in 2010.

The primary function of these plants was waste disposal when they were designed, and original plant designs did not include expensive energy efficiency capital investments that make more sense in large scale plants. Typical thermal efficiency of a 100% raw biomass fueled direct combustion power plant is 23% (Wiltsee, 2000). Past research estimates that plants in Humboldt County achieve 18%-19% efficiency, which is further discussed in the Power Pathways section of this review.

Avoided emissions

Alternative processes for timber harvest waste utilization are in-field decay or pile and burn. If timber harvest waste is left in the field rather than harvested to fuel a power plant, it must be disposed of by the timber company. Waste disposal processes are required by law to reduce the probability and intensity of wildfires (The California Department of Forestry and Fire Protection, 2013).

In field Decay

In-field decay follows "lop and scatter" or mastication operations. During lop and scatter, the tops and limbs of a tree are removed at the location where the tree is cut. They are strewn about the forest for dispersal to reduce fuel density and postharvest depth below the maximum allowed by forest fire prevention regulations (California Department of Forestry and Fire Protection, 2013). Emissions from in-field decay consist of CO_2, CH_4 and N_2O.

Mastication operations utilize a specialized machine to grind timber harvest waste before strewing it onto the forest floor. It creates a dense mat of chipped fuel that appears similar to mulch across the landscape (**Error! Reference source not found.**). Ongoing studies are assessing the potential for this treatment to produce unwanted GHG CH_4. Results are not yet available and are not considered in this study.

Figure 6. Completed mastication in one portion of Musser Hill FMZ Stage II, 2007 (Graham, 2008)

Another consideration for the in-field decay alternative is the probability that the waste will be consumed in a wildfire. Estimating the emissions associated with the role of harvest waste in potential forest fires is complex. Due to the complexity of these estimates, this study does not include any credit for avoided forest fire emissions.

Pile and Burn

The alternative to in-field decay is termed “pile and burn,” or can be referred to as “pile burning.” During pile and burn operations, the entire harvested timber tree is moved to the road and the top and limbs are removed at the roadside. Tops and limbs are then piled, allowed to dry, and burned at a later time (Figure 7). Pile and burn emissions are determined by initial carbon input and a combustion factor (Jones 2010, Zhang 2013, Hardy 1996). Pile and burn emissions included in this study are CO_2 and CH_4.

Figure 7. Slash piles in three experimental plots were burned on 2 Nov 2006 (Halpern, 2012)

The effect of black carbon (BC) is considered in the discussion section of this paper. BC was recently identified as the second most potent overall global warming forcer (Bond et al., 2013), a position previously held by CH_4. BC is a result of incomplete combustion and a known product of open fires. Limited literature exists on BC emissions from pile and burn. This study uses BC emissions “open biomass burning” emissions reported by Bond et al. (2013). Open biomass burning is categorized in three ways, as grassland fires, forest fires and agricultural waste burning, all of which occur over a vast spatial area rather than at a point of piled fuel. Open biomass burning would have different characteristics than a moderately sized, densely packed pile burning. This is indicated by the equation for open biomass burning, which includes estimating “fuel load” and area of burn, factors commonly used by foresters to describe landscape-size burns rather than a series of bonfire-type burns. In addition, Bond et. al. (2013) disclose that agricultural waste burning only includes large fires. A current study on the Blodgett Forest Research Station in California is evaluating black carbon released in pile-and-burn operations (Springsteen, 2012). Data may be available in 2015.

Although black carbon is considered an extremely potent emission, the overall climate forcing effect of open biomass burning, or influence of open biomass burning on the climate, is likely small because a high percent of carbon released is organic carbon rather than black carbon (Bond et al., 2013). Organic carbon is light in color and actually has a cooling effect on the climate, potentially offsetting a majority of the warming effect of black carbon for these types of fires. The unknown differences between pile burning and land clearing burning and the relative ratio of black carbon to organic carbon are areas for future study.

Torrefaction

Torrefaction is a thermochemical biomass fuel pre-treatment process. During the process, uniform pieces of biomass are heated at 200-300°C in an oxygen-free environment. Such exposure volatilizes water and other species in the fuel, like hydrogen and nitrogen (Tumuluru, Sokhansanj, & Wright, 2010), producing a torrefied material with a higher carbon fraction and better fuel characteristics.

Several characteristics of torrefied biomass make it a compatible fuel for coal combustion machinery (Happonen, 2011). Torrefied biomass can be pulverized to a fine dust, has a higher energy density than raw biomass and can be stored without high risk of absorbing water (Shah, 2012; Uslu, 2008). The energy density of torrefied material is not as high as high quality coal, but the cost may be lower. Pulverized torrefied fuel is handled and combusts similarly to coal, allowing it to directly replace coal as fuel without major retrofits. In fact, some campaigns have called torrefied biomass “bio-coal” to represent the similarities between the fuels (Bergman, 2005).

Power Pathways

This study estimates emissions of two biomass-fueled power pathways. The business-as-usual pathway is a currently active, small (<30MW) power plant fueled with raw biomass. It is referred to in this study as the raw biomass pathway and is modeled after the DG Fairhaven plant in Fairhaven, CA.

The comparison pathway includes torrefaction preprocessing and combustion in a large-scale (> 300 MW) power plant and is referred to as the torrefied biomass pathway. Pre-treatment and large-scale combustion is considered as an option for reducing greenhouse gas emissions but is not commercially proven. Coal and torrefied wood co-firing pilot burns have been done (ECN, 2014), but full scale torrefied burns have not been completed, in part due to lack of feedstock (Koppejan, Sokhansanj, Melin, & Madrali, 2012). The plant considered in this study is a 615 MW coal fueled power plant named Boardman, located near Boardman, OR and the Columbia River. It will cease to burn coal in 2020 due to air quality restrictions (Lewis, 2012).

Both pathways include timber harvest waste as fuel and direct combustion conversion technology. This study considers harvest waste in Humboldt County and biomass transportation from the forest to Fairhaven, CA. In the torrefied biomass process, this study assumes that fuel will be torrefied at the Fairhaven site and will then be shipped to Boardman, OR.

Raw Biomass

The small size and age of Humboldt County biomass power plants indicate low overall efficiencies, meaning they require more fuel to create the same amount of power compared to a larger, newer plant. Efficiency has been recognized as an important component of renewable energy system analysis by many studies (Sebastián, Cofiring versus biomass-fired power plants: GHG (Greenhouse Gases) emissions savings comparison by means of LCA (Life-cycle Assessment) methodology, 2011; Djomo, 2011; Stolzfus, 2006).

The business as usual pathway in this study includes a small scale, biomass only power plant that does not utilize waste thermal energy for external heating services. The lower efficiency plant will release more emissions and possibly have a bigger impact on climate change.

Humboldt County has more coastline than any county in California. The northern coastal climate is known for cool weather and rain, resulting in above average humidity. Two of the three regional raw biomass power plants practice open air storage of chipped and non-chipped fuel. Grinding and chipping biomass increases the amount of surface area per unit volume and removes protective bark, allowing the fuel to absorb moisture more easily than before chipping. Fuel is then piled for storage, which reduces oxygen permeability and creates an environment in which the fuel can decay anaerobically. This process creates CH_4, which is 34 times more potent than CO_2.

The literature does not estimate decay behavior or emissions for pile storage. Wihersaari (2005) made a rough estimate that 2-4% of pile mass could be lost to decay every month, resulting in CO_2, CH_4 and N_20 emissions, causing an additional GHG impact of 5-10 g CO_2e kWh^{-1}. More recent studies have recognized changed combustion properties due to decomposition could reduce plant efficiency, and some modeling about the temperature of piles has been completed (Casal, Gil, Pevide, & Rubiera, 2010). This study utilizes calculations based on Wihersaari’s assumption that 2% of the pile decays each month.

This analysis considers an existing, 18 MW biomass power plant in Fairhaven, CA. Timber harvest is ground and hauled to the plant, where it is stored in an outdoor yard. The fuel is then moved to the combustion chamber where it is burned to create heat, which is used to produce electricity. Combustion also produces waste ash, which is transported to agricultural lands for disposal.

Torrefied Biomass

The torrefied biomass pathway has several additional steps to the raw biomass pathway. The torrefied biomass harvest process is also more intensive than the raw biomass harvest process. In the torrefied biomass pathway, fuel passes through a grinder and a chipper before being transported to the torrefaction plant. The higher value of torrefied biomass will lead to a larger economical distance for transportation, increasing biomass fuel availability.

The torrefaction plant is co-located with the chip export dock in Fairhaven, CA. Co-location avoids costs and emissions associated with handling and transporting torrefied fuel in an additional step. Raw biomass fuel is delivered to the torrefaction plant in Fairhaven and torrefied at a stationary location. Torrefaction is a continuous process during which the biomass enters several phases of transformation. It is exposed to low levels of heat in an oxygen free environment, during which time mostly non-carbon elements are removed from the fuel (Tumuluru, Sokhansanj, & Wright, 2010). Some refer to this process as “roasting.”

During startup, an external energy source heats the reaction chamber. In this study, the volatilizing impurities are combusted to provide heat for the reaction chamber, though not all torrefaction systems are designed to do this. At the steady operating state there is a continuous evolution and subsequent combustion of volatiles. Under some conditions there is the potential to provide all of the heat required for the process so that no external energy is required, called auto-thermal operation. The volatile emissions are combusted and not released to the environment until they are converted into CO_2 and water (Shah, 2012).

After torrefaction, the fuel is stored outdoors in the fuel storage yard near the chip export terminal until enough is produced to fill a barge. Torrefied biomass is hydrophobic, preventing it from absorbing moisture during storage (Chew, 2011). Low-moisture or moisture-free fuel resists biological breakdown and does not emit CH_4 or CO_2.

Efficiency Effect

Co-firing raw timber harvest waste biomass with fossil fuels in a large-scale power plant can reduce emissions from fossil fuel while maintaining high levels of efficiency. A recent analysis conducted by the Electric Power Research Institute found emissions from biomass while co-firing timber harvest waste with coal has a mean of only 40 g CO_2 kWh^{-1} (O'Conner, 2013). Other studies including forest waste biomass evaluate gasification conversion technologies,[3] which have different efficiencies and

[3] Gasification systems extract the chemical energy in wood and form a gas fuel that can be combusted efficiently (Schmieder, et al., 2000). The additional conversion step in gasification can lead to some losses, though increased efficiency for combustion and power generation typical result in an overall increase in efficiency.

require different fuel characteristics. Studies considering gasification technologies find emissions of over 100 g CO_2 kWh^{-1} (Hsu, 2010).

EPRI's study evaluates results that represent the carbon intensity of forestry waste biomass directly combusted in a large power plant co-fired with coal. In those systems, power plant efficiency can be as high as 35 or 40% (O'Conner, 2013). Small-scale biomass power plants in Humboldt County have efficiencies of 19% or less (Apple, 2010; Tingleff, 2006). Van Den Broek et. al. (1996) found other direct combustion biomass power plants, sized 28-50 MW, to have 25-28% efficiency.

This study calculates an "efficiency effect" for both pathways. It is the amount of chemical energy in raw timber harvest waste biomass that is converted to electrical energy at the end of the pathway. The efficiency effect is a conversion that accounts for changes within the entire pathway. It is useful for directly comparing the advantages of a higher efficiency power system.

Transport

Truck and marine transport are the main modes of transport considered in this study. Logging machinery and conveyor systems are also used in each pathway, but contribute relatively little to the overall process emissions. Logging machinery and handling systems are included in waste harvest emissions. "Chip vans" are trailers designed for carrying wood chips. Chip vans are used to transport timber harvest waste from the timber harvest landing to Fairhaven in Humboldt County, CA, for power production or torrefaction. All trucks considered in this study consume diesel fuel. They are also used to transport torrefied material from the port in Boardman, OR to the Boardman power plant in the torrefied biomass pathway. The torrefaction facility and chip export port are co-located in Fairhaven, CA, and transport between the two is not needed. Torrefied biomass is transported by barge from the chip export dock to the port in Boardman, OR (Figure 8).

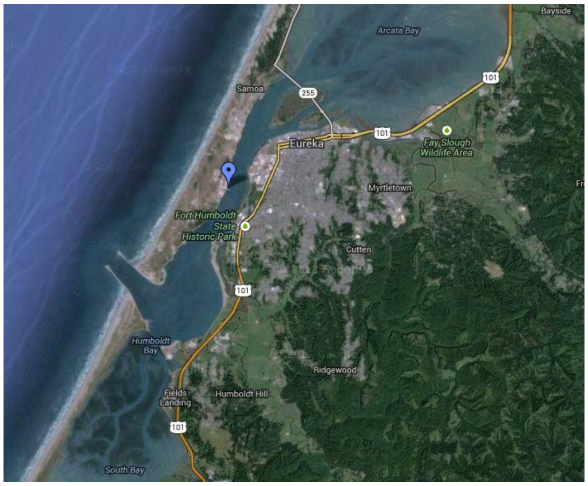

Figure 8. Biomass chip dock, Fairhaven, Humboldt County, California (Google , 2014)

In the torrefied biomass pathway, up to 10,000 tons of torrefied fuel is loaded onto an articulated tug-barge (ATB) in Humboldt County and hauled to Boardman power plant (Figure 9). Torrefied material is loaded onto the ATB with cranes and bobcats (Figure 10). Marine shipping emissions are well studied. Although marine shipping is more fuel efficient than truck or rail transport, it utilizes low quality fuel and little to no exhaust emissions after treatment, leading to a larger relative impact on air quality than other transport modes (Wang, 2007; Corbett J. J., 2003; Capaldo, 1999). This will affect the amount of black carbon released by the shipping process, but not the other emissions considered in this study.

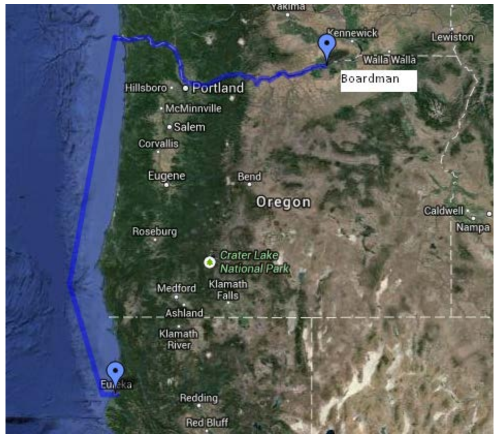

Figure 9. Shipping route from Humboldt County, CA to Boardman, OR (Google , 2014)

Figure 10. Bobcat used to transport fuel wood. Burney Mountain Power, Burney, California. July 17, 2003. John Stewart (Federal Woody Biomass Utilization Group, 2010)

This pathway includes the smallest size of ATBs for shipment to the power plant (Figure 11). The port in Boardman, OR, is not deep enough to facilitate larger barges. The smallest ATB is currently utilized to transport wood chips along the same route considered in this study. These small ATBs are capable of hauling 19,200 short tons using 4200 horsepower diesel engines and have a 25 foot draft, or vertical distance between water level and lowest part of the hull (Kratochvil, 2004).The Humboldt Bay Harbor, Recreation and Conservation District completed the Humboldt Bay Channel Deepening Project in 2000, deepening the North Bay area around the Samoa Pacific Chip Export Dock to 38 feet deep, more than sufficient for the ATBs (PB Ports & Marine, 2003).

In this study, for the torrefied biomass pathway, torrefied fuel would be shipped 436 nautical miles up the coast to the mouth of the Columbia River (U.S. Department of Commerce, 2012). This type of shipping is considered “short sea shipping” (SSS), and 3-4 million tons of petroleum products are shipped between San Francisco and Portland in this way every year (Pacific Northwest Waterways Association, 2005).

Figure 11. Articulated Tug Barge (http://www.seatransport.com/products-cargo-ptb.php)

The ATB then travels up the Columbia river an additional 262 nautical miles to the Wood Chip Dock at the Port of Morrow, Oregon (National Oceanic and Atmospheric Administration, 2014). The Boardman Wood Chip Dock, owned by the Port of Morrow, has a depth of 27 feet and an outdoor chip storage area (Port of Morrow). This study assumes that torrefied fuel will be stored on site for only the time needed to fill trucks.

Torrefied material is unloaded from the Boardman Wood Chip Dock (Figure 11) and trucked 13 miles to the Portland Gas and Electric Boardman power plant (Figure 12). Once at the plant (Figure **13**), the torrefied material is pulverized and fed into the combustion chamber in the same way that coal is currently handled. Few to no system updates are expected, so handling and pulverizing is assumed to consume the same amount of energy as the coal handling currently does. Therefore, energy consumption is accounted for in the overall Boardman power plant efficiency.

Figure 11. Boardman Wood Chip Dock, (Google, 2014)

Figure 12. 13 mile route from Port of Morrow and Boardman Power Plant, OR (Google, 2014)

Heat from the combustion chamber is used to generate electricity. The generation of electrical power, and power plant emissions, are the boundary of this analysis. It has been observed that the same quality that leads to favorable grindability characteristics can also lead to breakdown during storage, potentially causing dust problems on site and during shipping and handling (Tumurulu, 2011). This characteristic could lead to constraints that are beyond the scope of this paper.

Figure 13**. Portland Gas and Electric's Boardman Power Plant (Google, 2014)**

METHODS

The purpose of this study is to compare greenhouse gas emissions from two direct-combustion biomass pathways, termed "raw biomass" and "torrefied biomass." In each pathway, known and avoided emissions for a chain of processes are summed to determine their cumulative carbon dioxide equivalent GHG emissions. That value is reported as a ratio of emissions

per unit electricity produced $\left(\frac{Total\ system\ emissions\ (g\ CO_2\ e)}{kWh_e}\right)$

and per BDT of timber harvest waste $\left(\frac{Total\ system\ emissions\ (g\ CO_2\ e)}{BDT_{timber\ harvest\ waste}}\right)$.

This LCA of emissions is completed for a raw biomass and a torrefied biomass pathway separately, and then the results are compared.

Life Cycle Assessment

This assessment combines carbon dioxide equivalent emission measurements from timber harvest waste harvest in the forest to electricity production for two pathways (Figure 14). To address the difference between assuming zero carbon for a bio-based fuel and accounting for combusted carbon, this study uses two life cycle assessment boundaries, termed "Zero biogenic carbon, no alternative" and "All carbon, alternative included". Both pathways are considered in each LCA boundary.

Combustion and avoided emissions, those that would have occurred if the timber harvest waste were not used for bioenergy, are biogenic emissions. They are combined with non-biogenic emissions, or those that occur as a result of handling, transforming or transporting biomass.

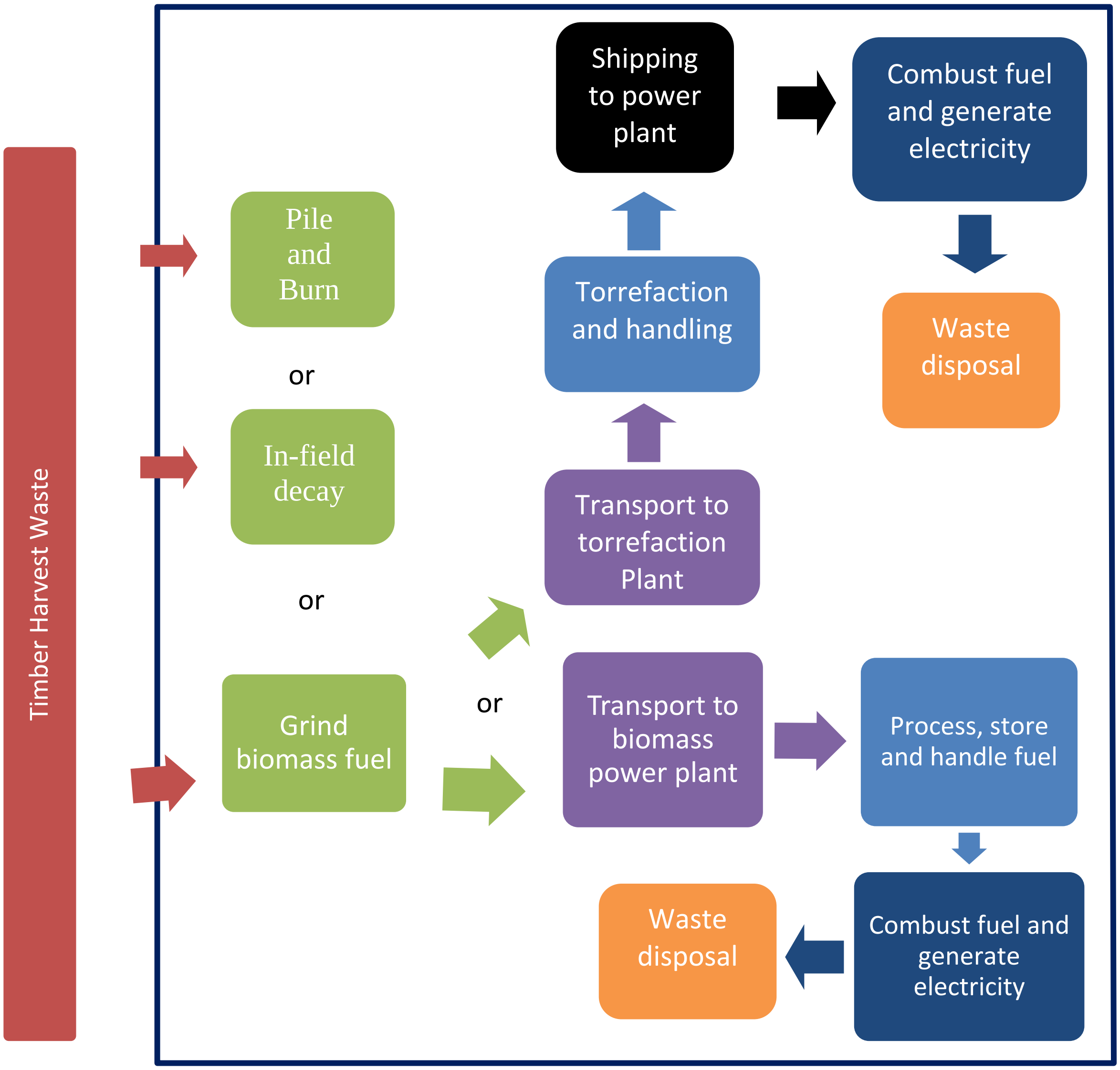

Figure 14. Pathway boundary by process.

Emissions sequestration and release during the growth and harvest of timber are allocated to timber products, according to market value allocation. There is no economic value of timber harvest waste, in fact there is a disposal cost to the landowner. Timber provides 100% of the economic value of products from the timber harvest process, so 100% of the emissions from timber harvest are allocated to timber and therefore are not considered in the biomass power pathways analysis.

Timber waste harvest, grinding and transportation to the biomass or torrefaction plant are similar for both pathways. All occur after timber harvest waste is left in the forest and before the waste arrives at the biomass or torrefaction plant. Avoided emissions from current forestry waste disposal methods are then subtracted.

Further processes for the raw biomass pathway in this study are fuel handling, storage and combustion and waste disposal. Values are summed with total for harvest and processing, transport, and alternative emissions (Equation 1).

$$\textbf{\textit{Total Raw Biomass Pathway Emissions}}\left(\frac{g\ CO_2\ e}{kWh_{elec}}\right) = \left(\frac{g\ CO_2\ e}{BDT}_{harvest\ and\ processing} + \frac{g\ CO_2\ e}{BDT}_{transportation\ to\ power\ plant} - \frac{g\ CO_2\ e}{BDT}_{alternative\ waste\ disposal\ process}\right) * \frac{BDT}{kWh_e} + \left(\frac{g\ CO_2\ e_{storage\ and\ handling}}{kWh_{elec}} + \frac{g\ CO_2\ e_{combustion}}{kWh_{elec}} + \frac{g\ CO_2\ e_{waste\ disposal}}{kWh_{elec}}\right)$$ **Equation 1**

Initial results are calculated in grams of carbon dioxide equivalent per bone dry ton (g CO_2e BDT^{-1}). The total is then converted to g CO_2e kWh_{elec}^{-1} (Equation 2).

$$\frac{g\ CO_2 e}{kWh_{elec}} = \frac{g\ CO_2 e}{BDT} * \frac{ton}{kg} * \frac{kg}{MJ} * \frac{MJ}{BTU} * \frac{BTU}{kWh} * \textbf{\textit{power plant efficiency}}$$ **Equation 2**

The torrefied biomass pathway has the same processes, plus an additional 50% harvest and processing emissions and two extra processes, torrefaction and shipping to power plant (Equation 3). This study assumes that torrefaction occurs at an industrial site co-located with the chip export dock in Fairhaven, CA, on Humboldt Bay.

No part of this study includes emissions sequestered during timber growth or released during timber harvest. Those emissions are allocated to timber according to economic LCA. Timber harvest occurs independently of waste utilization, and all timber emissions are allocated to the timber, because the waste has negligible or negative economic value.

$$\boldsymbol{Total\ Torrefied\ Biomass\ Pathway\ Emissions}\ \left(\frac{g\ CO_2\ e}{kWh_{elec}}\right) = \left(\left(\frac{g\ CO_2\ e}{BDT}_{raw\ biomass\ harvest\ and\ processing}\right) * \mathbf{1.5} + \frac{g\ CO_2\ e}{BDT}_{transportation\ to\ torrefaction\ plant} - \frac{g\ CO_2\ e}{BDT}_{alternative\ waste\ disposal\ process}\right) * \frac{BDT}{kWh_{elec}} + \left(\frac{g\ CO_2\ e_{torrefaction}}{kWh_{elec}} + \frac{g\ CO_2\ e_{shipping}}{kWh_{elec}} + \frac{g\ CO_2\ e_{combustion}}{kWh_{elec}} + \frac{g\ CO_2\ e_{waste\ disposal}}{kWh_{elec}}\right)$$ **Equation 3**

Avoided Emissions

In-field decay and pile and burn are management options that can occur in the absence of harvest for bioenergy fuel. If timber harvest waste were not harvested for bioenergy fuel, it would emit GHGs through one of these management options. This study takes credit for avoiding those processes, called here “lop and scatter” and “pile and burn”.

A registered professional forester (RPF) with more than 20 years of experience in the biomass to energy industry in California estimates that, of timber harvest waste not harvested for bioenergy, 72-78% is currently pile burned and the rest is left to decay (Mason, 2014). The estimate is based on recent fuel assessments in Northern California. Avoided emissions are calculated as a weighted average based on this assessment. They are subtracted from biomass waste harvest, processing and transport emissions for both the raw and torrefied biomass pathways.

Lop and Scatter

Timber harvest waste decays when left in the field. Over time, carbon converts to CO_2, CH_4 and nitrogen to N_2O. Under aerobic conditions, organic molecules decay to form CO_2. Under anaerobic conditions they decay to CH_4. Percent C and N by weight are taken from the ultimate analysis of logging slash published in Phanphanich (2010), the same numbers that are used in torrefaction emissions calculations. This study uses the common assumption made in biopower LCAs that 90% of the carbon becomes CO_2 and the remaining 10% becomes CH_4, (Mann and Spath, 2001). Nitrogen stored in the waste can be converted to N_2O emissions. This study assumes that 1.2% of the nitrogen in the material is converted to N_2O (Prototype Carbon Fund, 2002). Emissions are calculated per BDT of timber harvest waste (Equation 4).

$$\boldsymbol{Decomposition\ emissions}\left(\frac{CO_2e}{BDT}\right) = \boldsymbol{Mass\ of\ waste}\ (g) * \%\ \boldsymbol{element} * \boldsymbol{decay\ product}\ \% * \boldsymbol{GWP\ of\ decay\ product}\left(\frac{CO_2e}{g}\right)$$ **Equation 4**

Where:

GHG =	CO_2, CH_4 or N_2O
Mass of waste =	1 bone dry ton
% element =	47.3% for C[4]; 0.42% for N[5]
Decay product =	90% of C becomes CO_2, 10% of C becomes CH_4[6]; 1.2% of N_2 becomes N_2O[7]
100 year GWP =	1 for CO_2; 25 for CH_4; 310 for N_2O[8]

Pile and Burn

Pile and burn emissions are determined by initial carbon input and an emission factor (Jones, 2010; Zhang, 2013; Hardy, 1996). Pile and burn is a time consuming and expensive activity, and understanding the amount of material contained in piles and the effect of combustion on the environment has been critically researched by the private and public sector.

Emissions for pile and burn include CO_2 and CH_4. This study calculates emissions for 1 BDT using emission factors published in Jones 2010 (Table 2). To use the emission factor, timber harvest waste is converted from 1 BDT to a number of green tons using an assumed moisture content. This study assumes 35% moisture content to remain consistent with moisture content assumptions in harvest and transport calculations. The result is then converted from kg BDT^{-1} to g CO_2e BDT^{-1} (Equation 5).

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[4] (Phanphanich, 2010)
[5] (Kurkela, 1996)
[6] (Mann and Spath, 2001)
[7] (Prototype Carbon Fund, 2002)
[8] (Myhre, 2013)

Table 2. Pile and burn emissions for GHG (Jones, 2010)

GHG	kg BDT^{-1}
CO_2	1460.085
CH_4	5.089

The same decay assumptions used for the Lop and Scatter process are also applied to residue not consumed in the pile and burn alternative. Assumptions do not apply to ash or biochar, which are not susceptible to moisture and decay.

$$\textbf{\textit{Pile and burn emissions}}\left(\frac{g\,CO_2e}{BDT}\right) =$$

$$\left(\left(\frac{1\,BDT_{timber\ harvest\ waste}}{1\,BDT_{timber\ harvest\ waste} - (1\,BDT_{timber\ harvest\ waste} * 35\%\ moisture\ content_{timber\ harvest\ waste})}\right) *\right.$$

$$\left.\left(1460.085\,kg\,CO_2\,t^{-1} + \left(5.089\,kg\,CH_4\,t^{-1} * GWP_{CH_4}\right)\right) * \frac{1000\,g}{kg}\right) \quad \textbf{Equation 5}$$

The GWP of black carbon is taken from Bond, et al. (2013), with uncertainties of -90% and +100% for a 90% confidence interval. The pile and burn value error is calculated based on this uncertainty.

Efficiency Effect

To determine the fraction of chemical energy in biomass that is converted to electrical energy in each pathway, an energy effect was calculated for each pathway. The energy content of the wood per unit mass is converted to final electric energy per unit mass (Equation 6). This is used to convert the result value from g CO_2e BDT^{-1} to g CO_2e kWh^{-1}.

$$\frac{ton}{kWh_{power\ pathway}} = \frac{kg}{MJ} * \frac{ton}{kg} * \frac{MJ}{kWh} * \frac{1}{\%\ efficiency_{power\ system}}$$ **Equation 6**

Raw Biomass Pathway

The raw biomass pathway is described through four processes considered spatially and procedurally distinct.

Fuel harvest and processing

This section evaluates emissions from gathering and chipping timber harvest waste, termed waste biomass, and loading it into a chip van for transport.

Fuel harvest data were presented at Forest Products Society 66th International Convention (Han, 2012). The presented LCA of biomass feedstock supply includes a component termed slash recovery operations, which measures life cycle emissions of gathering, processing, and loading timber harvest waste independent from timber harvest. Two types of operations provide a high and low value for harvest and processing for the current biomass market. Results are converted from kg CO_2e per bone dry metric ton (BDmT) to g CO_2e BDT^{-1} for timber harvest waste with 35% moisture content (Table 3).

Presented values are averaged and used in the raw biomass pathway in this study. Error for this process is based on the range between the values for each operation type.

Table 3. Emissions values for timber harvest waste harvest operations (Han, 2012)

Waste Harvest Operation	(kg CO_2 e/BDT)
Pile-to-pile operations	19
Hook-lift shuttle and centralized grinding operations	27

<u>Transportation to power plant</u>

Timber harvest waste is processed and deposited into a chip van and hauled to the processing plant. The rule of thumb economic limit for hauling timber harvest waste from forest to raw biomass power plant gate is 50 miles (Han, 2012b). This study assumes fuel for the raw biomass pathway is transported 50 miles.

Moisture content affects transportation emissions because the weight of water contained in the fuel can increase the weight being transported per BDT of chip. High moisture content increases the amount of diesel fuel needed to move the truck and biomass fuel 50 miles. This study assumes 35% moisture content during transport to processing plant.

Results are presented in kg CO_2e $BDmT^{-1}$ (Han, 2012). They are converted to g CO_2e BDT^{-1} with the same conversion factors used to convert fuel harvest and processing emissions (Equation 7).

$$\textit{Fuel harvest and processing emissions}\left(\frac{g\ CO_2e}{BDT}\right) = \frac{\text{kg}\ CO_2\ \text{e}}{BDmT} * \frac{1\ BDmT}{1.1023\ BDT} * \frac{1000g}{kg}$$ **Equation 7**

Table 4. Initial transport to processing plant emissions (Han, 2012)

Transportation Distance (mi)	Moisture Content (%)	Emissions (kg CO_2e $BDmT^{-1}$)
50	35	29
50	45	34

Pile Decomposition

DG Fairhaven does not track or report pile storage emissions. Tingleff (2006) calculated storage pile emissions at DG Fairhaven to be in the range of 74-188 g CO_2e kWh^{-1} for DG Fairhaven. Inputs to Tingleff's data are from Wihersaari (2005), assuming 2 and 4% mass loss in 1 month increments during storage for 6-12 months. Our analysis utilizes the mean of Tingleff's data.

Combustion and Electricity Generation

Limited literature exists on the study of carbon emissions for first generation, small scale biomass plants. Further, woody biomass in Humboldt County has above average moisture content, decreasing plant efficiency and thus increasing emissions per electrical energy produced.

To produce an accurate emissions inventory, this study utilizes public data on emissions from an 18 MW currently operational biomass power plant on the Humboldt County coast. DG Fairhaven Power Company submits data about the Fairhaven power plant annually. Data is monitored and provided by the North Coast Unified Air Quality Management District and the California Energy Commission. Personal interviews with the plant manager provide additional information.

Handling and combustion emissions are dependent on the amount and quality of fuel consumed. Public information from the power plant provides average g CO_2 for the year. No other GHG emissions are considered for combustion at the power plant. Fuel consumption is reported by type, device, and month (North Coast Unified Air Quality Management District, 2013).

Woody biomass is the primary fuel at DG Fairhaven, but natural gas is used to co-fire when additional heat is needed in the combustion chamber. The data used in this study includes the amount of wood and natural gas fuel consumed in 2011. Emissions for each woody fuel (Equation 8) and natural gas (Equation 9) are calculated for each month. This study assumes complete combustion of natural gas, but 2% of timber harvest waste and ash does not combust. Ash is calculated using a reported value.

Total fuel carbon combusted is converted to CO_2 for each month. Values are then summed to total CO_2 emissions for the year.

$$g\ CO_{2_{2011}} = BDT_{woody\ fuel, Jan\ 2011-Dec\ 2011} * (1 - \%\ ash\ content) * \%\ carbon_{weight} * \frac{3.67\ ton\ CO_2}{ton\ C} * \frac{kg}{ton} * \frac{g}{kg}$$ **Equation 8**

$$g\ CO_{2_{2011}} = ft^3{}_{natural\ gas, Jan\ 2011-Dec\ 2011} * \frac{BTU_{natural\ gas}}{ft^3{}_{natural\ gas}} * \frac{lbs\ \mathrm{CO_2}}{BTU_{natural\ gas}} * \frac{kg}{lbs} * \frac{g}{kg}$$ **Equation 9**

Conversion factors adopted from the literature are listed in Table 5.

Table 5. Conversion factors for raw biomass combustion emissions.

Calculation	Factor	Value
Logging Slash[9]	% ash by weight	1.7%
	% C by weight	47.3%
	mass ratio CO_2:C	3.67
Natural Gas[10]	BTU/ft^3	1023
	lbs CO_2/BTU natural gas	0.001023

Total electricity generated at DG Fairhaven for each month in 2011 is reported in the California Energy Almanac (California Energy Commission, 2013). This study sums net MWh $month^{-1}$ to determine total energy produced in 2011 (Equation 10).

$$\boldsymbol{average\ \frac{kWh}{month_{2011}} = \frac{1}{12} * \sum_{January_{2011}}^{December_{2011}} MWh * \frac{kWh}{MWh}} \qquad \textbf{Equation 10}$$

Total average emissions per month for both fuels in 2011 are then divided by average electricity production per month in 2011 to produce average emissions per unit energy (Equation 11). Error is based on range of emissions between 2010-2011.

$$\frac{g\ CO_2}{kWh_e} fuel\ combustion_{2011} = \frac{\frac{g\ CO_2}{month_{2011}}}{\frac{kWh_e}{month_{2011}}} \qquad \textbf{Equation 11}$$

<u>Waste Disposal</u>

Timber harvest waste is 1.7% ash by weight (Phanphanich, 2010). Ash does not combust and will be hauled by truck 25 miles round trip once a week. Total waste disposal emissions are calculated for the year then divided by total energy produced

[9] Phanphanich 2010

[10] EIA 2013

during the year (Equation 12). This value is small compared to other processes. In the results, it is contained in the process "storage and handling at power plant".

$$\frac{g\ CO_2e_{raw\ fuel\ ash\ disposal}}{kWh_{elec}} = \frac{\frac{tons_{raw\ fuel}}{year} * \%\ ash_{raw\ fuel} * \frac{kg\ CO_2\ e}{ton*mi} * disposal\ miles * \frac{g}{kg}}{kWh_{elec}}$$ **Equation 12**

Torrefied Biomass Pathway

The torrefied biomass pathway is described through five distinct processes.

<u>Fuel harvest and processing</u>

The torrefied biomass pathway includes harvest from more remote locations than in the raw biomass pathway and requires use of an additional chipper to create uniform sized chips for torrefaction. The account for this, this study multiplies input values used in the raw biomass pathway by 1.5 to represent an up to 50% increase in emissions that will occur (Han, 2012b). Error is again based on the range of emissions between two harvest processes presented in Han 2012b.

<u>Transportation to torrefaction plant</u>

In the torrefied biomass pathway, transportation is expanded to 75 miles from the timber harvest site torrefaction plant. This reflects the need for more feedstock to fuel a larger energy system, and higher transport costs are supported by the increased value of torrefied product. Moisture content is assumed to be 35%, and the error is based on the range of emissions between 35-45% moisture content.

Torrefaction of biomass fuel

Emissions in the torrefaction process occur in three ways. Energy is used to handle the raw biomass before, and to handle the torrefied fuel after, the torrefaction process. Natural gas is burned as external energy to get the torrefaction process to a certain temperature, which releases emissions. As the fuel is torrefied, it also volatilizes fuel that combusts to provide heat. Net external energy use is calculated using data from Shah (2012) for fuel with 35% moisture content at 250°C. Emissions from handling the fuel, starting the torrefaction process, and emissions that occur during torrefaction are summed to give total emissions for the torrefaction process.

Under the correct conditions, auto-thermal operation can be achieved, eliminating external fuel consumption following start up. Heat is instead generated by the combustion of volatilized gases. This study does not consider an auto-thermal system because the moisture content of the input feedstock is too high.

Data on emissions from torrefaction handling are not well represented in the literature. This study uses data from handling and transport of sawdust (Raymer, 2006). Raymer reports 12 kWh diesel consumption over the handling life cycle of 1 m^3 sawdust from spruce. That unit is converted to g CO_2e BDT^{-1} (Equation 13).

$$\frac{g\ CO_2e}{BDT}_{sawdust,handling} = \frac{kWh_{diesel}}{m^3{}_{sawdust}} * \frac{m^3{}_{sawdust}}{BDT_{sawdust}} * \frac{kg\ CO_2e}{kWh_{diesel}} * \frac{g}{kg} \qquad \textbf{Equation 13}$$

The torrefaction temperature is assumed to be 250 °C. Available data for startup emissions (Shah, 2012) and analysis of torrefied logging slash (Phanphanich, 2010) assume 250°C. Residence time in Phanphanich (2010) is 0.5 hours. Under such conditions, 81% of mass on a dry basis and 91% of energy are retained in the torrefied product, resulting in an energy density of 19.79 MJ kg^{-1} (Phanphanich, 2010). Emissions from process startup are expected to be minimal due to the fact that this phase of operation is expected to account for only a very small fraction of the operating time. Net external energy required for startup of a torrefaction process at 250°C for 0.5 hours as published in Shah (2012) is presented in (Table 6).

Moisture content is assumed to be 35%, and energy input is assumed to be fueled by natural gas. Reported MJ $mTon^{-1}$ is converted to g CO_2 e BDT^{-1} (Equation 14) using energy content for natural gas from Oak Ridge National Laboratory (Kovacs, 2002) and an emissions factor for industrial natural gas combustion published in the United States National Inventory Report to the United Nations Framework Convention on Climate Change (Environmental Protection Agency, 2011).

Table 6. Net external energy input for torrefaction process (Shah, 2012)

Torrefaction Temperature (°C)	Moisture Content (%)	MJ $mTon^{-1}$
250	35	100

$$\frac{g\ CO_2e}{BDT}_{startup,torrefaction} = \frac{MJ}{mTon} * \frac{mTon}{1000kg} * \frac{m^3{}_{natural\ gas}}{MJ} * \frac{g\ CO_2e}{m^3} * \frac{kg}{BDT} \qquad \textbf{Equation 14}$$

Finally, emissions are released from volatilizing elements during the torrefaction process. Chew (2011) published ultimate analysis of raw and torrefied “logging slash” based on the Phanphanich (2010) study of pine chips, bark, tree tops and other particles. The analysis presented in this document uses the change in percent carbon by weight from raw biomass to torrefied biomass, when torrefied at 250°C for 0.5 hours, to calculate CO_2 emissions during the torrefaction process (Equation 15). Error in the result is based on standard deviation for percent carbon retained as presented in Phanphanich.

Emissions for each source during the torrefaction process are summed, and then added to other phase one emissions for the torrefied biomass pathway.

$$\frac{g\ CO_2e}{BDT_{volitilizaion,\ torrefaction}} = \Big(\big(1\ BDT_{raw\ biomas} * \%\ C\ by\ weight_{before\ torrefaction}\big) - \Big(\big(1\ BDT_{raw\ biomas} * \%\ Mass\ Yield_{after\ torrefaction}\big) * \%\ C\ by\ weight_{after\ torrefaction}\Big)\Big) * mass\ ratio_{\frac{CO_2}{C}} * \frac{kg}{short\ ton} * \frac{g}{kg} \quad \textbf{Equation 15}$$

Shipping to power plant

In the torrefaction pathway, shipping to power plant includes loading, moving and unloading a ship and loading, moving and unloading a truck to move torrefied fuel from the torrefaction plant to the power plant. Emissions for short sea shipping by ATB are calculated in g CO_2e per BDT and converted to g CO_2e kWh^{-1}. Error is assumed to be one standard deviation of the total result.

Transport and Handling

Torrefied biomass fuel is loaded onto an ATB and moved 698 miles through the Pacific Ocean and Columbia River. Torrefied biomass is then moved from the ATB into trucks and moved 13 miles inland to the Boardman Power plant.

Corbett, Winebrake, & Hatcher (2007) developed and demonstrate a Freight Routing and Emissions Analysis Tool (FREAT) to estimate emissions from land and marine shipping in the United States. Emissions factors grams CO and CO_2 per ship-mile (g/ship-mi) for marine transport by ATB (Table 7) and per truck-mile (g/truck-mi) for land transport (Table 8) from the FREAT model are used as inputs to this study.

Table 7. Marine transport GHG emissions (Corbett, Winebrake, & Hatcher, 2007)

Ship Designations- 10,000 ton ATB	
Pollutant	grams/ship-mi
CO	6,869
CO_2	1.464×10^6

Table 8. Truck transport GHG emissions (Corbett, Winebrake, & Hatcher, 2007)

Truck Designations	
Pollutant	g/ truck-mi
CO	3.27
CO2	2,002

The U.S. Department of Transportation Federal Motor Carrier Safety Administration published an Environmental Assessment (FMCSA) report including values used to calculate emissions from drayage in grams of CO_2e per mile (2011). Drayage is the logistical movement of fuel from one transportation type to another, such as moving fuel from a ship to a truck. The FMSCA study only published drayage values for trucks. We apply the data to both the marine and land transport miles to determine drayage emissions (Equation 16). Drayage emissions from trucks are assumed to be higher than those for ships, so this is a conservative assumption. FMSCA reports that drayage for shipping by truck releases 0.007 g CO_2e per mile. We assume that all CO converts to CO_2.

$$\frac{g\ CO_2e_{drayage}}{BDT} = \left(\frac{g_{CO_{transport}}}{ship\ mi} + \frac{g\ CO_{2\,transport}}{ship\ mi} + \frac{g\ CO_2e_{drayage}}{ship\ mi}\right) * \boldsymbol{miles} * \frac{ship}{BDT} \qquad \textbf{Equation 2}$$

<u>Combustion and generation</u>

Combustion occurs in a large scale pulverized fuel boiler. Emissions for power plant combustion consist of CO_2. This study assumes complete combustion. The carbon in one BDT of torrefied fuel is converted to CO_2 with the exception of ash in the fuel (Equation 17). Torrefied logging slash processed at 250°C is 55% C by weight (Phanphanich, 2010). The standard deviation for this input used in uncertainty calculations is published with the value.

$$\frac{g\ CO_2e_{combustion}}{BDT} = \frac{kg}{ton} * \%\ C_{weight,torrefied\ biomass} * \frac{CO_2}{C} * \frac{g}{kg} \qquad \textbf{Equation 17}$$

<u>Energy Conversion</u>

When running at steady state, full capacity, the heat rate at Boardman Power Plant is 9,876 BTU/kWh giving a 34.55% efficiency (Rodgers, 2002). Logging slash that is torrefied at 250°C for 30 minutes has an energy density of 19.79 MJ kg^{-1} (Chew, 2011). The energy density value is converted to an amount of energy per ton and 34.55% is converted to electricity (Equation 18).

$$kWh_{elec,BDT} = \frac{MJ}{BDT} * \frac{kWh}{MJ} * 34.55\% \qquad \textbf{Equation 3}$$

Total (g CO_2e kWh^{-1}) for the torrefied biomass pathway is the sum of emissions released per BDT divided by the captured energy content of one BDT.

Waste Disposal

Torrefied timber harvest waste is 10% ash by weight (Chew, 2011). Ash does not combust and will be hauled by truck 50 miles one way to a landfill. We assume the backhaul will contain a different product and emissions for the return trip are not included. Total waste disposal emissions are calculated for 10,000 tons torrefied biomass (Equation 19).

$$\frac{g\ CO_2e_{torrefied\ fuel\ ash\ disposal}}{10{,}000\ BDT_{torrefied\ biomass}} = \frac{kg_{raw\ fuel}}{10{,}000\ BDT_{torrefied\ biomass}} * \%\ ash_{torrefied\ fuel} * \frac{ton}{kg_{torrefied\ fuel\ ash}} * \frac{kg\ CO_2\ e}{ton*mi} * disposal\ miles * \frac{g}{kg}$$

Equation 4

Uncertainty Analysis

This study uses standard propagation of errors to measure uncertainty. The standard deviation (SD) of each input is used to take the derivative with respect to each input. The SD is determined based on the amount of information published with the assumed value input. SD may be reported in the literature, calculated by taking 25% of the published range for that input, or calculated as 10% of the assumed value. Inputs are listed with source of SD in Appendix A.

A finite difference estimate of the derivatives was calculated with respect to each variable input by dividing the difference between original study result and result with input changed by 1% of SD by the difference between the assumed value and the new input value with additional 1% of SD, or new input value (Equation 20).

$$\frac{\partial y}{\partial x} = \frac{\text{result calculated with assumed input value} - \text{result calculated with new input value}}{(\text{assumed input value} + 1\%\ SD) - \text{assumed input value input}}$$ **Equation 20**

Variance for each input was then calculated squaring the product of the derivative and the standard deviation of the input. The square root of the sum of the variance for each input is the estimated standard deviation of the total result (Equation 21). Estimated SD was calculated for each unit of study for each pathway.

$$\textbf{Estimated SD} = \sqrt{\sum_{input_0}^{input_i} \left(\frac{\partial y}{\partial x} * SD_{input}\right)^2}$$ **Equation 215**

In addition to estimated standard deviation for each result, propagation of errors ranks the most influential inputs. Variance for each input was divided by the sum of the variances for all inputs to determine which made the greatest contribution to total variance. The top three most influential inputs were noted. Estimated standard deviation was then recalculated as though each of those inputs had no variance to amplify the next most influential inputs.

RESULTS

Units of study are reported for each pathway. Results for processes within each pathway are also included. Data are reduced to two significant figures, the smallest number of significant figures for input data.

Alternative Fuel Use

This study evaluates two alternative waste processes, pile and burn and in-field decay (Table 9). In-field decay was found to emit more than twice as much greenhouse gas as pile and burn. Total emissions for each pathway were determined assuming a weighted average for avoided emissions, 75.5% of the material would have been disposed of through pile and burn and 24.5% through in field decay.

Table 9. Avoided emission processes

Process	g CO_2 e BDT^{-1}
Pile and Burn	1.6×10^6
In field decay	3.1×10^6
Weighted Average	2.0×10^6

Raw Biomass

Average emissions for the raw biomass pathway are -370 ± 920 g CO_2e kWh_{elec}^{-1} and -330,000 ± 180,000 g CO_2e BDT^{-1}. The largest source of emissions is combustion and electricity production, which releases 1,800 g CO_2e kWh^{-1} or 1,600,000 g CO_2e BDT^{-1}. Avoided emissions from the weighted alternative waste biomass disposal options are

2,300 g CO_2e kWh_{elec}^{-1} or 2,100,000 g CO_2e BDT^{-1}. Avoided emissions more than offset the emissions released during combustion at the power plant and during all logistical processes. The third largest source of emissions is storage and handling at the power plant, 130 g CO_2e kWh_{elec}^{-1} or 120,000 g CO_2e BDT^{-1}. Values for all processes are listed in Table 100.

Table 10. Raw Biomass pathway emissions

	Emissions	
Process	(g CO_2e kWh^{-1})	(g CO_2e BDT^{-1})
Harvest and Processing in Forest	17	15,000
Transportation to Biomass Power Plant	35	31,000
Storage and Handling at Power Plant	130	120,000
Combustion and Electricity Production	1,800	1,600,000
Avoided Emissions	-2,300	-2,100,000
Total Pathway Emissions	**-370 ± 920**	**-230,000 ± 180,000**

Figure 15 represents the emissions for each process with the range as found in this study. Emissions from alternative waste processes are represented as a negative number because they are avoided in the raw biomass pathway.

Total non-biogenic emissions and pile storage emissions are 170,000 g CO_2e BDT^{-1}. Non-biogenic emissions are due to external fuel consumption and pile storage emissions are included because of the greater GWP of methane from decompositions compared to the CO_2 that would be emitted when the wood was burned. The logistical step of storing the biomass is not a natural process so those emissions are grouped with non-biogenic emissions. Storage and handling emissions make up 72% of non-biogenic emissions (Figure 16). This is a significant portion of the total non-biogenic emissions, and the calculation is based on understudied data. As indicated in the introduction, we found several studies that considered mass and energy loss during storage at biomass power plants, but only one study on methane emissions during storage. It will be important in future LCAs of raw biomass pathways, or any pathway that requires storing untreated biomass for longer than a couple of months, to further understand the likelihood and rate for biogenic material to decompose and produce methane.

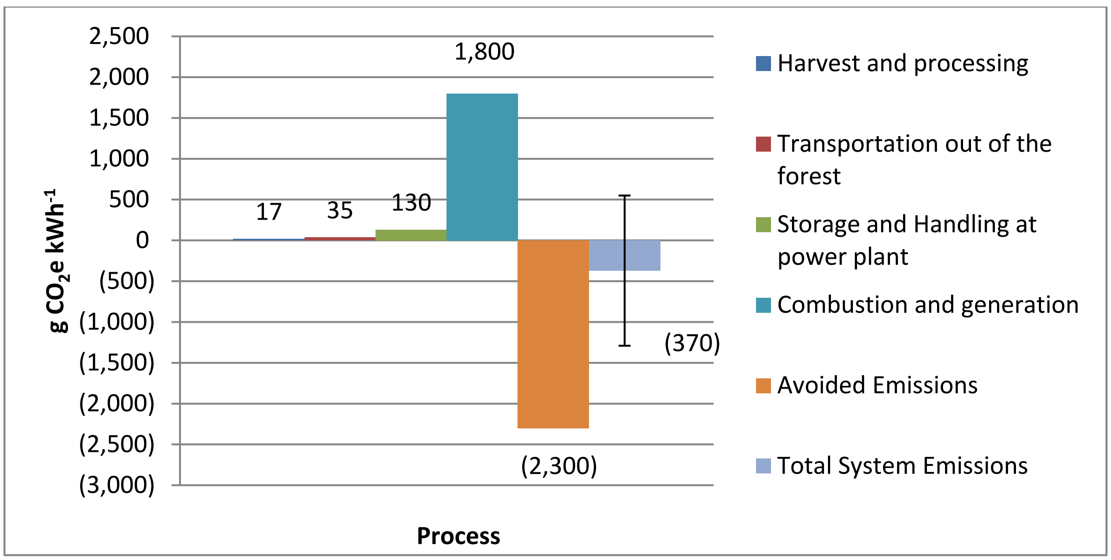

Figure 15. Emission values for each raw biomass process in g CO_2e kWh^{-1}.

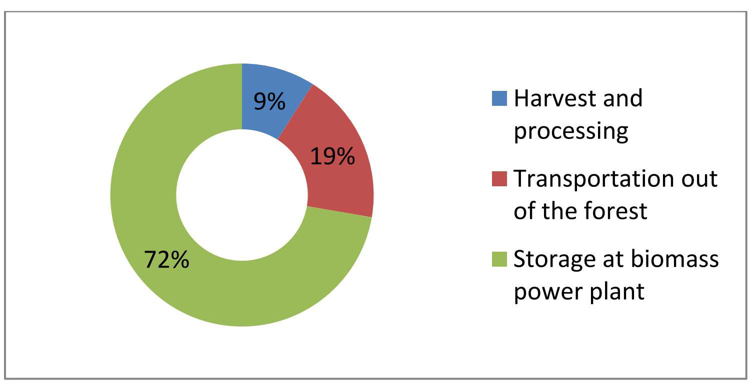

Figure 16. Logistical emissions for raw biomass pathway, process by percent of total

Torrefied biomass pathway

Average emissions for the torrefied biomass pathway are -240 ± 920 g CO_2e kWh_{elec}^{-1} and -360,000 ± 76,000 g CO_2e BDT^{-1}. The largest source of emissions is combustion, which release 990 g CO_2 equivalent kWh_{elec}^{-1} or 1,500,000 g CO_2 equivalent BDT^{-1}. Avoided emissions, 1,400 g CO_2 equivalent kWh^{-1} or 2,100,000 g CO_2 equivalent BDT^{-1}, contribute a negative value to the pathway total. The third largest value represents emissions from shipping between torrefaction and power plant, 62 g CO_2 equivalent kWh_{elec}^{-1}or 94,000 g CO_2 equivalent BDT^{-1}. Values for all processes are listed in Table 11 and represented in Figure 17.

Table 11. Torrefied Biomass Total pathway emissions with deviation for emissions GWP

	Emissions	
Process	(g CO_2e kWh^{-1})	(g CO_2e BDT^{-1})
Harvest and Processing in Forest	15	23,000
Transportation to Torrefaction Plant	29	44,000
Torrefaction	62	94,000
Shipping to Power Plant	56	83,000
Combustion and Electricity Production	990	1,500,000
Avoided Emissions	-1,400	-2,100,000
Total Pathway Emissions	**-240 ± 810**	**-360,000 ± 76,000**

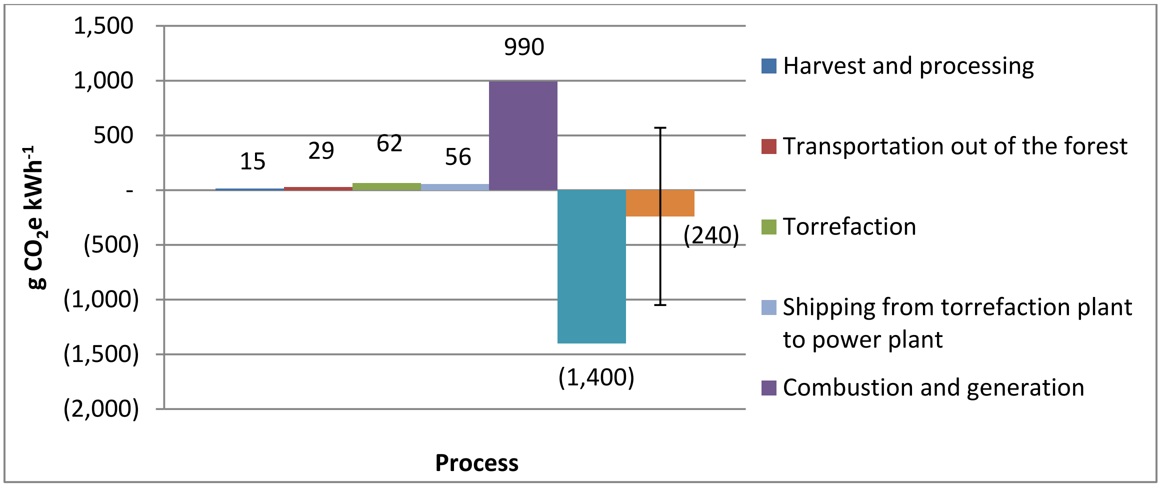

Figure 17. Emission values for each torrefied biomass process in g CO_2e kWh^{-1}. Parentheses indicate negative values.

Harvest and transport to the torrefaction plant, torrefaction, and shipping to the power plant contribute to logistical emissions almost equally with a total of 160,000 g CO_2e BDT^{-1} (Figure 18).

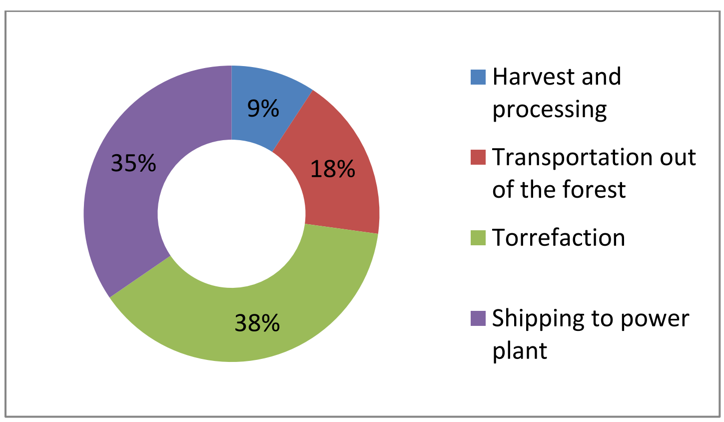

Figure 18. Non-biogenic emissions for torrefied biomass pathway, process by percent

Comparison

Emissions per unit electrical energy produced for all processes in the raw biomass pathway are lower than in the torrefied biomass pathway (Table 12). The torrefied biomass pathway includes two additional processes.

Avoided emissions have a larger negative value for the raw biomass pathway because the raw biomass power plant requires a greater mass of wood to produce one kWh of energy than the torrefied biomass plant. Plant inefficiency drives waste consumption that provides emissions benefits compared to the alternative disposal methods. These results imply that inefficient power plants are beneficial, but does not account for biomass fuel as a limited resource. If society will capture the benefits of using biomass waste to displace fossil fuel energy, rather than allowing the biomass to decay or be burned, then the benefits will be greater with greater efficiency of electricity generation from the biomass.

Table 12. Emissions by process for both pathways in terms of electricity produced

Process	Raw biomass pathway (g CO_{2e} kWh_{elec}^{-1})	Torrefied biomass pathway (g CO_2 e kWh_{elec}^{-1})
Harvest and Processing in Forest	17	15
Transportation	35	29
Storage and Handling	130	-
Torrefaction	-	62
Shipping from torrefaction plant to power plant	-	56
Combustion and Electricity Production	1,800	990
Avoided emissions	-2,300	-1,400
Total Pathway Emissions	**-370± 920**	**-240 ± 810**

Comparing emissions by pathway and process in terms of BDT, a mass rather than energy term, is useful for further investigating the effect of power plant efficiency. In terms of mass, harvest and processing, transport and avoided emissions for each pathway are similar (Table 13).

Table 13. Emissions by pathway and process in terms of BDT of raw timber harvest waste

Process	Raw biomass pathway (g CO_{2e} BDT^{-1})	Torrefied biomass pathway (g CO_2 e BDT^{-1})
Harvest and Processing in Forest	15,000	23,000
Transportation	31,000	44,000
Storage and Handling	120,000	-
Torrefaction	-	94,000
Shipping from torrefaction plant to power plant	-	83,000
Combustion and Electricity Production	1,600,000	1,500,000
Avoided pile and burn emissions	-2,100,000	-2,100,000
Total Pathway Emissions	**-330,000 ± 180,000**	**-360,000 ± 76,000**

Uncertainty Analysis

Estimated standard deviation of each result is listed in Table 14.

Table 14. Estimated Standard Deviation of Results

	Raw Biomass Pathway (g CO_2e BDT^{-1})	Torrefied Biomass Pathway (g CO_2e BDT^{-1})	Raw Biomass Pathway (g CO_2e kWh^{-1})	Torrefied Biomass Pathway (g CO_2e kWh^{-1})
estimated standard deviation of result	180,000	76,000	920	810

The uncertainties in this study are large in comparison to the final results because The sum of two large numbers, one positive and one negative, make the final result. The top three most influential inputs on estimated standard deviation are different for each pathway and each unit of study. For the raw biomass pathway, GWP of CH_4 and N_2O and the mass of woody fuel combusted at the raw biomass power plant are the most influential inputs on emissions per unit mass (g CO_2e BDT^{-1}). Variance in the mass of fuel combusted contributes 79% of total variance. Mass of woody fuel combusted at the raw power plant is not an input for the torrefied pathway. For the torrefied biomass pathway, GWP of CH_4 and N_2O and the ratio of pile and burn to in field decay alternatives are the top three most influential inputs on emissions per unit mass (g CO_2e BDT^{-1}). Variance in the GWP of N_2O contributes 48% of total variance. Energy density of raw and torrefied biomass contribute an overwhelming majority of the variance, 90% and 97%, of emissions per unit energy for the raw and torrefied biomass pathways, repsectively. Inputs that contributed at least 1% of total variance are shown for both pathways and units in Figures 20-23.

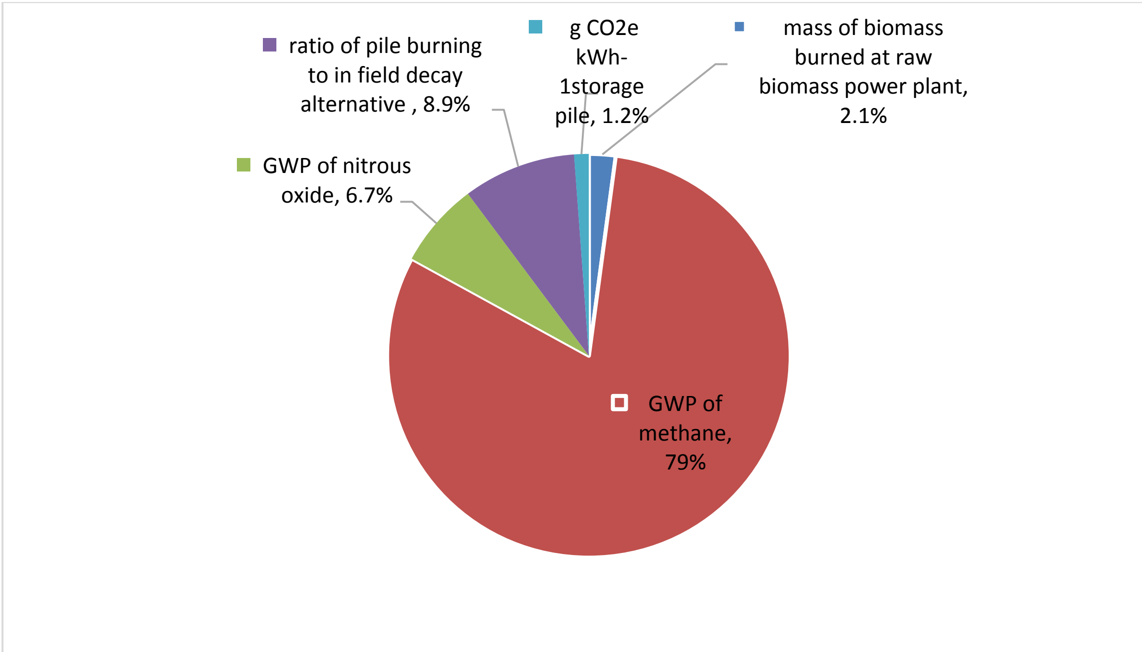

Figure 19. Fraction of uncertainty in emissions (g CO_2e BDT^{-1}) for raw biomass pathway by input value

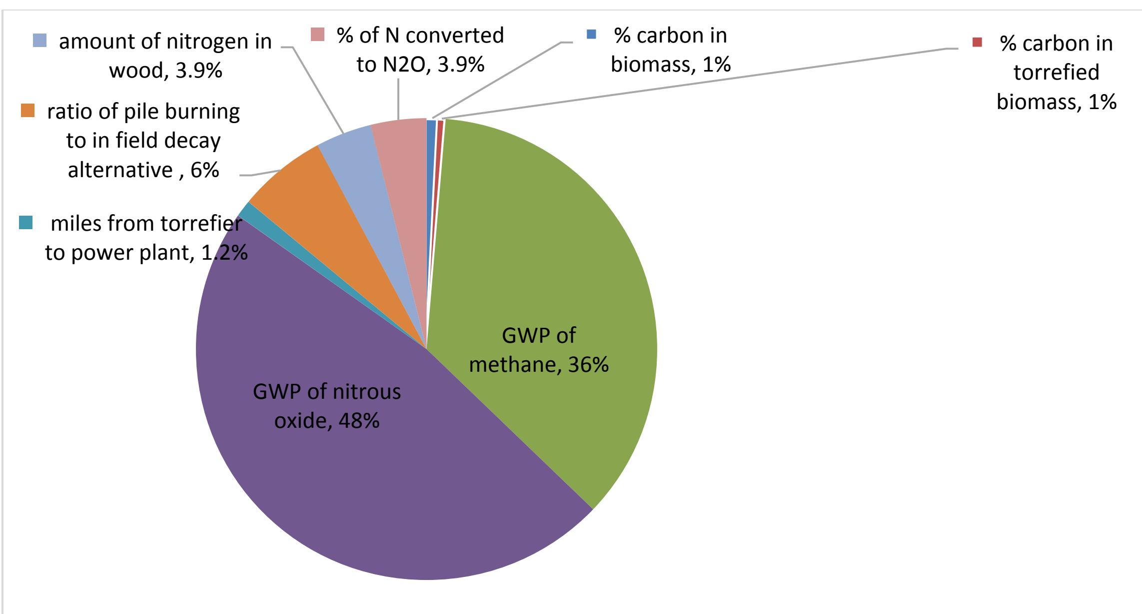

Figure 20. Fraction of uncertainty in emissions (g CO_2e BDT^{-1}) for torrefied biomass pathway by input value

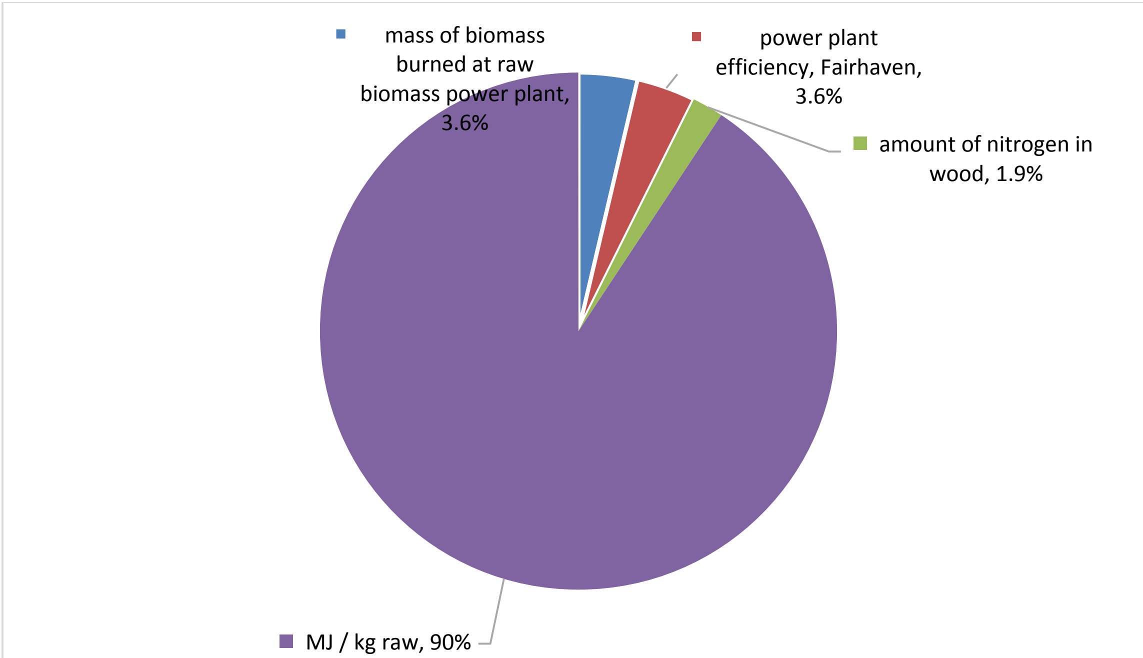

Figure 21. Fraction of uncertainty in emissions (g CO_2e kWh^{-1}) for raw biomass pathway by input value

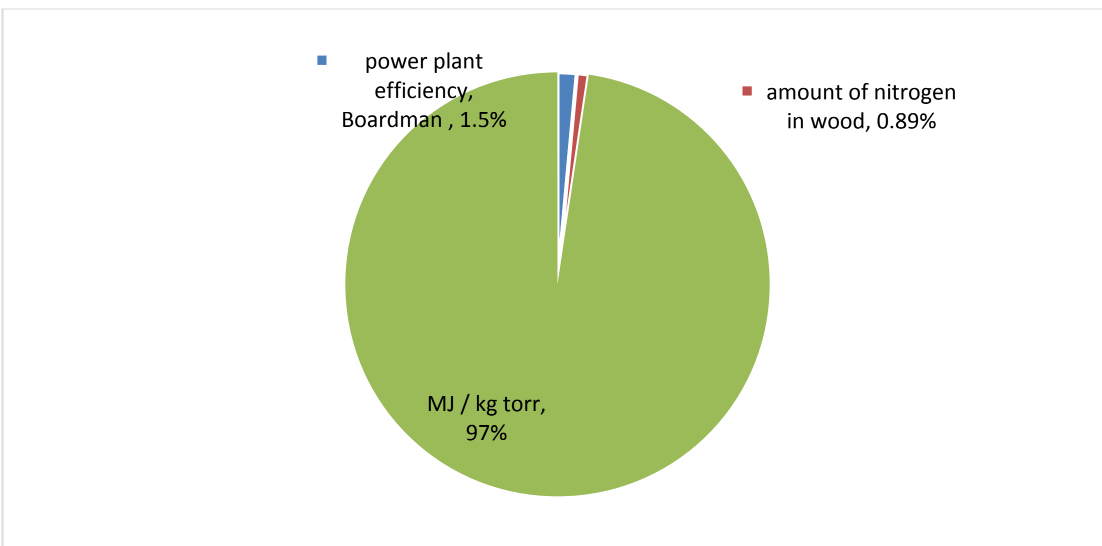

Figure 22. Fraction of uncertainty in emissions (g CO_2e kWh^{-1}) for raw biomass pathway by input value

Total estimated standard deviation was calculated if the variance of each of the three most influential inputs to each pathway were zero and if the variance of all of the inputs were zero. Alternative estimated standard deviation for each unit of study and pathway if each or all of the top three most influential inputs had zero variance are listed in tables 15 and 16.

Table 15. Estimated standard deviation of result if variance of unit = 0, g CO_2e BDT^{-1}

Raw Biomass Pathway		Torrefied Biomass Pathway	
Input with 0 uncertainty	New SD	Input with 0 uncertainty	New SD
GWP CH_4	170,000	GWP CH_4	61,000
mass of biomass burned at Fairhaven	80,000	ratio of pile burning to in field decay alternative	55,000
GWP N_2O	170,000	GWP N_2O	74,000
estimated standard deviation of result if variance of all inputs = 0	40,000	estimated standard deviation of result if variance of all inputs = 0	25,000

Table 16. Estimated standard deviation of result if variance of unit = 0, g CO_2e kWh^{-1}

Raw Biomass Pathway		Torrefied Biomass Pathway	
Input with 0 uncertainty	New SD	Input with 0 uncertainty	New SD
Mass of biomass burned at Fairhaven	900	Efficiency of Boardman power plant	800
Efficiency of Fairhaven power plant	900	Amount of nitrogen in wood	810
Energy density of raw wood	290	Energy density of torrefied wood	130
Estimated standard deviation of result if variance of all inputs = 0	150	Estimated standard deviation of result if variance of all inputs = 0	50

DISCUSSION

Approximately one third of electricity production capacity in Humboldt County composed of traditional raw biomass power plants. While the current biomass power pathway has advantages over the fossil fuel pathway, torrefaction offers further emissions reductions and additional environmental opportunities in the form of additional timber harvest waste utilization, greenhouse gas reduction and increased production of electricity.

Power Plant Scale

Increasing the size of a power plant may increase efficiency. It also increases capacity, the rate at which electricity can be produced and therefore the rate that fuel is required to run the plant. In this study, fuel usage drives total emissions in such a way that considering plant efficiency but also total fuel consumption is important in estimating potential emissions benefits for a pathway.

Efficiency Gains

When considering emissions per kWh electricity produced, increasing power plant efficiency decreases the magnitude of the less than zero emissions because less biomass is consumed and there are less avoided disposal emissions. Emissions per kWh for power plants in each of the pathways in this study and a plant with efficiency between those are calculated to demonstrate that increased efficiency will decrease saved emissions. Newer biomass power plants can achieve efficiencies as high as 28%. Table

17 lists emissions by process for the raw biomass pathway, a raw biomass pathway with a 28% efficient power plant rather than the DG Fairhaven plant, and the torrefied biomass pathway for comparison.

Table 17. Emissions Comparison with 28% efficient power plant (g CO_2equivalent kWh_{elec}^{-1})

Process	DG Fairhaven, first generation raw biomass power plant (20% efficient)	Current Generation Raw Biomass Power Plant (28% efficient)	Torrefied biomass pathway (35% efficient)
Harvest and Processing in Forest	33	22	17
Transportation to Biomass Power Plant	68	44	27
Storage and Handling at Power Plant	130	95	-
Torrefaction and Additional Shipping	-	-	57
Combustion and Electricity Production	3,200	2,300	1,100
Avoided Emissions from Alternative	4,200	3,000	1,600
Total Pathway Emissions	-370	-260	-240

<u>Capacity Gains</u>

Because the alternative biomass disposal methods release significant emissions, the more biomass that is consumed the lower the net emissions. This leads to the less than zero result when avoided alternative disposal emissions are subtracted from the emissions for each biomass power plant pathway considered. The more pile burning or in-field decay that a pathway can prevent, the more emissions benefits it will offer. Therefore the system that utilizes the most fuel will result in the largest total emissions reduction.

Considering emissions over a one year period for each pathway includes the effect of system size in overall emissions. Total emissions are driven by the amount of biomass fuel consumed. Boardman's nameplate generating capacity is 615 MW. An Oregon Department of Energy official is investigating limited conversion of the plant from coal to torrefied biomass and assumes Boardman will be run at 585 MW for four months per year. In comparison, Fairhaven has a capacity of 18 MW and net output of around 16 MW. The sum net capacity of raw biomass power plants in Humboldt County, those plants to which the fuel is close enough to deliver, is about 50 MW and they typically run 48 weeks per year.

If we assume those operating conditions, Boardman will produce 1.7 billion kWh and save 415 billion g CO_2e. That compares to only 43 billion g CO_2e saved with an the Fairhaven power plant, or 133 billion g CO_2e saved with all the raw biomass power plants in Humboldt County.

Due to the much larger scale in the torrefaction pathway, over a year the torrefaction pathway would save three times the emissions that all the raw biomass plants in Humboldt County could save. Switching from distributed, small scale biomass systems to torrefaction with large scale power plant systems is recommended when considering biomass energy options from a greenhouse gas perspective, despite additional emissions from torrefaction process and transport. Emissions from the raw biomass pathway have the potential to be even lower if storage methods are changed or efficiency is increased, but cannot be competitive with emissions from the torrefied biomass pathway over a year without large investments to increase capacity.

Removing Alternative Waste Credits

Adjusting the boundaries of the LCA to remove avoided emissions and the effect of negative contributions provides another perspective. Removing avoided emissions highlights the effect of power plant efficiency because it removes the benefit of using as much fuel as possible.

Biogenic Carbon Credits

GHG emissions formed from biogenic carbon can be considered less threatening as a contributor to climate change than those formed by fossil carbon because it is a part of the carbon cycle in which our modern ecosystem formed, rather than an addition to the atmosphere from carbon that has been stored for millions of years. To consider this, the following analysis considers all timber harvest waste CO_2 emissions, or biogenic emissions, released during combustion to be carbon neutral and also ignores avoided disposal emissions. If we do not include biogenic CO_2 as a GHG emission, total raw biomass emissions are 220,000 g CO_2e BDT^{-1} or 250 g CO_2e kWh^{-1} and total torrefied biomass emissions are just 150,000 g CO_2e BDT^{-1} or 100 g CO_2e kWh^{-1}, or 41% of raw biomass emissions.

It is important to note that emissions from both the raw biomass and torrefied biomass pathways are lower than the most efficient natural gas systems, approximately 290 g CO_2e kWh^{-1} (Moomaw et al., 2011) if biogenic carbon is not counted. This is consistent with mainstream pro-biomass emissions arguments in the policy sphere. This study demonstrates that boundaries and assumptions have a significant effect on the environmental impacts of both systems.

No Credits

To remove the complication of negative avoided emissions and the controversy of biogenic and fossil carbon, the following analysis compares the pathways without accounting for any credits. Not including any avoided emissions, emissions for the raw biomass pathway are 1,800,000 g CO_2 e BDT^{-1} and 1,700,000 g CO_2 e BDT^{-1} for the torrefied biomass pathway. Although there are additional non-biogenic emissions released in the torrefied biomass pathway that are not present in the raw biomass pathway, reduced emissions in the combustion process in the torrefied biomass pathway reduce total emissions below those of the raw biomass pathway. On a per kWh of electricity basis this gives 2,000 g CO_2 e kWh^{-1} for the raw biomass pathway and only 1,200 g CO_2 e kWh^{-1} for the torrefied biomass pathway. When considering only positive emissions, the torrefied biomass pathway emits only 66% of the climate forcing emissions as the raw biomass pathway does, for the same amount of energy.

Avoided Emissions from Alternative Waste Disposal

Pile-and-burn operations emit black carbon, a potent climate forcing agent with large uncertainty in values reported in the literature. In biomass applications, GHG analysis that include BC emissions should also consider brown carbon emissions, since brown carbon may have negative GHG forcing and thus offset some or all of the effects of black carbon. Because of the potential potency of black carbon emissions, and because pile-and-burn is the most likely waste disposal method (Wright & Vihnanek, 2010), it is important to thoroughly understand this process. Specific research on the black carbon emissions factor for pile-and-burn is ongoing and likely to be published in 2014. Potential effects are further discussed in the next section.

State regulation and insurance requirements restrict in-field decay to remote locations in California. It is included in this analysis as reference for operations outside of the Wildland-Urban Interface. In California, in-field decay is likely to contribute to wildfire risk. If the material is mostly decayed when the fire occurs or if it is consumed by a wildfire of medium intensity, emissions may not be greater than decay alone. However, if the fire burns slowly through moist material, also known as smoldering, or if the scattered waste increases the intensity of the fire in such a way that more live material is consumed than would be if the waste were not left in the forest, then emissions can be much higher. Wildfire models have been developing quickly in the past seven years, but still do not contain enough information about wildfire behavior to estimate the effect of added timber harvest waste fuel on wildfire and greenhouse gas emissions. Due to the complexity of these estimates, this study does not include any credit for avoided forest fire emissions. Avoided forest fire emissions would include the burning of live trees that either would not have burned, or which would not have burned as much without the extra fuel on the ground from timber harvest. This credit would increase the amount of avoided emissions and lower total emissions for the energy system.   Estimating the effect of timber harvest waste on wildfire emissions can and should be the subject of a large, detailed study.

Black Carbon

Black carbon is dark particulate matter that is propelled into the atmosphere when unmanaged, incomplete combustion of organic material occurs. Pile and burn is listed with black carbon effects and without, but organic carbon values are not included. Pile and burn emissions without the effect of black carbon are 160,000 g CO_2e BDT^{-1}. The effect of black carbon increases emissions from pile and burn activity to 2,000,000 g CO_2e BDT^{-1} when using an average rate of 0.56 g BC released per kg biomass burned and a 100-year GWP of 910 (Bond, 2013) (Table 18).

Table 18. Avoided emissions per BDT by management option and energy pathway

Alternative	Value (g CO_2e BDT^{-1})
Pile and Burn with BC	2,000,000
Pile and Burn without BC	1,600,000
In-field decay	3,500,000

Although alternative waste disposal emissions credits per BDT are the same for each pathway, the fact that the two pathways produce different quantities of electricity per kg of biomass means that the alternative waste disposal emissions credits are not the same when considering avoided emissions per unit energy produced. Table 1919 shows avoided emissions per kWh produced for each pathway. The torrefied biomass pathway avoids fewer emissions per kWh because it does not require as much fuel to make one unit of energy. However, the torrefied biomass pathway can produce 585 MW of power in this scenario, compared to 18 MW in the raw biomass pathway. The torrefied biomass pathway will actually utilize more biomass fuel than the raw biomass pathway, resulting in more avoided emissions. To further address this point, it would be necessary to identify additional specifics about the amount of waste biomass that can actually be moved to each type of power plant and possibly the economics of building several distributed raw biomass power plants. Such a study would require a thorough spatial and economic analysis and is an area for future work.

Table 19. Avoided emissions per unit energy by management option and energy pathway

	Raw Biomass (g CO_2e kWh^{-1})	Torrefied Biomass (g CO_2e kWh^{-1})
Pile and burn without black carbon	1,800	1,100
Pile and burn with black carbon	2,300	1,400
In field decay	3,900	2,300
Weighted avoided emission value with black carbon	2,700	1,600

The pile-and-burn alternative including the effect of black carbon is based on under-studied values and is not included in overall emissions results for either pathway. Further research on factor accuracy and scenario testing is recommended before implementing black carbon calculations. Such research is outside the scope of this study.

Transportation

Data acquired for this process included information about moisture content of the material during transport. Although emissions for transportation are approximately 30%

of total pathway emissions after discounting for avoided waste disposal emissions, and only 8% of production chain emissions, it is a process that managers can control. One option is to allow the waste biomass to remain at the timber harvest site during dry weather to reduce moisture content. This is not recommended during high risk wildfire seasons or in areas that have above average wildfire risk. Reducing transportation distance can occur though planning processes by developing smaller, efficient distributed power plants or conducting fuel pre-treatment at the waste harvest site. Portable pyrolysis and torrefaction machines are being developed for pre-treatment at the waste harvest site, but no pilot scale demonstration units are currently deployed.

Transport and Handling/Drayage

Emissions from storage and handling form the majority of emissions for the raw biomass pathway when combustion emissions and credit for avoided waste disposal emissions are not considered. This is due to the CH_4 created by large piles of biomass combined with the relatively high global warming potential of CH_4. Limited literature is available on the factors affecting pile emissions, leading to a large range of values. Factors that may change the value are ambient temperature, fuel moisture content, ambient humidity, pile age and pile size. Of those factors, Humboldt County likely has unusual values for temperature, moisture content and humidity. If actual emissions from storage are lower than the average used in this study, forest waste fueled small scale biomass may approach carbon neutral when only pile and burn is the avoided disposal emission. This part of the study has potential to be very important, and further local research is encouraged.

Storage emissions for torrefaction are negligible since the product is hydrophobic and biologically inert. This study assumes no storage of raw chips before the torrefaction process. Transportation to a remote power plant leads to higher transportation and drayage emissions than the raw biomass pathway. Both can be improved with use of more efficient vehicles, cleaner transportation fuels and use of electric rather than diesel drayage machinery in the torrefied biomass pathway.

Transmission Losses

Distributed generation power plants are often smaller and closer to the end user than centralized power plants. Transporting power from small local plants rather than more distant large power plants results in fewer transmission losses. Transmission losses are a source of power loss that can increase the amount of emissions per unit energy delivered for a pathway. Electrical current experiences resistance as it travels along a transmission or distribution line. Resistance causes some of the electrical power to become heat. The heat energy is not delivered to a customer, and represents an energy loss. Transmission losses range from 2-10% (Mann, Whitaker, & Driver, 2011). Including it in a pathway will increase emission per electrical energy proportional to the loss experienced. Including this effect may have increased emissions for the torrefied biomass pathway more than the raw biomass pathway because transmission loss is expected to be higher for the torrefied biomass pathway, which likely has longer transmission distances than the raw biomass pathway. Transmission losses are outside of the scope of this study.

CONCLUSION

Renewable energy systems are important for the development and continuance of human culture. Biomass as a renewable energy fuel can be an important part of renewable energy production and a source of ecosystem restoration by removing an overabundance of wood from under harvested forests and keeping fossil carbon out of the global atmosphere.

Efficient use of biomass fuel can reduce emissions associated with harvest, transport and combustion of biomass for energy. If we hope to reduce climate change effects, it is important that we reduce emissions as much as possible and it is particularly important to develop pathways that have potential to sequester carbon or avoid methane emissions.

Torrefied biomass pathway emissions in this study total -240 ± 810 g CO_2 equivalent kWh^{-1}, representing a savings of GHG emissions. The business-as-usual raw biomass pathway emissions total -370 ± 920 g CO_2 equivalent kWh^{-1}. Both the raw and torrefied biomass pathways produce less GHG emissions than the most efficient fossil fuel pathways.

The Boardman power plant represented in the torrefied biomass pathway has a capacity of 615 MW and a thermal efficiency of approximately 34.55%. This large scale requires a large supply of torrefied biomass fuel and the relatively high efficiency leads to the production of more valuable electricity per biomass consumed.

A torrefied biomass energy pathway that fuels a large scale power plant has the ability to achieve significantly larger net negative GHG emissions than raw biomass energy pathways even with additional transportation emissions and emission from biomass torrefaction. Research and development for improvement in the GHG emissions from biomass energy should focus on pretreatment options that allow the fuel to be used in larger, more efficient, existing power plants. Once existing infrastructure is optimally utilized, research and investment should focus on increasing the efficiency of smaller biomass fueled plants.

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APPENDIX A

Inputs to Model

Name of Input	Unit	Source	Type of measure of variability
harvest	$\frac{\mathrm{kg\ CO_2\ e}}{\mathrm{BDmT}}_{harvest}$	Sup-Han, H. L. (2012, June 3). Biomass Feedstock Supply: Cost and Life Cycle Analysis. Washington, D.C. Retrieved from http://www.corrim.org/presentations/video/2012/FPS_WADC/02_Han/flash/index.html	assumed SD = 25% of published range
transport out of forest to power plant	$\frac{\mathrm{kg\ CO_2\ e}}{\mathrm{BDmT}}_{transport, raw}$		assumed SD = 25% of published range
transport out of forest to torrefier	$\frac{\mathrm{kg\ CO_2\ e}}{\mathrm{BDmT}}_{transport, torr}$		assumed SD = 25% of published range
harvest multiplier	n/a	Han, H.-S. (2012b, October). Personal communitcation regarding timber harvest waste harvesting emissions for torrefaction systems. (A. Lottes, Interviewer)	assumed SD = 25% of range; range based on professional opinion
storage pile emissions	g CO2e $\mathrm{kWh}^{-1}_{storage\ pile}$	Production in Finland. Biomass and Bioenergy, 28(5), 435-443.	assumed SD = 25% of published range
biomass burned at Fairhaven	$BDT_{woody\ fuel,\ 2011}$	North Coast Unified Air Quality Management District. (2013, March). Process Data for Year 2011. CA, Humboldt County .	assumed SD = 10% of assumed value

Name of Input	Unit	Source	Type of measure of variability
% carbon in biomass	%	Phanphanich M, Mani S. Impact of torrefaction on the grindability and fuel characteristics of forest biomass. Bioresource Technology 2010;102:1246–53.	published SD
% carbon in torrefied biomass	%		published SD
Energy density torrefied logging slash	$\frac{MJ}{kg}$		published SD
Energy density raw logging slash	$\frac{MJ}{kg}$		published SD
volume of natural gas burned at Fairhaven	million $ft^3{}_{natural\ gas,\ Jan-Dec}$	North Coast Unified Air Quality Management District. (2013, March). Process Data for Year 2011. CA, Humboldt County .	assumed SD = 10% of assumed value
GWP of methane	$(\frac{CO_2e}{g})$	Forster, P. V. (2007). Changes in Atmospheric Constituents and in Radiative Forcing. In S. D. Solomon (Ed.), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.	published SD
GWP of Nitrous Oxide	$(\frac{CO_2e}{g})$		published SD
distance from torrefier to power plant	miles		assumed SD = 10% of assumed value

Name of Input	Unit	Source	Type of measure of variability
power plant efficiency, Boardman	%	Rodgers, D. T. (2002). Performance Improvements at the Boardman Coal Plant as a Result of Testing and Input/Loss Monitoring. International Joint Power Generation Conference. Phoenix, AZ: American Society of Mechanical Engineers.	assumed SD = 10% of assumed value
power plant efficiency, Fairhaven	%	Tingleff, B. (2006). *Fairhaven Power Plant.* Humboldt State University. n.p.	assumed SD = 10% of assumed value
ratio of pile burning to in field decay alternative	n/a	Tad Mason, R. (2014, April 9). CEO, TSS Consultants. (A. Lottes, Interviewer)	assumed SD = 25% of published range
amount of nitrogen in wood (ultimate analysis)	%	E. Kurkela: Formation and removal of biomass-derived contaminants in fluidized-bed gasification processes, VTT Publications 287, Espoo, Finland, VTT, 47 p. (1996).	assumed SD = 10% of assumed value
% of N converted to N_2O	%	-	published SD

Uncertainty by Input

	Uncertainty in raw biomass pathway (g CO_2e BDT^{-1})			Uncertainty in torrefied biomass pathway (g CO_2e BDT^{-1})			Uncertainty in raw biomass pathway (g CO_2e kWh^{-1})			Uncertainty in torrefied biomass pathway (g CO_2e kWh^{-1})		
Name of Input	**dy/dx**	**((dy / dx) * sx)^2**	**fraction of variance contributed by input**	**(dy / dx)**	**((dy / dx) * sx)^2**	**fraction of variance contributed by input**	**(dy / dx)**	**((dy / dx) * sx)^2**	**fraction of variance contributed by input**	**(dy / dx)**	**((dy / dx) * sx)^2**	**fraction of variance contributed by input**
harvest	907.19	1,851,752.34	0.0000%	1,360.79	4,166,442.78	0.07%	1.01	2.29	0.00%	0.91	1.86	0.00%
transport out of forest	907.19	6,223,945.38	0.020%	-	-	-	1.01	7.69	0.00%	-	-	-
transport out of forest	-	-	-	907.19	11,573,452.16	0.20%	-	-	-	0.61	5.17	0.00%

	Uncertainty in raw biomass pathway (g CO_2e BDT^{-1})			Uncertainty in torrefied biomass pathway (g CO_2e BDT^{-1})			Uncertainty in raw biomass pathway (g CO_2e kWh^{-1})			Uncertainty in torrefied biomass pathway (g CO_2e kWh^{-1})		
Name of Input	**dy/dx**	**((dy / dx) * sx)^2**	**fraction of variance contributed by input**	**(dy / dx)**	**((dy / dx) * sx)^2**	**fraction of variance contributed by input**	**(dy / dx)**	**((dy / dx) * sx)^2**	**fraction of variance contributed by input**	**(dy / dx)**	**((dy / dx) * sx)^2**	**fraction of variance contributed by input**
harvest multiplier	-	-	-	15,422.30	594,618.25	0.01%	-	-	-	10.31	0.27	0.00%
storage pile emissions	899.65	657,411,356.37	2.1%	-	-	-	1.00	812.25	0.10%	-	-	-
biomass burned at Fairhaven	(13.97)	25,134,990,468	79%	-	-	-	(0.02)	30,688.68	3.65%	-	-	-

	Uncertainty in raw biomass pathway (g CO_2e BDT^{-1})			Uncertainty in torrefied biomass pathway (g CO_2e BDT^{-1})			Uncertainty in raw biomass pathway (g CO_2e kWh^{-1})			Uncertainty in torrefied biomass pathway (g CO_2e kWh^{-1})		
Name of Input	**dy/dx**	**((dy / dx) * sx)^2**	**fraction of variance contributed by input**	**(dy / dx)**	**((dy / dx) * sx)^2**	**fraction of variance contributed by input**	**(dy / dx)**	**((dy / dx) * sx)^2**	**fraction of variance contributed by input**	**(dy / dx)**	**((dy / dx) * sx)^2**	**fraction of variance contributed by input**
% carbon in biomass	1,776,233.39	43,192,019.41	0.14%	1,839,557.99	46,326,598.64	0.79%	1,974.36	53.36	0.01%	1,229.83	20.71	0.00%
% carbon in torrefied biomass	-	-	-	(2,696,788.85)	30,019,276.65	0.51%	-	-	-	(1,802.93)	13.42	0.00%
volume of natural gas burned at Fairhaven	-	-	-	-	-	-	2.58	39.78	0.00%	-	-	-
GWP of methane	-	-	-	(3,842.20)	209051230302%	35.76%	(4.27)	2,582.89	0.31%	(2.57)	934.37	0.14%
GWP of Nitrous Oxide	2,322.89	32,198,248.85	0.10%	(506.75)	277753962063%	47.51%	(0.56)	3,431.73	0.41%	(0.34)	1,241.44	0.19%

	Uncertainty in raw biomass pathway (g CO_2e BDT^{-1})			Uncertainty in torrefied biomass pathway (g CO_2e BDT^{-1})			Uncertainty in raw biomass pathway (g CO_2e kWh^{-1})			Uncertainty in torrefied biomass pathway (g CO_2e kWh^{-1})		
Name of Input	**dy/dx**	**((dy / dx) * sx)^2**	**fraction of variance contributed by input**	**(dy / dx)**	**((dy / dx) * sx)^2**	**fraction of variance contributed by input**	**(dy / dx)**	**((dy / dx) * sx)^2**	**fraction of variance contributed by input**	**(dy / dx)**	**((dy / dx) * sx)^2**	**fraction of variance contributed by input**
distance from torrefier to power plant	(3,842.20)	2,090,512,303.02	6.6%	119.15	69,170,041.90	1.18%	-	-	-	0.08	30.92	0.00%
power plant efficiency, Boardman	(506.75)	2,777,539,620.64	8.8%	-	-	-	-	-	-	(2,838.43)	9,617.27	1.45%
power plant efficiency, Fairhaven	-	-	-	-	-	-	(9,220.10)	30,688.68	3.65%	-	-	-
ratio of pile burning to in field decay alternative	-	-	-	1,518,599.96	36033528796%	6.16%	1,687.99	445.20	0.05%	1,015.26	161.05	0.02%
amount of nitrogen in wood	-	-	-	(794,802.92)	22804791833%	3.90%	6,707.54	16,241.76	1.93%	4,034.31	5,875.52	0.89%

	Uncertainty in raw biomass pathway (g CO_2e BDT^{-1})			Uncertainty in torrefied biomass pathway (g CO_2e BDT^{-1})			Uncertainty in raw biomass pathway (g CO_2e kWh^{-1})			Uncertainty in torrefied biomass pathway (g CO_2e kWh^{-1})		
Name of Input	**dy/dx**	**((dy / dx) * sx)^2**	**fraction of variance contributed by input**	**(dy / dx)**	**((dy / dx) * sx)^2**	**fraction of variance contributed by input**	**(dy / dx)**	**((dy / dx) * sx)^2**	**fraction of variance contributed by input**	**(dy / dx)**	**((dy / dx) * sx)^2**	**fraction of variance contributed by input**
% of N converted to N_2O	1,858,905.97	539,926,781.68	1.7%	(12,584,379.60)	228,047,918.33	3.90%	(13,988.08)	281.76	0.03%	(8,413.27)	101.93	0.02%
MJ / kg torr	(794,802.92)	228,047,918.33	0.72%	-	-	-	-	-	-	(26,755.77)	644,283.92	97.28%
MJ / kg raw	(12,584,379.60)	228,047,918.33	0.72%	-	-	-	86,983.90	756,619.88	89.87%	-	-	-