Life Cycle Analysis of Renewable Fuel Standard Implementation for Thermal Pathways for Wood Pellets and Chips

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DISCLAIMER

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TERMS AND ABBREVIATIONS

ANL	Argonne National Laboratory
AR	As Received, weight includes moisture
ARB	California Air Resources Board
BD	Bone dry
Btu	British Thermal Unit
CA	California
CI	Carbon intensity
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
CWD	Coarse Woody Debris
EPA	U.S. Environmental Protection Agency
g CO_2e	Grams of carbon dioxide equivalent
GHG	Greenhouse Gas
GREET	The Greenhouse gas, Regulated Emissions, and Energy use in Transportation model
GWP	Global Warming Potential
HHV	Higher Heating Value
LCA	Life Cycle Analysis or Life Cycle Assessment
LCFS	Low Carbon Fuel Standard
LHV	Lower Heating Value
MC	Moisture Content
MJ	MegaJoule
MMBtu	Million Btu
N_2O	Nitrous oxide
NG	Natural gas
NO_x	Oxides of nitrogen
RIA	Regulatory Impact Analysis
RFS2	Revised Federal Renewable Fuels Standard
UWW	Urban Wood Waste
VOC	Volatile Organic Compound
WTT	Well-To-Tank
WTW	Well-To-Wheels

Executive Summary

The Biomass Thermal Energy Council (BTEC) and the United States Department of Agriculture (USDA) Forest Service are examining the possibility of adding biomass thermal conversion as a fuel pathway to Renewable Fuel Standard (RFS). This Study evaluates the usage of wood chips and wood pellets as substitutes for fossil heating oil and natural gas for the U.S.

Currently, the EPA RFS2 does not include a fuel pathway for woody biomass as a heating fuel; however, this Rule includes numerous pathways that use biomass, including forest residue, as feedstock to produce liquid biofuels which replace fossil fuels. Woody biomass itself is a source of energy if burned in wood stoves or boilers, and can reduce greenhouse gas (GHG) emissions if substituted for fossil fuels such as heating oil and natural gas. Since woody biomass is categorized under the RFS2 as a renewable source of energy when sustainable forest practices are employed, and since its use results in significantly lower GHG emissions compared to fossil fuels, the use of biomass as a heating fuel under the RFS2 would be consistent with the application of the Rule. Moreover, since heating oil from cellulosic biomass has a defined pathway under RFS (L, D7) (Table 2), and wood pellets and wood chips are substitutes for fossil heating oil, woody biomass replacing heating oil or natural gas should qualify for a pathway under the RFS2.

The GHG emissions of wood pellets and wood chips produced from various biomass waste sources including, forest residue, forest products mill waste, urban wood waste, fire hazard reduction/insect-killed standing dead trees, and pulp wood planted trees were estimated using Argonne National Laboratories' GREET1_2019 model[1] to determine upstream life cycle inputs. The treatment of sustainable forestry practices was also examined.

The range of life cycle GHG emissions were 0 to 7.0 g CO_2e/MJ for wood chips and 0 to 23.5 g CO_2e/MJ for wood pellets. In many situations the avoided emissions associated with burning waste biomass, avoided wildfire risk, or composting are greater than the life cycle emissions from pellet fuel use. These ranges depend on multiple factors, and are largely influenced by emissions associated with feedstock and product transportation, and in the case of wood pellets, energy to dry and pelletize feedstock. The emissions associated with wood pellet fuel represent approximately 3% of this fuel's energy value. The GHG emissions of natural gas and heating oil, two predominant fuels used for heating, were calculated using GREET1_2019, as well as the older version of GREET (_1.8c) that was employed in the RFS2 regulatory impact analysis. Biomass fuels result in a 65 to over 100% reduction in GHG emissions in comparison to these conventional heating fuels, which exceeds the targeted 60% GHG reduction requirement for cellulosic biofuels under the RFS2 (EPA, 2010). GHG reduction programs such as the RFS and the California LCFS express life cycle GHG emissions on a comparable basis, per megajoule (MJ) of energy, which is the functional unit of analysis. This functional unit, as described in Section 2.1, provides a consistent point of comparison for fuels used in comparable applications. In the case of wood pellet fuel, a MJ of energy from wood pellets provides the same heating effort as

[1] All GREET models are peer-reviewed and calculate life cycle emissions based on energy inputs.

a MJ of space-heating oil. The GHG emissions per tonne of wood pellet fuel are also calculated in this Study. However, due to differences in composition and moisture content comparison, using the energy basis is desirable.

Since wood pellets and wood chips meet the GHG reduction targets under the RFS, are often made from waste biomass sourced from forest product mills, forest residue, fire hazard reduction, and culling of insect-infested standing dead trees, and have a significantly lower CI compared to heating oil and natural gas, it is recommended that EPA reevaluate the RFS and consider creating a pathway for thermal conversion of biomass as heating energy. Bipartisan legislation, S.1614, introduced in 2019 by U.S. Senator Ron Wyden, D-Oregon proposed to allow the use of biomass waste from certain federal lands for making renewable fuels, indicating a record of congressional support for this recommendation.

1. Introduction

The Biomass Thermal Energy Council (BTEC) and the United States Department of Agriculture (USDA) Forest Service made an agreement to assess the implications of adding biomass thermal conversion as a fuel pathway to the Renewable Fuel Standard (RFS). The scope of the agreement is to promote usage of sustainably harvested wood chips and wood pellets as substitutes for fossil heating oil and natural gas.

Life Cycle Associates, LLC was contracted to complete a life cycle analysis of the greenhouse gas (GHG) emission impacts (this Study) associated with utilizing woody biomass (pellets and chips) for thermal energy applications. The alternative fuel use is heating oil or natural gas[2]. The major steps of the life cycle analysis implemented in this Study are:

1) Quantify life cycle GHG emissions associated with using woody biomass feedstocks currently eligible under the Renewable Fuel Standard (RFS) for use in thermal energy applications. Two pathways are considered: wood chipped directly from eligible feedstocks, and wood pellets produced from eligible feedstocks;

2) Quantify life cycle greenhouse gas emissions associated with using fossil fuels for thermal energy applications. Two fuels are considered: natural gas and heating/fuel oil;

3) Compare the life cycle greenhouse gas emissions for the woody biomass thermal applications with those of the fossil fuels considered; and

4) Compare the greenhouse gas benefits/impacts of these pathways for using eligible woody biomass feedstocks to those already approved for Renewable Identification Number (RIN) generation in the RFS.

1.1 Study Contents

This Study includes the following sections:

1. Introduction
2. Methods and Data
3. LCA Results
4. Sustainability Assessment
5. Conclusions

Section 1 provides an introduction to the woody biomass, GHG emissions, and LCA. The methods and data used in the Study are described in Section 2, which includes a description of upstream fuel cycle inputs, as well as the energy inputs for wood pellet and chip production and other data. Section 3 takes the data in Section 2 and estimates the environmental impacts of wood pellets and chips used in heating and compares them with those of heating oil and

[2] This Study calculates the GHG reductions based on different displaced fuels. While natural gas is not considered a baseline fuel under the RFS, the comparison is still of interest.

natural gas. Section 4 provides an overview of current sustainability programs in the US. Section 5 summarizes the conclusions of this Study.

1.2 Background

Recently, agriculture and forestry have emerged as potential mechanisms to meet U.S. energy demands and to address resource and climate change concerns through biomass-based energy. The potential benefits, such as increased domestic energy security, reduced GHG emissions, and increased support for rural and agricultural economic development, have focused the attention of industry, policymakers, and the environmental and scientific communities on the development of biomass-based energy. Since agriculture, forestry, and energy production all have significant impacts on resources and the environment, developing sustainable[3] production methods and consumption patterns in each of these sectors is critical.

1.3 Regulation for Biofuels and Biomaterials

Use of biofuels is on the rise in the United States. An important driver of the increased use of biofuels in the United States is the federal and state level regulations and tax incentives that have been passed over the past decades. The Federal Renewable Fuel Standard program was created to reduce greenhouse gas emissions and expand the renewable fuels sector while reducing reliance on fossil fuels.

1.4 Renewable Fuel Standard (Federal)

The Renewable Fuel Standard (RFS) was signed into law under the Energy Policy Act of 2005, and was expanded through the Energy Independence and Security Act of 2007 (EISA). The RFS program establishes requirements for volumes of renewable fuel that must be blended into on- and off-road petroleum fuels, with the dual goals of increasing energy independence and reducing climate change impacts. The RFS legislation falls under the Clean Air Act (CAA), and the Environmental Protection Agency (EPA) has the responsibility of setting annual renewable standard amounts. The RFS2, the current set of regulations enacted in 2007, requires the use of 36 billion gallons of renewable fuel annually by 2022 in the United States, 21 billion of which must be non-cornstarch ethanol biofuels such as cellulosic biofuel or biomass-based diesel. It required the use of 16.55 billion gallons of renewable fuel in 2013, 1.28 billion gallons of which had to be biomass-based diesel substitutes. However, production of cellulosic biofuels has so far been well below required levels (EIA, 2012¿ EPA, 2020).

Under the RFS2, gasoline and diesel fuel refiners and importers are required to purchase a certain quantity of renewable fuels annually. This is called their Renewable Volume Obligation. In order to verify that their obligations have been met, refiners must submit renewable fuel credits to the EPA. These tradable credits are called Renewable Identification Numbers (RINs), which are generated through the production of biofuels. One RIN corresponds to 1 gallon of ethanol equivalent. RINs are generated when renewable fuels can be shown to achieve a certain percentage reduction in life cycle greenhouse gas emissions as compared to a

[3] See Reijnders (2006) for a discussion of sustainable forestry management practices.

petroleum fuel baseline. The emissions are measured in terms of kilogram of emissions per MJ of fuel, commonly known as a fuel's carbon intensity (CI). The required reduction percentage varies by biofuel. Currently, this percentage is 20% for corn ethanol, 50% for advanced biofuels, and 60% for cellulosic biofuels. Table 1 shows the official RFS definitions for the renewable fuels covered in the regulation.

Each batch of renewable fuel is assigned a unique identifier that applies to a given calendar year and producer, and this is its renewable identification number (RIN). A batch can be any volume less than 1 million gallon-RINs. A RIN is assigned to a batch of fuel at the time when its ownership is being transferred (EPA, 2012).

Table 1. Product Definitions Under the RFS2

Products	RFS2 Definition
Advanced biofuel	a renewable fuel, other than ethanol derived from cornstarch, that has life cycle greenhouse gas emissions that are at least 50 percent less than baseline life cycle greenhouse gas emissions.
Biomass-based diesel	a renewable fuel[a] that has life cycle greenhouse gas emissions that are at least 50 percent less than baseline life cycle greenhouse gas emissions and meets all of the requirements of paragraph (1) of this definition: (i) Is a transportation fuel, transportation fuel additive, heating oil, or jet fuel. (ii) Meets the definition of either biodiesel or non-ester renewable diesel. (iii) Is registered as a motor vehicle fuel or fuel additive under 40 CFR part 79, if the fuel or fuel additive is intended for use in a motor vehicle.
Biodiesel	a mono-alkyl ester that meets ASTM D 6751 (incorporated by reference, *see* §80.1468).
Cellulosic biofuel	a renewable fuel derived from any cellulose, hemi-cellulose, or lignin that has life cycle greenhouse gas emissions that are at least 60 percent less than the baseline life cycle greenhouse gas emissions.
Cellulosic diesel	any renewable fuel which meets both the definitions of cellulosic biofuel and biomass-based diesel, as defined in this section 80.1401. Cellulosic diesel includes heating oil and jet fuel made from cellulosic feedstocks.
Renewable gasoline blendstock	a blendstock made from renewable biomass that is composed of only hydrocarbons and which meets the definition of gasoline blendstock in §80.2(s).
Non-ester renewable diesel (NERD)	A renewable fuel which is all of the following: (1) A fuel which can be used in an engine designed to operate on conventional diesel fuel, or be heating oil or jet fuel. (2) Not a mono-alkyl ester.

[a] Note that a renewable fuel that is co-processed with petroleum is not considered to be biomass-based diesel.

Table 2 describes several pathways for cellulosic biofuels (table excerpted from 40 CFR 80.146) made from waste feedstocks that would otherwise decompose and produce GHG or might be repurposed into lower-value products such as crop residue. As the RFS endorses converting vegetative waste streams into high-value heating oil in exchange for the highest-value RIN (D3), it logically follows that cellulosic feedstock such as slash, pre-commercial thinnings, and tree residue ought to be similarly endorsed under the RFS for the purpose of space-heating via cellulosic (wood) pellets. In the U.S., wood pellets and cord wood account for approximately 2 percent of the primary residential space heating fuel (Voegele, 2019). The Northern Forest Region of New England (Buchholz et al., 2017) as well as many other regions in the U.S. are well-situated to support switching to wood pellet heat and to utilize wood chips as heating fuel.

Table 2. RIN Pathways for Cellulosic Feedstocks

Path	Fuel Type	Feedstock	Production Process Requirements	D-Code
L	Cellulosic diesel, jet fuel and heating oil.	Cellulosic biomass from crop residue, slash, pre-commercial thinnings and tree residue, annual cover crops, switchgrass, miscanthus, energy cane *Arundo donax* and *Pennisetum purpureum;* cellulosic components of separated yard waste; cellulosic components of separated food waste; and cellulosic components of separated municipal solid waste (MSW).	Any	7 (cellulosic biofuel or biomass-based diesel)
M	Renewable gasoline and renewable gasoline blendstock.	Cellulosic biomass from crop residue, slash, pre-commercial thinnings and tree residue, annual cover crops; cellulosic components of separated yard waste; cellulosic components of separated food waste; and cellulosic components of separated MSW.	Must utilize natural gas, biogas, and/or biomass as the only process energy sources	3 (cellulosic biofuel)

Currently, the EPA RFS2 does not include a fuel pathway for biomass as process fuel or space-heating fuel, however, there are numerous pathways that use biomass, including forest residue, as feedstock to produce biofuels that replace fossil fuels. Included in these pathways are biomass to space-heating oil pathways. Biomass itself is a source of energy. When burned in wood stoves or boilers, or industrial boilers as a substitute for fossil fuels, it can reduce GHG emissions. Sustainable forest management practices enable the monitoring and verification of best harvesting practices[4] and assure that the net carbon balance of a forest is neutral, with

[4] Per Sustainable Forest Management Standards (Sustainable Forestry Initiative, 2019).

new growth making up for harvested material. In addition, the RFS has specific requirements for the treatment of slash and thinnings[5] with additional insight from Forest Service Publications (Power, 2013; Graham, 1999).

Since biomass-based fuel qualifies as a renewable feedstock under the RFS (Table 3), its use for heating would be consistent with RIN generation under the RFS2. Moreover, since heating oil from cellulosic biomass has a defined pathway under the RFS (L, D7) (Table 2), and wood pellets and wood chips are substitutes for fossil heating oil, their treatment as an additional fuel under pathway L would also follow.

Table 3. U.S. Renewable Fuel Volumes Produced under RFS2

	Fuel Volumes (Billion Gallons/year)				
	2019	2020	2020	2020	2021
Fuel Category	**Actual**	**Statutory**	**EPA Proposed**	**EPA Final**	**EPA Final**
Cellulosic biofuel	0.42	10.5	0.54	0.59	N/A
Biomass-based diesel	2.1	≥1.0	N/A	2.43	2.43
Advanced biofuel	4.92	15	5.04	5.09	N/A
Renewable fuel	19.92	30	20.04	20.09	N/A

1.5 Feedstock and Pelleting Options

Wood pellets and wood chips are two common forms of biomass fuels. Wood pellets are primarily used for residential and small commercial heating, while wood chips are used for commercial and institutional heating.

1.5.1 Pellet Mill Operations

Wood pellet mills are located throughout North America and are most abundant in the eastern third of the U.S. (Figure 1. Locations of wood pellet mills in North America. Wood pellets are made from various woody biomass sources within their regions, however, in order to comply with RFS and generate RINs, sources should correspond to one of the biomass types required under the RFS. The source of woody biomass feedstock can be classified into two main categories: wood residue and harvested trees. According to the RFS, in order to use harvested trees from tree plantations for bioenergy purpose, the bioenergy must be obtained from non-federal lands.

Wood pellets serve several markets including industrial and home heating for domestic use as well as export to Europe. Many pelleting operations serve local markets, however, those exporting to Europe are predominantly located in the southeastern U.S.

[5] https://www.epa.gov/fuels-registration-reporting-and-compliance-help/what-materials-non-federal-forestlands-meet

The function of pelleting is to take woody biomass feedstock and process it though a pelleting mill to produce pellets that meet moisture specifications. Pellet processing is powered by biomass fuel or natural gas. Mechanical work required to move or cut/chip source material at pellet plants is accomplished using electric power. This analysis considers both natural gas and biomass energy sources.

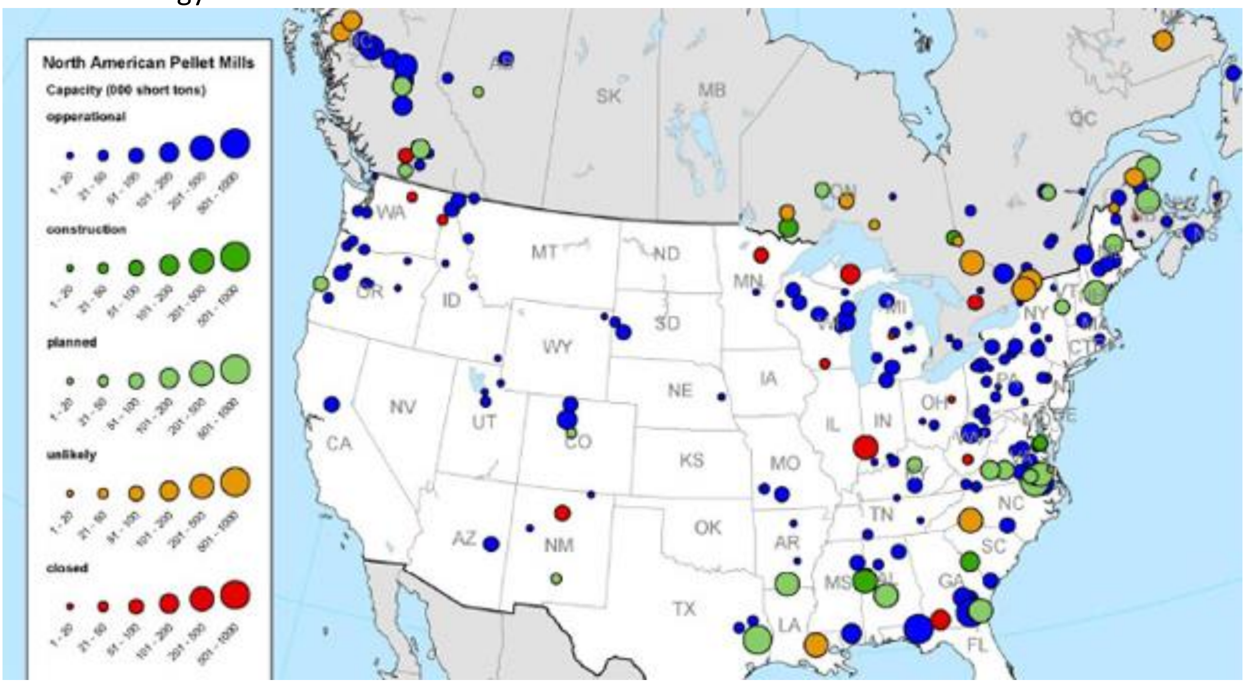

Figure 1. Locations of wood pellet mills in North America.
Source: Thran et al., 2017.

Woody Biomass Processing Description

This section provides a brief overview of the steps required to convert raw material woody biomass into woodchips and pellets.

<u>Feedstock collection/transportation/production</u>
Feedstock is sourced from a variety of woody biomass (for example, see Figure 2 for pellet sourcing). The amount of energy consumed to collect and transport woody biomass feedstock varies depending on a number of factors, including whether the source is from urban or forested areas, whether it is chipped in the field or transported to a chipping mill, the distance traveled from source location to either storage facility or chipping/pellet mill, and the type of fuel used to power the in-field chippers, transportation vehicles, as well as equipment in the chipping facilities, including forklifts and chipping machines. Emissions associated with renewable power sources will be lower than for conventional fossil-based fuels, such as diesel.

<u>Transport Distances</u>
Typically finished product wood chips and pellets require two phases of transport: distance travelled from the feedstock source to a chipping or pelleting plant, and distance travelled from the chipping or pelleting plant to market. In some cases, woody biomass feedstock may be chipped at the source location, for example, within a forest, and shipped directly to market.

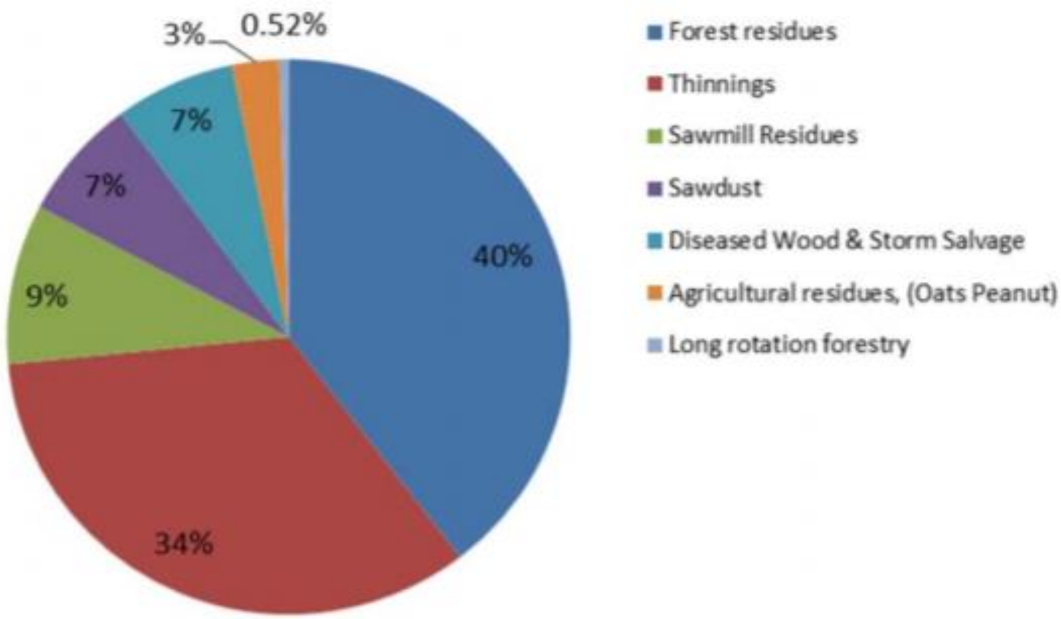

Figure 2. Wood pellet feedstock sourcing.
Source: Drax, 2014.

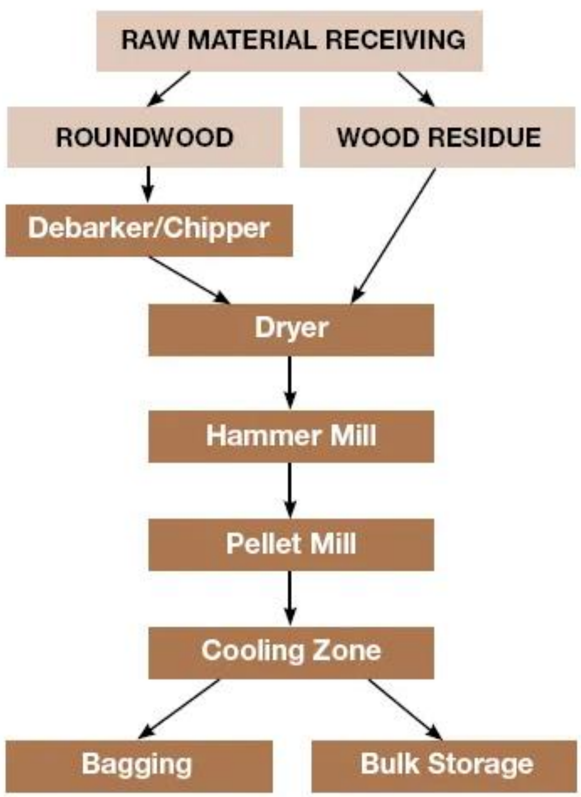

Figure 3. Biomass pelletization process.
Source: Zafar, 2020.

Pelletization Process

The biomass pelletization process consists of multiple steps including raw material preparation, pelletization and post-treatment. Feedstock preparation includes selecting suitable feedstock, filtration to remove unwanted materials, debarking and chipping, storing excess material, drying, cutting feedstock to appropriate size in a hammer mill, pelletizing, cooling, packaging, and shipping (Figure 3).

The moisture content (MC) in biomass feedstock can vary greatly. For example, freshly cut forest residue and urban tree removal/trimmings are typically about 50% moisture, ranging from 35-60% depending on vegetation type and time of year when harvesting occurs (Badger, 2002). Moisture content at time of transportation from source area is typically 45% (Argonne National Labs, 2019). Drier biomass feedstocks include insect-infested forest residue (10 – 16% MC (for lodgepole pine, Page et al., 2014)) and shipping pallets and donnage (12 - 15% MC (Donovan, 1994)). The maximum moisture content permissible for wood to be used as a fuel is in the range of 65 to 68 percent (Badger, 2002). Above this moisture content, the energy required to evaporate the moisture is greater than the energy in the dry matter of wood, and combustion cannot be sustained without a supply of external energy. Therefore, feedstock moisture content is an important operational parameter to factor into an LCA, as it needs to be reduced to 10 to 15% prior to pelletization. The wood pellet product moisture content is typically 6 to 10% (MA Division of Energy Resources, 2007; Pellet Fuels Institute, 2020).

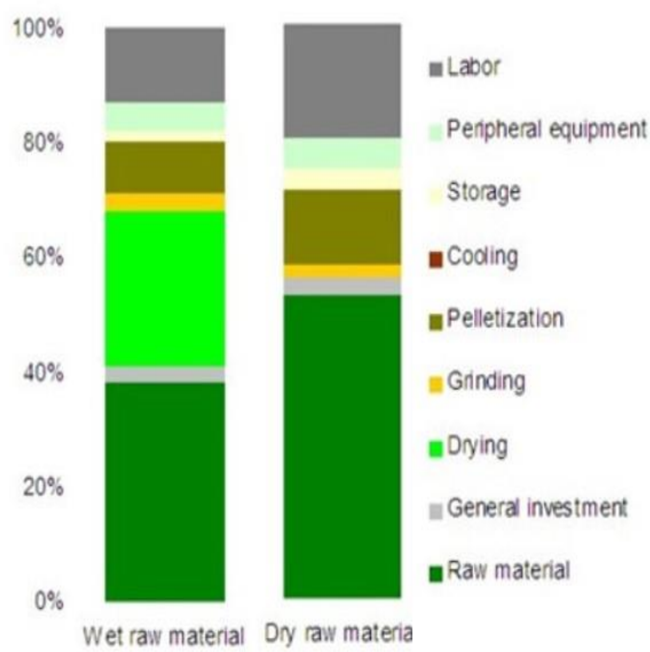

Figure 4. Pellet plant costs.
Source: Huang, 2013.

The feedstock drying process is energy intensive and can account for 70% of the total energy used in the pelletization process, and approximately 25% of the cost to run a pellet plant (Figure 4). Rotary drum dryers are the most common equipment used for this purpose. A typical industrial-level wood pellet mill has the capacity to run two rotary dryers (Biomass Magazine, 2020). Superheated steam dryers, flash dryers, spouted bed dryers and belt dryers can also be used. Drying increases the efficiency of biomass and produces virtually no smoke on combustion. Feedstock chipping comprises a considerable portion of a plant's processing energy. A typical industrial pellet plant is equipped with approximately two 1,200 horsepower (hp) chipper lines, and ten 400 hp hammer mills (Biomass Magazine, 2020).

1.5.2 Feedstock Categories

The source of woody biomass feedstock falls into two main categories: wood residue and harvested trees. According to the RFS, in order to use harvested trees from tree plantations for bioenergy purpose, the biomass must be obtained from non-federal lands (

Table **4** and Table 5).

Table 4. RFS-Compliant Biomass Feedstocks for Wood Pellets and Wood Chips

Feedstock	Source	Land Type per RFS	Current Fate
Clean sawdust from sawmill and planning mills	Planted trees[a]	Non-federal forestland	MDF/particleboard/ wood pellets/animal bedding/mulch/energy/ landfilling/pile decomposition
Clean sawdust from furniture industry	Planted trees[a]	Non-federal forestland	Pellets, mulch, landfill, energy
Salvaged material (insect/disease, ice storms, wind events), fire hazard reduction	Pre-commercial thinnings/ salvage harvest	Non-federal forestland	Firewood/hog fuel/ decomposing to CO_2/fire/on-site burning
Logging residue	Slash/pre-commercial thinnings/ planted trees	Non-federal forestland	On site burning/ hog fuel/slash piles/ firewood
Urban wood waste (UWW)[b]		Non-federal lands	Landfilling/composting/ mulch/pile decomposition
Hardwood and softwood pulpwood	Planted and naturally regenerated trees	Non-federal lands	Pulp and paper

[a]Trees and tree residue from actively managed tree plantations on non-federal land cleared at any time prior to December 19, 2007 (US EPA, 2010). These are primarily located in VA, GA, and SC.
[b]The portion of the wood waste stream that can include sawn lumber, pruned branches, stumps, and whole trees from street and park maintenance. The primary constituents of UWW are used lumber, trim, shipping pallets, trees, branches, and other wood debris from construction and demolition clearing and grubbing activities (CalRecycle, 2020). Construction debris is not a likely RFS feedstock since the source of the wood cannot be readily proven.

Table 5. Sources of Biomass under RFS

Category	Federal Land	Non-Federal Land
Slash/Residue from tree plantation	No	Yes
Natural Forests	TBD[a]	Yes
Harvest from plantations	No	Yes, if planted before 2007[b]

[a] The RFS rule explicitly prohibits the use of tree residue from tree plantations on federal land. The language in this exclusion does not prohibit the use of tree residue from natural forests such as those damaged by bark beetles. The use of these materials is subject to interpretation from the EPA.
[b] Definition of plantation varies by region.

While the prohibition (Figure 5) on removal of slash and residue from non-plantation (natural forest) federal lands is unclear, slash and wood residue generate GHG through decomposition, planned burns, and wildfires. As demonstrated in this Study, were EPA to interpret the collection of slash and tree residues from federal lands as allowable under the RFS, such residues could have alternative fates involving more favorable climate effects.

Cellulosic residues are defined under the RFS and include planted trees from actively managed tree plantations on non-federal land. The regulatory impact analysis EPA (2010) defines a tree plantation as a stand of no less than one acre composed primarily of hand-planted or machine-planted trees, however, trees originating from natural seeding by mature trees growing on a plantation can also be categorized as renewable biomass. Therefore, EPA's definition excludes materials from forests that are managed to allow natural tree regrowth in the Lake States, Northern New England, Central Appalachians, and other regions. Including such managed forests in the RFS would require revisions to its definition of renewable biomass. Converting planted tree residue to wood pellets, however, may generate stakeholder concern due to net carbon balance, or indirect land use conversion.

Several cellulosic biofuel producers are planning to use pre-commercial thinnings, tree residue from tree plantations or the cellulosic portions of yard waste as feedstock.[21] This material has many qualities that make it desirable as a cellulosic biofuel feedstock. It tends to be relatively inexpensive and is readily available in some regions of the United States. It is also available year round rather than seasonally, significantly reducing the need for large scale

[17] Solecki M, Dougherty A, Epstein B. Advanced Biofuel Market Report 2012: Meeting U.S. Fuel Standards. Environmental Entrepreneurs. September 6, 2012. Available Online <http://www.e2.org/ext/doc/E2AdvancedBiofuelMarketReport2012.pdf>.

[18] Nielsen, Peder Holk. "The Path to Commercialization of Cellulosic Ethanol – A Brighter Future." PowerPoint Presentation. Conference Call. February 22, 2012. Available Online <http://www.novozymes.com/en/investor/events-presentations/Documents/Cellic3_conf_call_220212.pdf>.

[19] Nielsen, Peder Holk. "The Path to Commercialization of Cellulosic Ethanol – A Brighter Future." PowerPoint Presentation. Conference Call. February 22, 2012.

[20] Department of Energy. Biomass Multi-Year Program Plan. April 2012. DOE/EE-0702. Available Online http://www1.eere.energy.gov/biomass/pdfs/mypp_april_2012.pdf

[21] Pre-commercial thinnings and tree residue from tree plantations must come from non-federal lands and meet the definition of a renewable biomass definition and be eligible to generate RINs.

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Figure 5. The RFS2 prohibits the use of forest residue from tree plantations on federal land. Source: EPA, 2013.

The RFS2 prohibition, as stated in Figure 5, does not exclude the use of thinnings and residues from non-tree-plantation federal lands. The use of non-federal lands, however, is the most straightforward source of forest material under the RFS.

1.6 Sustainable Biomass Production

The use of woody biomass for energy purposes has been increasing in recent decades, implying the importance of woody resources in sustainable economies, due to opportunities to replace consumption of fossil fuel with renewable resources and reduce GHG emissions (Quinteiro et al., 2019). While some argue that harvesting woody biomass for bioenergy production endangers biodiversity and reduces carbon stock in forests, several studies have shown that harvesting biomass from sustainably managed forest lands for bioenergy purposes not only reduces the GHG emission by reducing fossil energy usage but also increases the carbon stock in forests (Dale et al., 2017; Kim et al., 2018; IEA Bioenergy, 2018).

Dale et al. (2017) studied the impact of wood-based pellet production on forest conditions in the southeastern United States by using the U.S. Department of Agriculture Forest Service (USFS) Forest Inventory and Analysis (FIA) annual survey data for 2002–2014. In this study several fuelsheds including Chesapeake, Virginia, and Savannah, Georgia, were assessed. The results showed that production of wood-based pellets in the southeast US enhances GHG sequestration. In another study, Kim et al. (2018) evaluated the impact of growth in biomass demand on global forests and concluded that bioenergy expansion can drive forest resource investment at the intensive and extensive margins, resulting in a net increase in forest carbon stocks for most regions of the world, including the U.S.

1.7 Greenhouse Gases and Climate Change

1.7.1 The Greenhouse Effect

The greenhouse effect is a natural process that results in warmer temperatures on the surface of the earth than that which would occur without it. The effect is due to concentrations of certain gases in the atmosphere that trap heat as infrared radiation from the earth is re-radiated back to outer space. The greenhouse effect is essential to the survival of most life on earth, by keeping some of the sun’s warmth from reflecting back into space and sustaining temperature that make the Earth livable (Myhre et al., 2013).

1.7.2 Greenhouse Gases

The gases emitted globally that contribute to the greenhouse effect are known as greenhouse gases (or GHG). Primary GHG include water vapor, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and other trace gases. Natural sources of GHG include biological and geological sources such as plant and animal respiration, forest fires and volcanoes. However, industrial sources of GHG are the primary concern. The GHG of primary importance are CO_2, CH_4, and N_2O because they represent the majority of the GHG emitted by industry. Because CO_2 is the most abundant of these gases, GHG are usually quantified in terms of CO_2 equivalent (CO_2e), based on the relative longevity in the atmosphere and the related global warming potential (GWP).

1.7.3 Wildfire Risk

The increase in the size and acreage burned by wildfires, particularly in the Western US, is another risk of great concern associated with climate change (Congressional Research Service, 2019). Although wildfire is not a factor in the RFS, it effectively displaces wood combustion, and therefore is factored into this analysis as an alternative fate. Recent bark beetle infestations (Collins et al., 2012) and drought (Stephens et al., 2018) have also resulted in widespread tree mortality and caused concern regarding the associated increased fuel load. Climate change and disease have increased wildfire risk, creating a concern that wildfires are inevitable, and therefore, a pragmatic solution for harnessing this fuel load into predictable and useable fuel sources is a good idea. Wildfires result in much higher methane emissions than combustion in a stove and presumably less than decomposition (US EPA, 1995; CARB, 2000; CARB 2020a). Table 6 lists emission factors used in regulatory contexts (US EPA, 1995; Jenkins, 1996; Argonne National Laboratory, 2019), and otherwise reported (Akagi et al., 2011; Springsteen et al., 2011; Urbanski, 2013; Whittaker et al., 2016) illustrating that values for the GREET model used in this Study approximate the median of these reported ranges.

Table 6. Open Field Burning Emission Factors

		Emission Factors g/dry kg[c]		
Data Source	**System**	**CH_4**	**N_2O**	**CO_2**
Prichard et al., 2020[a]	Forest	4.294 (3.387 SD)	1.304 (0.839 SD)	1595.6 (166.2 SD)
Argonne National Laboratory, 2019	Sugarcane Bagasse	2.7	0.07	1660
California Air Resources Board, 2018a [b, c]	Rice Straw	1.17	0.02	1830
Urbanski, 2013[a,d]	SE Conifer, Prescribed	2.32 (1.09)	0.16 (0.21)	1703 (171)
	SW Conifer, Prescribed	3.15 (0.91)	0.16 (0.21)	1653 (34)
	NW Conifer, Prescribed	4.86 (1.37)	0.16 (0.21)	1598 (39)
	Western Shrubland Prescribed	3.69 (1.36)	0.25 (0.18)	1674 (38)
	NW Conifer Wildfire	7.32 (0.59)	0.16 (0.21)	1600 (19)
Springsteen et al., 2011[a]	Woody Biomass Open Piles	3	N/A	1833
Akagi et al., 2011[a]	Temperate Forest	3.92 (2.39)	0.16 (0.21)	1637 (71)
	Crop Residue	5.82 (3.56)	N/A	1585 (100)
U.S. EPA, 1995 (AP42)	Conifer Logging Slash, Piled	1.0 - 8.5[f]	N/A	NA
	Pile Burn	1.0 - 4.7[g]	N/A	NA

Values reported in brackets represent authors' estimates of observed parameter variation, unless otherwise specified as standard deviation (SD).
[a] These references report multiple emission factors from previously conducted studies.
[b] Based on Jenkins, 1996; unit is % of fuel dry mass.
[c] For this Study, 3 g CH_4/dry kg and 0.16 g N_2O/dry kg. This is a conservative value within the reported range presented here.
[d] N_2O values listed are from Akagi et al., 2011.
[e] A wide range of methane and nitrous dioxide have been attributed to avoided wildfire. For the purposes of this study, the methane estimates from Springsteen, 2011 and Akagi et al.,2011 provided an estimate of the GHG intensity (15,073 g CO_2e/MMBtu, HHV) with the AR4 GWP factors.
[f] Reported range reflects the following combustion categories: flaming, fire, and smoldering
[g] Range reflects various conifer species.
Whittaker et al., 2016a,c

The methane, nitrous oxide and carbon dioxide emission factors listed in Table 6 include the fraction of smoldering emissions in contrast to those produced from high temperature combustion in boilers.

Interest and investment in forest carbon offset projects has increased recently, however, the concordant spate of wildfires in the Western U.S., and doubling of the mean 100-year integrated risk of moderate and severe wildfire across U.S. ecosystems between 2000 and 2017 (Anderegg et al., 2020) has demonstrated the fragility of the permanence of forest carbon credits. this situation has led some to question the sufficiency of the buffer pool mechanism for programs such as the California Cap and Trade that constitutes an insurance program to hedge risk of fire (2-4%), drought, insect infestation, or other unintended events that may cause a loss of carbon from forest carbon projects (Anderegg et al., 2020; Herbert et al., 2020). In this context, forest wildfire risk management may both serve to increase the relative permanency of forest carbon projects and reduce GHG emissions if culled material is processed into alternative biomass fuels.

1.7.4 Biomass Composting

Many types of feedstock, such as urban wood waste, are processed by composting which generates methane emissions. The avoided methane emissions represented in this Study are calculated based on the Tier 1 Biomethane-derived from Anaerobic Digestion of Organic Waste Calculator provided for the California Low-Carbon Fuel Standard. This calculator estimates an overall emission factor for urban landscaping waste of 277 grams CO_2e per wet kg based on the range of values in Table 7. These values include calculations from the CARB tier1 calculator that examined emissions from landfilling of urban landscaping waste and wood waste as well as composting these materials. The emission factors in the CARB model are based on controlled landfills (Lee, 2017)[6] and CARB's assessment of composting emissions. However, residue piles from forest product mills are not actively managed and aerated. Therefore, the midpoint of the IPCC emission factors for composting provide the basis for this Study. Note that emissions from managed composting may be lower; however, this situation is not the likely treatment for many of the alternative fates. Some studies show higher emissions from unmanaged sawdust piles (Pier & Kelley) with 7 times higher GHG emissions than those assumed here.

[6] The tier1 1 OW calculator also shows 3315.4 g CH_4/wet tonne with 60% moisture wood. These emissions would correspond to 41,44 g CH_4/wet ton with 50% moisture (0.5 kg dry matter/0.4 kg dry matter); so, the 4,097 value in the tier1 OW model provided the basis for the calculations in this study.

Table 7. Composting and Landfilling Emission Factors for Wood Waste

Data Source	Material	Fate	Emission Factors g/AR kg CH_4	N_2O	CO_2e	Moisture (%)
California Air Resources Board, 2018b	Wood Waste[a]	Landfilling, 75% CH_4 capture	9.16	0.09	255.9	45%
	Wood Waste[a]	Managed Composting	0.82	0.09	47.3	45%
	Wood Waste[a]	64.1% Compositing, 35.9% landfilling	3.81	0.09	122.2	45%
	Wood Waste[a]	64.1% composting 35.9% Landfill 50% CH_4 Capture	13.2	0.09	357.1	45%
Pier & Kelley	Forest Products Mill Waste	Waste Piles	78	0	1,950	62.9±1.1
Amlinger et al., 2008	Green Waste[ab]	Managed Composting [cd]	0.604	0.178	68	50%
Pipatti et al.; IPCC 2006	Solid Waste[bc]	Range of Composting	10 (0.08 to 20)	0.6	429	60%
This Study	Woody Biomass	Unmanaged Composting	10	0.09	277	45%

[a] CH_4 and N_2O emissions calculated from CARB tier1 OW calculator. CO2e emissions exclude the net emissions from stored carbon in the landfill (which does not apply to composting). The values are based on wood waste only with 45% moisture (excluding yard waste).
[b]garden and park sources
[c]food, garden, and park
[d]Includes aeration via regular mechanical turning

1.7.5 Global Warming Potential

GWP is a measure of the potential of a gas to have an effect that could lead to climate change due to prolonged residence time in the atmosphere. The GWP can be used to quantify and communicate the relative and absolute contributions to climate change of emissions of different GHG (Myhre et al., 2013) and of emissions from countries or sources. Table 8 shows the GWP values from the Intergovernmental Panel on Climate Change (IPCC), an international body founded by the United Nations for the 100-year and 20-year time horizons from the two latest IPCC Assessment Reports, (AR4 and AR5), about the state of scientific, technical and socio-economic knowledge on climate change.

Table 8. Global Warming Potential of GHG Pollutants

IPCC Assessment	AR5[a]		AR4[b]	
GWP Time Horizon	100	20	100	20
CO_2	1	1	1	1
CH_4	30[a]	85	25[a]	72
N_2O	265	264	298	289

[a] IPCC Fifth Assessment Report 5 (AR5) published in 2014 includes a GWP of 28 for biogenic CH_4. Since the biogenic source would be emitted either as CO_2 or CH_4, the difference between the GWP of 30 and 28 represents in the indirect effects of methane decomposition to CO_2. (Myhre, 2013)
[b] Fourth IPCC Assessment report published in 2007

The United Nations Framework Convention on Climate Change uses the 100-year GWP. The United States primarily uses the 100-year GWP for reporting of GHG emissions. The State of Washington Greenhouse Gas Reporting program (Section 173-441 of the Washington Administrative Code) also uses the 100-year GWP. The 20-year GWP is sometimes used as an alternative to the 100-year GWP. The 20-year GWP prioritizes gases with shorter lifetimes, because it does not consider impacts that happen more than 20 years after the emissions occur. Because all GWPs are calculated relative to CO_2, emission calculations based on a 20-year GWP will be larger for gases with lifetimes shorter than that of CO_2, and smaller for gases with lifetimes longer than CO_2 (EPA). Values in this Study are based on the AR4 100-year GWP for consistency with International and United States reporting requirements.

In addition to more well-known GHG gases, including carbon dioxide, nitrous oxide, and methane, the GREET model is also configured with particulate matter and black carbon emissions on a life cycle basis. The AR4 values with zero GWP for black carbon were used in the 2010 EPA Regulatory Impact Analysis (RIA) for Air Pollution Regulations. This Study will examine the sensitivity of the GWP factors. Particulate emissions from wood combustion, including black carbon, are a concern for local air quality, as shown in Figure 6.

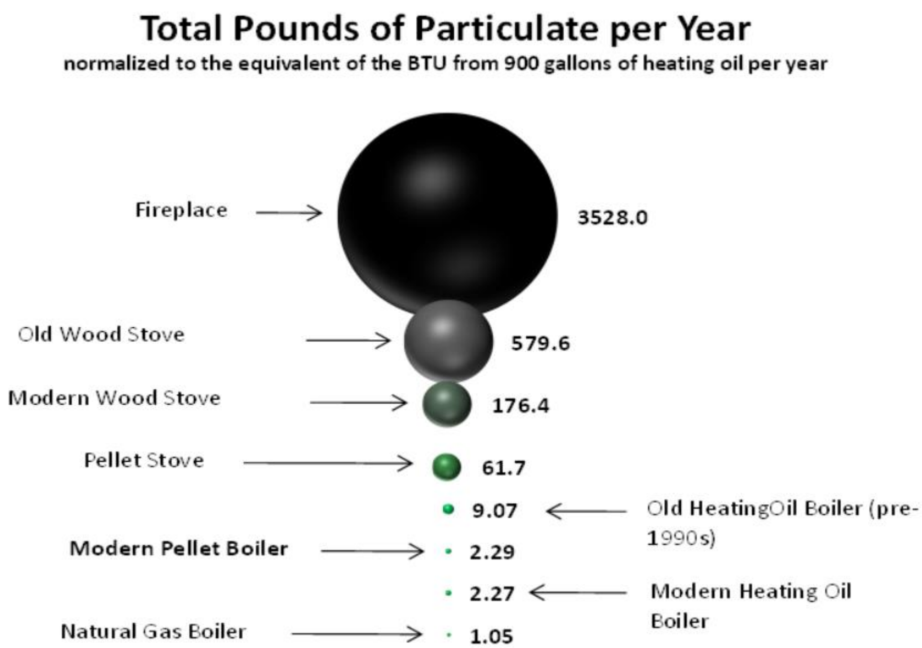

Figure 6. Particulate emissions associated with heating fuels.
Source: analysis by FutureMetrics using US EPA and OkoFEN data

Climate Change

The phenomena of natural and human-caused effects on the atmosphere that cause changes in long-term meteorological patterns due to global warming and other factors is generally referred to as climate change. The global climate changes continuously, as evidenced by repeated episodes of warming and cooling documented in the geologic record. But the rate of change has typically been incremental, with warming or cooling trends occurring over the course of thousands of years. The past 10,000 years have been marked by a period of incremental warming, as glaciers have steadily retreated across the globe. However, scientists have observed an unprecedented increase in the rate of warming over the past 150 years (IPCC, 2018). This recent warming has coincided with the Industrial Revolution, which resulted in widespread deforestation to accommodate development and agriculture along with increasing use of fossil fuels. These changes in land uses and consumption of fossil-based, carbon-laden fuels have resulted in the release of substantial quantities of greenhouse gases – to the extent that atmospheric concentrations have reached levels unprecedented in the modern geologic record.

The accumulation of GHG in the atmosphere affects the earth's temperature. While research has shown that the Earth's climate has natural warming and cooling cycles, the overwhelming preponderance of evidence indicates that emissions related to human activities have elevated the concentration of GHG in the atmosphere far beyond the level of naturally-occurring concentrations, and that this, in turn, is resulting in more heat being held within the atmosphere. The IPCC has concluded that it is "very likely" – representing a probability of greater than 90 percent – that human activities and fossil fuels, commonly referred to as anthropogenic emissions, explain most of the warming over the past 50 years (IPCC 2018).

The IPCC (2018) predicts that under current human GHG emission trends, the following results could be realized within the next 100 years:

- global temperature increases between 1.1 to 6.4 degrees Celsius;
- potential sea level rise between 18 to 59 centimeters or 7 to 22 inches
- reduction in snow cover and sea ice;
- potential for more intense and frequent heat waves, tropical cycles and heavy precipitation; and
- impacts to biodiversity, disease outbreaks, drinking water and food supplies.

GHG affect climate change in the same manner irrespective of the location of emissions, and the impacts on climate are felt globally. Emissions from combustion as a wood stove fuel, or as decomposition of forest material, have the same affects across locations. While general consensus is that anthropogenic GHG emissions are a cause of climate change, it is the cumulative effect of all emission sources in the atmosphere rather than individual sources that is the cause. It is not generally possible to equate a specific climate change response to a specific emissions source from an individual project.

1.8 Goal and Scope Definition

The goal of this Study is to quantify the GHG emissions associated with burning wood pellets and wood chips as alternatives for heating oil and natural gas used for heating purpose. This Study also compares the life cycle GHG emissions for the woody biomass thermal applications with those of the fossil fuels. As part of EPA's 2010 Regulatory Impact Analysis (RIA) of the Renewable Fuel Standard (RFS), it conducted a life cycle assessment (LCA) of the biofuels specified in RFS2 using GREET_1.8c. Therefore, GHG emissions of wood pellets and wood chips are examined using GREET1_2019 (the most recent version of GREET) as well as GREET_1.8c.

1.9 Life Cycle Assessment Background

Since the effect of GHG emissions occur over a long duration, the life cycle and total global emissions are considered the relevant metric[7]. Life Cycle Assessment (LCA) is a technique used to model the environmental impacts associated with the production of a good. LCA models can assess environmental impacts over a range of categories, including GHG emissions as well as others. This is done by taking a full inventory of all the inputs and outputs involved in a product's life cycle. This Study takes a partial LCA approach by identifying GHG emissions associated with burning woody biomass, heating oil and natural gas for heating purposes. Upstream emission are calculated on a life cycle basis to enable the calculation of cradle to grave emissions in combination with direct or end-use emissions, which is consistent with the ISO 14040 methodology (ISO, 2006). The upstream life cycle emissions correspond to the Scope

[7] For example, consider electric cars with zero emissions during driving. The life cycle emissions including upstream emissions provide the relevant basis for comparison with other transportation options.

2 and Scope 3 emissions that are part of statewide inventory reporting (World Resources Institute, 2004).

Most LCA tools are spreadsheet or database models that use life cycle inventory ("LCI") data to calculate the environmental impacts associated with the material flows and inputs. Additionally, LCA has been used to support regulatory and/or legislative initiatives for renewable targets, such as targets for GHG emission reductions. This Study follows the process for Life Cycle Assessment defined by international standards shown in Figure 7. Life cycle emissions are generally considered to cover the full life cycle from resource extraction to end use. Life cycle assessments are generally limited to the manufacturing, construction and operation periods. An LCA includes the upstream emissions for inputs to a process. In most cases, upstream emissions occur in the production of upstream inputs. For example, producing the natural gas used for generation of electric power on site requires upstream energy inputs. Upstream energy inputs like these are accounted for in this Study.

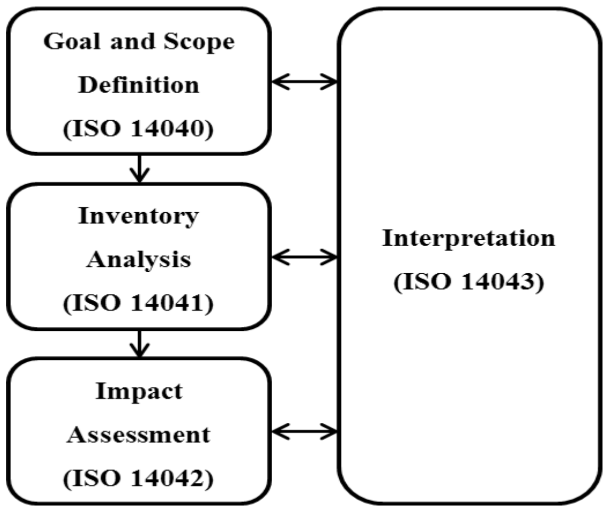

Figure 7. Process Framework for Life Cycle Assessment. Source: (ISO, 2006)

The boundaries of life cycle emissions typically expand beyond the regional scope of a region such as the Northeast. The production of feedstocks and materials can occur outside the region even if facility operations occur in the state. Global life cycle emissions represent an appropriate metric for GHG emissions because of the long-lasting effect of the pollutants.

Determining life cycle emissions for all of the project-related inputs requires an iterative analysis of these components. Several LCA models have been developed to perform these calculations for fuels and materials as shown in

Table 9. All the models include life cycle data for various products, including natural gas and diesel fuel used in wood pellet and wood chip processing.

Table 9. Life Cycle Models and Databases Used for Wood Pellet Production

Year	Organization	Location of Use	Scope of Products	Model/ Database	Citation
2009	NESCCAF	USA	Residential Heating	GREET 1.8b	(Unnasch and Riffel, 2009)
2015	University College Dublin	Ireland	Residential Heating	SimaPro/ Ecoinvent	(Murphy et al., 2015)
2017	USDA	USA	Residential Heating	SimaPro/ USLCI	(Brackley et al., 2017)
2019	CESAM	Portugal	Residential Heating	Ecoinvent	(Quinteiro et al., 2019)

1.9.1 Upstream Life Cycle Data

In this Study, the GREET_2019 model was used to calculate the GHG emissions of wood pellets and wood chips as well as heating oil and natural gas. GREET is a publicly available, peer-reviewed Life Cycle Analysis (LCA) model that provides transparency to calculations. GREET was developed by Argonne National Laboratory with support from several programs in the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy, including the Bioenergy Technologies Office, Vehicle Technologies Office, and Fuel Cell Technologies Office. GREET is structured to systematically examine the well-to-wheels (WTW) energy use and emissions associated with a wide range of vehicle technologies and feedstock sources for producing alternative fuels, and can be used to estimate emissions associated with non-transportation fuels, such as wood pellets and wood chips, because the emissions associated with woody feedstocks apply across different types of fuels derived from them. The number of woody biomass feedstocks included in GREET models continues to expand over time. The GREET models themselves do not provide specifics of harvesting practices and other environmental practices associated with woody feedstocks, however, the upstream inputs and associated emissions in GREET are based on the assumption that biogenic CO_2 emissions emitted through biofuel combustion are offset by atmospheric carbon uptake during biomass growth, thereby assuming carbon neutrality of biogenic carbon. The GREET model documents emissions associated with forest residue removal, urban demolition wood, and energy-crop harvested trees. The GREET model is also used in the Renewable Fuel Standard (RFS2) Final Rule to estimate the GHG emissions of various biofuels. The GREET model provides the basis for upstream life cycle inventory (LCI) data for this Study.

2. METHODS AND DATA

This Study examines the GHG emissions for wood pellets and wood chips used in heating. The emissions from wood pellets and chips are compared to the GHG emissions from petroleum heating oil and natural gas. This section describes the system boundary for the analysis, the approach for calculating life cycle emissions, scenarios considered in the Study, and data sources. The discussion of the approach describes a summary of the activity in each step of the life cycle and calculation methods. Since many of the data sources are common among life cycle stages, the discussion is grouped according to the type of emissions that occur.

2.1 System Boundary

The analysis of GHG emissions for woody biomass includes emissions associated with feedstock collection/production and transportation, the production of process fuels, the delivery of the product to the market, and burning the fuels. It is performed on a life cycle basis. Upstream emissions include natural gas[8] feedstock extraction, processing and transmission as well as imported grid power. Downstream emissions consist of transport and distribution emissions from delivering wood pellets and chips to the market. The system boundary for wood pellets and wood chips is shown in Figure 8. There are five reference systems in the system boundary which implies the fate of each biomass source.

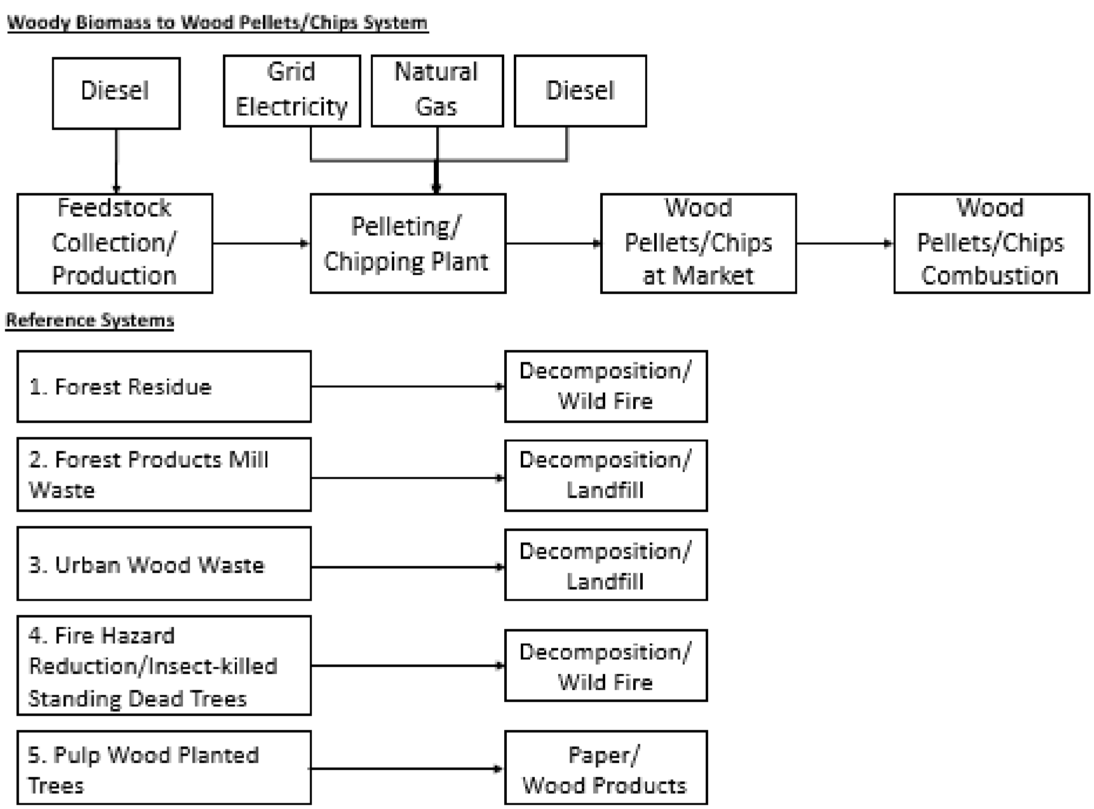

Figure 8. System boundary diagram for Life Cycle Assessment.

[8] Direct-fired rotary drum dryers are prevalent U.S. drying system commonly using natural gas or woody biomass.

Functional Unit

The functional unit for the Study is 1 MJ of useful thermal energy (e.g., lower heating value, LHV) delivered for heating. The LHV accounts for heat losses associated with moisture in the biomass fuels. The life cycle emissions are analyzed over this functional unit. The emissions are also reported per ton of wood pellets/chips delivered to the market. The higher heating value (HHV) represents the heat available without the heat of vaporization of water produced from combustion. Some condensing heat exchangers can take advantage of the higher heating value. However, the RFS2[9] and LCFS use the LHV as the functional unit for GHG analysis. This heating value is appropriate for transportation fuels since engines generally cannot take advantage of the higher heating value of a fuel. In principle, fuels with more hydrogen and a higher HHV/LHV spread can produce more productive heat with a condensing heat exchanger. However, the effect is equipment specific. Therefore, for the purposes of this study, the LHV is the functional unit with the moisture of the biomass fuel taken into account.

Life Cycle Criteria

This Study determines the GHG emissions from fuel combustion[10] and fugitive emissions including CO_2, CH_4, and N_2O. Other GHG emission sources include unburned and fugitive methane and nitrous oxide (N_2O) from fuel combustion. As discussed in Section 1.7.2, CO_2 emissions correspond to fully oxidized fuel per the reporting method used in the RIA. GHG emissions include numerous components, some of which cause local pollution, for example black carbon, characterized as either coarse particulate matter ($PM_{10\text{-}2.5}$) or fine ($PM_{2.5}$). PM standards are established by US EPA (2012). While black carbon is calculated in the GREET modeling system, it is not a criterion under the RFS. Therefore, even though black carbon has GHG impacts, these are not counted in the RFS or other fuel programs, and are not examined in this Study.

2.1.2 Life Cycle Analysis

Life cycle emissions generally consist of direct and upstream life cycle emissions. Argonne National Laboratory's (2019) GREET model has been extensively used for quantification of life cycle emissions associated with fuels and other products. This Study uses the GREET framework to calculate emission rates from cradle to gate (ANL, 2019)[11].

Each step in the life cycle analysis includes direct and upstream life cycle emission rates ($\mathbf{E}_u$). Upstream life cycle emission rates include a variety of energy inputs and emissions, including natural gas, petroleum fuels, and electric power. Emission rates ($\mathbf{E}_i$) for each step in the life cycle are calculated from the specific energy (S_i), direct emission factor ($\mathbf{EF}_i$), and upstream emission rates for the step such that:

[9] The RFS calculates GHG emission for 1 million Btu of fuel (MMBtu) on an LHV basis. The metric of one mega-Joule is more commonly used today (1 J = 1055.055 Btu). Fuels that generate credits under the RFS are counted as renewable identification numbers (RINs), with 1 RIN being equivalent to 77,000 Btu of denatured ethanol.

[10] Combustion sources include boilers, fired heaters, power generation equipment and engines for transport.

[11] Cradle to gate emissions are also referred to as well to tank or upstream life cycle. The term upstream life cycle is used in this Study. Fuel life cycle emissions are referred to as cradle to grave or well to wheels.

$$\mathbf{E}_i = S_i \times (\mathbf{EF}_i + \mathbf{E}_{ui}) \quad (1)$$

Where:

$\mathbf{E}_i$ = Life Cycle Emission rate for Step i

$\mathbf{EF}_i$ = Emission Factor for Step I, for each type of equipment and fuel

S_i = Specific Energy for Step i

$\mathbf{E}_{ui}$ = Upstream life cycle emission rate for fuel i

Typically, GHG calculations are tracked on a specific energy basis[12]. For example, the term S_i for natural gas use is represented in MMBtu/ton of woody biomass in this Study. The emission factor (**EF**) depends upon the carbon content of fuel as well as CH_4 and N_2O emissions for the type of equipment. For electric power, the term EF is zero but upstream emissions are calculated using the same principles. The terms **EF** and **E** represent a data array that includes CO_2, CH_4 and N_2O emissions.

Upstream life cycle emission rate ($\mathbf{E}_u$) depends on the energy inputs and emissions for each fuel or material, and are calculated in the same manner as shown in Equation 1. Upstream emissions for this Study are calculated using the GREET model with inputs described in Section 2.3.

Carbon Balance

<u>Carbon Balance in GREET</u>

The carbon balance for biofuels is well documented with the treatment of biofuels under the RFS2 and LCFS. Short cycle carbon is absorbed from the atmosphere by living plant biomass and converted to cellulose that is used to produce biofuels, which are combusted, releasing CO_2 to the atmosphere. The net carbon flux is accounted for through the analysis of indirect land use conversion (ILUC) associated with harvested biomass. Therefore, both ethanol or heating oil derived from cellulosic biomass conversion, are treated as carbon neutral fuels.

In contrast, fossil fuel-based products utilize carbon that has been stored underground for millions of years (Figure 9). With the accounting system in GREET, fermentation emissions are calculated as net zero. The emissions from fuel combustion for most liquid fuels, including heating oil, are comparable at 72 g CO_2/MJ; however, the short cycle carbon is not included in the WTW reporting for the RFS2, LCFS, and the Renewable Energy Directive (RED). The carbon factor for natural gas (55 g CO_2/MJ), is lower than for heating oil, and for wood, it ranges from 90 to 95 g CO_2/MJ.

This life cycle analysis assumes that emissions associated with conversion of woody biomass to wood pellets and wood chips are on a net carbon neutral basis, reflecting that biogenic CO_2 is removed from the atmosphere with no storage effect. While biogenic uptake and reforestation,

[12] GREET inputs are typically in Btu/MMBtu (million Btu). However, the calculations are the same for a functional unit of one tonne of methanol with the appropriate unit conversions. The nomenclature here assumes appropriate unit conversions.

as well as changes in forest growth do occur, they are not explicitly included in this model, and are treated as net zero, consistent with the RFS.

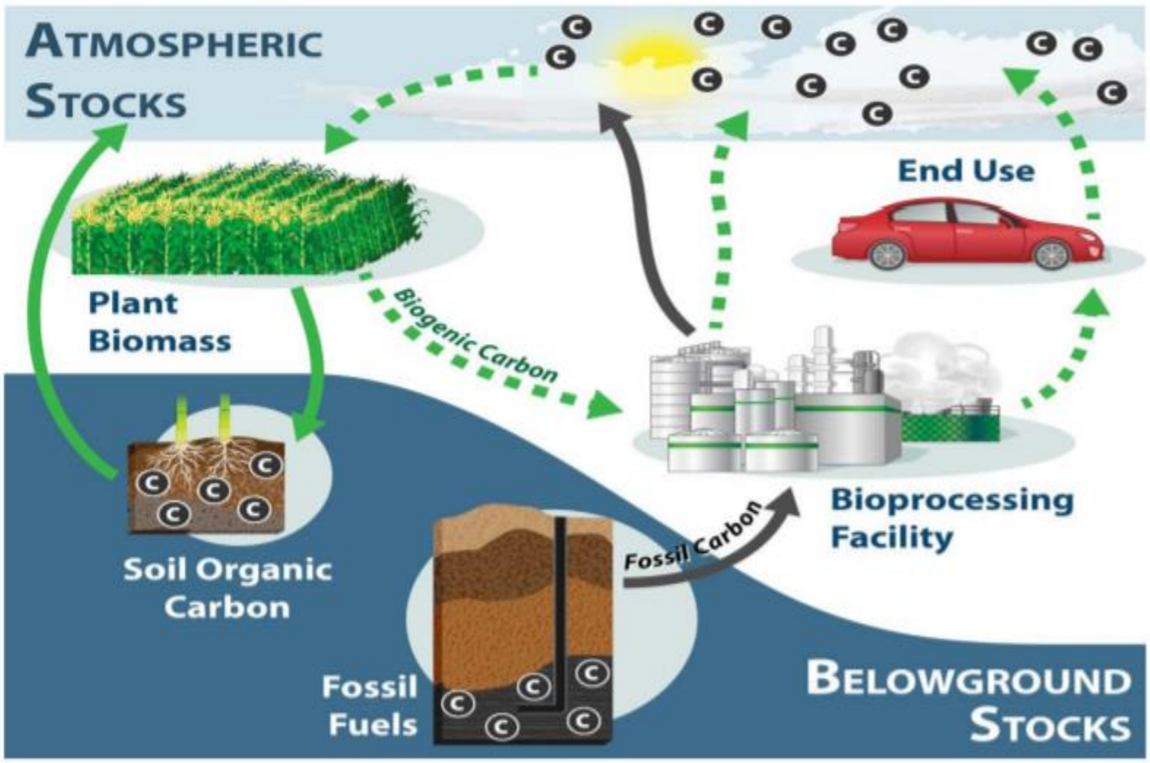

Figure 9. Carbon Balance for biofuels and fossil fuels.
Source: Kim, 2013.

Carbon Storage Policies and Voluntary Sustainability Certifications

Policies encouraging the development of forest biomass energy generally consider biomass to be a carbon neutral energy source by accounting for the carbon emissions as part of a natural cycle, wherein they are captured over time through forest growth. The following subsection of this Study briefly describes how different carbon accounting methods may challenge this assumption. The net carbon balance for forestry systems is consistent with the net increase in forest biomass shown in Figure 10.

Forest certification is a voluntary market-based approach designed to recognize sustainable forest management by labeling forest and the wood products from those forests as being managed under certified standards. Various certification programs exist including those managed through the Sustainable Forest Initiative (SFI), the Forest Stewardship Council (FSC), the Roundtable on Sustainable Biofuels (RSB-F), the Roundtable on Sustainable Biomaterials (RSB-M), and the Program for the Endorsement of Forest Certification (PEFC). SFI standards are commonly used in the U.S and include measures to protect water quality, biodiversity, wildlife habitat, species at risk and forests with exceptional conservation value. The standard is for any organization in the United States or Canada that owns or manages forests. FSC principles and criteria provide a foundation for forest management standards globally, and include the US Forest Management Standard (V1.0) for forest management certification in the U.S. The RSB-F has recognized FSC forest management standards and certifications since 2013, after concluding that principles and criteria from FSC and RSB standards were aligned. In most cases, therefore, FSC-certified forests are considered to be in compliance with RSB-F's principles and criteria. In a comparison of forest certification programs, Garzon et al. (2020) found the FSC to be more detailed and prescriptive in nearly all aspects considered for forest certification.

Forest management certifications are intended to provide environmental, social, and economic benefits to forest landowners who choose to become certified. Sustainable certification, however, is not required by the RFS, and does not influence RFS pathways; a sustainable certification does not assure compliance with the RFS, and vice versa.

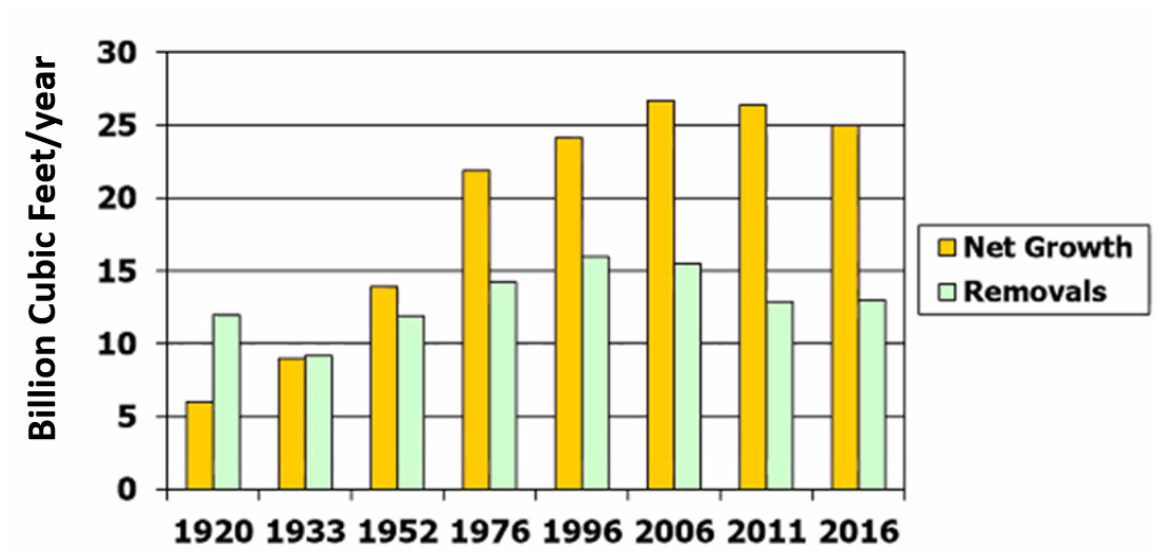

Figure 10. U.S. Timber Growth and Removals.
Source: USDA Forest Service ,2016.

Alternative Methods of Carbon Accounting

Comparisons of GHG from different fuel sources can vary depending on the bioenergy combustion technology and fossil fuel technology employed, the biophysical and forest management characteristics of the forests from which biomass is harvested, and the starting point of the analysis. Forest carbon accounting results that are based on a static stand-level versus a dynamic forest landscape management approach, will greatly differ. As illustrated below, a single stand-level analysis will reflect a carbon debt-then-dividend that occurs over a longer timeframe than a dynamic carbon balance for a managed forest landscape.

Using a stand-level approach, Walker et al. (2013)[13] showed that during the initial period of forest growth, approximately 32 years, GHG emissions from forests exceeded those of energy-equivalent fossil fuel combustion, accumulating carbon debt in these forest systems. Thereafter, forest GHG decreased incrementally in relation to fossil fuel combustion, yielding carbon dividends in the respective forest systems (Figure 11). They also found that replacing

[13] Also commonly referred to as the Manomet Study.

fossil fuels in thermal or combined heat and power (CHP) applications typically has lower initial carbon debts than do utility-scale biomass electric plants because the thermal and CHP technologies achieve greater relative efficiency in converting biomass to useable energy. Subsequently, the time needed to pay off the carbon debt and begin accruing the benefits of biomass energy are shorter for thermal and CHP technologies when the same forest management approaches are used in harvesting wood.

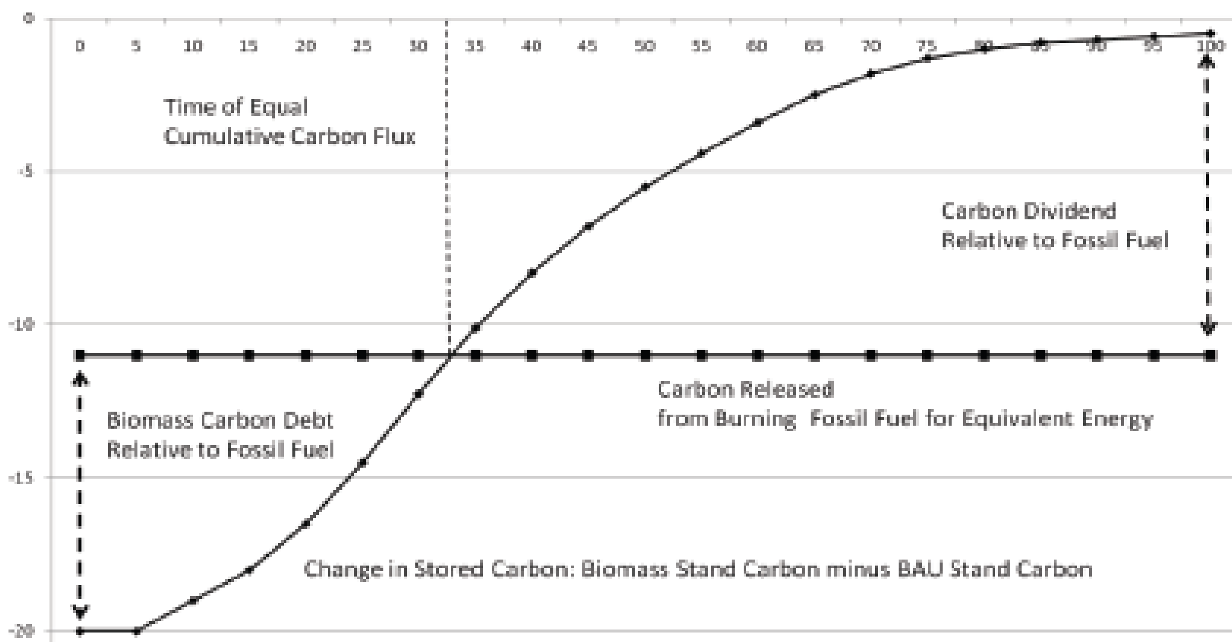

Figure 11. Incremental carbon storage (in tonnes) for a forest stand scenario compared to fossil fuel combustion. Source: Walker et al., 2013. Note: BAU represents a typically harvested stand

In contrast to the common assumption of forest carbon neutrality, (Warner et al., 2017) found that living tree trunks and coarse woody debris (CWD) emit methane. In general, they found that fresher CWD emits more methane than older CWD, however, they also found a high rate of variability among CWD methane emissions. The stand-level approach only considers harvesting standing living trees, whereas the majority of the bioenergy scenarios discussed in this Study utilize non-living waste material that otherwise has GHG-producing alternative fates.

Applying a landscape-level approach to forest carbon accounting, (Strauss, 2011) demonstrated that, assuming sustainable forestry practices, carbon released by combustion from selective harvesting is offset by carbon accumulation from the rest of the system's continued growth, thus, portraying forest carbon accounting as a dividend-then-debt scenario (Figure 12).

In the "debt-then-dividend" perspective (Walker et al., 2013), the timeline for the carbon accounting starts when a tree is harvested. In the dividend-then-benefit perspective (Strauss, 2011), biomass that is selectively harvested from existing forests that will be sustainably managed in the future, does not deplete the net stock as long as the growth-to-harvest ratio is greater than one. Therefore, no carbon debt is incurred.

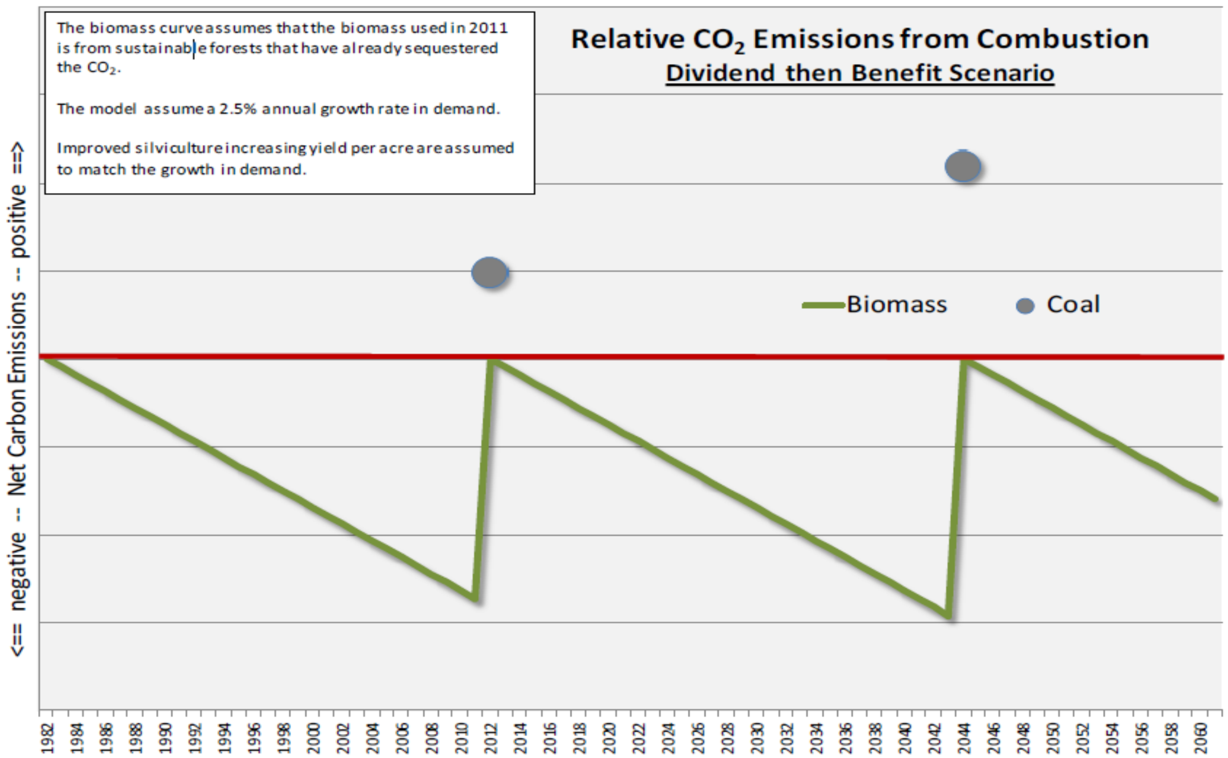

Figure 12. Incremental carbon storage and associated emissions in sustainably harvested forests. Source: Strauss, 2011.

Argonne National Laboratory (2018) analyzed carbon dynamics for a stand-level framework compared to a landscape-level dynamic framework and concluded that a landscape-level analysis is appropriate for conducting LCAs of products from forests managed using sustainable forestry management goals, i.e., a steady supply of forest biomass to customers and steady revenue to the respective landowner. They also found that slower-growing forestry-derived bioenergy feedstocks have larger variations in GHG emissions compared to short-rotation woody crops (SRWCs) that have relatively shorter growth cycles and faster growth rates, and that the increased elapsed time between biomass growth and biofuel combustion may weaken the assumption of carbon neutrality.

Dale et al. (2017) analyzed fuel sheds in southeastern (SE) United States, and demonstrated significant increases in timberland volume, acreage of large trees, harvestable carbon or all carbon pools following the expansion of woody pellet export beginning in 2009. They concluded that despite its growth in the region, the wood pellet industry, when employing sustainable forest management practices, has accrued environmental benefits- providing a pathway to reduce GHG emissions while retaining land in forests that provide ecosystem services - and that urbanization is the greatest cause of forest loss in the SE. Life cycle analysis carbon accounting approaches using GREET inputs (Argonne National Laboratory, 2019) are discussed below.

2.2 Scenarios for GHG Impacts

In this Study, we examine multiple scenarios. The baseline scenario includes using fossil fuels (e.g., heating oil and natural gas) for heating, and woody biomass either remains in the forest or is sent to a landfill. The five bioenergy scenarios include utilizing different sources of woody biomass to produce wood pellets and wood chips that are substituted for fossil fuels.

Baseline Scenario

The baseline scenario represents the current situation in which heating oil and natural gas are used as sources of heating in the U.S. In this scenario, if tree residues and slash are not harvested, and remain in the forests, they will decompose and slowly release CO_2 and methane, or possibly burn during wildfires and release a broader spectrum of GHG and particulates; mature forests reach a growth to mortality equilibrium and no longer sequester additional carbon (Jiang et al., 2020; Pukkula, 2017); excess biomass in the forests that have not been burning under a natural fire regime increase the likelihood of wildfires that ultimately reduce forest carbon stock and produce GHG emissions.

Bioenergy Scenarios

In the bioenergy scenarios, five sources of woody biomass are collected and used to produce wood pellets and wood chips. Part of the fossil fuel load is replaced with wood pellets and chips, and the impacts of bioenergy usage in heating on GHG emissions are assessed. Sources of woody biomass used to produce wood pellets and wood chips in this Study's bioenergy scenarios include those listed in Table 10.

In the case of forest residue, material is often left in slash piles to decompose, or the slash piles are burned to facilitate the rapid re-use of the land. Trees that have died due to insect infestation can slowly decompose over time but are also at risk for forest fires.

The decomposition process is a form of unmanaged composting. Forest product mill waste includes sawdust as well as the many types of milling residues, including bark and unfinished wood cuts. Typically mill waste is not sent to landfills, as the tipping fees increase costs[14]. Urban wood waste includes construction, large tree removal, pallets, and other materials that are processed at material recovery facilities. The material decomposes through several mechanisms, including wood chips for landscaping, composting, and using some material as landfill cover.

[14] Landfilling most organic materials will be prohibited in California in 2022 based on SB 1383.

Table 10. Bioenergy Scenarios Overview

Woody Biomass Feedstock	Alternative Fate	Technology	Pelleting/ Chipping Location
Forest Residue	Decomposition/ Wildfire	Pelleting Chipping	Nearby In-situ
Forest Products Mill Waste	Decomposition/ Landfill	Pelleting Chipping	Nearby In-situ
Urban Wood Waste	Decomposition/ Landfill	Pelleting Chipping	Nearby In-situ
Fire Hazard Reduction/ Insect-killed Standing Dead Trees	Decomposition/ Wildfire	Pelleting Chipping	Nearby In-situ
Pulp Wood Planted Trees[a]	Paper/Wood Products	Pelleting Chipping	Nearby In-situ

[a] Primarily sourced from the southeastern U.S.

2.3 Data Sources

Calculations of life cycle GHG emissions are based on the energy inputs and emissions for each step in the wood pellet and wood chip production process. The data sources for direct emissions, wood pellet and wood chip production, and inputs for the upstream and downstream emissions in the life cycle are described below.

2.3.1 Wood Pellets and Chips Production Energy Inputs

Logging and Feedstock Collection

The feedstock inputs include fertilizer application, and wood harvesting activities. Fertilizer input values (Argonne National Laboratories, 2019; Wells and Allen, 1985) are listed in

Table **11**. Wood harvesting activities typically include felling the trees with chainsaws or mechanical felling machines, and moving the logs to a central location (skidding). The equipment used for these activities predominantly runs on diesel. The use of chain saws versus commercial scale logging equipment depends on the outcome of evaluating the greater productivity and safety associated with commercial scale equipment versus the potential for greater residual damage than would likely be caused by using traditional chainsaw methods, particularly in heavily forested regions. The portion of the tree that is converted to biomass feedstock is chipped on-site and then transported for biomass energy or pulp/paper operations. The portions of the log that are not converted to lumber still require handling and chipping and a preliminary estimate of the energy requirements is the same as that for forest residue. The alternative fate of the forest products mill residues can also be considered as an activity requiring energy to store such material in debris piles.

Table 11. Feedstock Fertilizer Inputs

Source	GREET1_2019				Wells & Allen, 1985	
	Willow	Poplar	Forest Residue	Clean Pine	Low	High
Farming or Collection Energy Use: Btu	185,416	268,597	132,180	144,177		
Fertilizer Input gram per Dry Ton Harvested/Collected						
Nitrogen	1,462	1,970		2,840	2,018	1,135
Phosphate as P_2O_5	650	591		1,523		568
Potash as K_2O	1,002	522		401		
Lime as $CaCO_3$	0	23,237		16,619		
Pesticide Use						
Herbicide	16.1	61.7		0	0	0
Insecticide	0.0	11.8		0	0	0

Low corresponds to low application rate, low yield; High Corresponds to high application high yield.
Source: Argonne National Laboratory, 2019, and Wells and Allen, 1985.

For this Study, several sources were consulted to estimate energy inputs for collection of woody feedstocks.

Table 12 lists values from the GREET1_2019 model and those derived for this Study. Considerations for the latter category include the following: since feedstock to forest product mills is already transported for that purpose, the emissions associated with feedstock transportation are zero; for urban wood waste, feedstock transport emissions are estimated as an average of those for forest residue and forest products mill waste.

Table 12. Data for Diesel Consumption for Collection of Woody Feedstocks

Biomass Type	gal/BD[a] ton	Btu/BD ton	MC[b]	gal/AR[c] ton
Source: GREET				
Willow	185,000	1.44	30%	2.06
Poplar	268,597	2.09 [d]	30%	2.99
Clean Pine	144,177	1.12	30%	1.60
Forest Residue	132,180	1.03	30%	1.47
Construction & Demolition Waste	408,068	3.18	15%	3.74
Source: Derived in Study				
Forest Product Mill Waste	0	0	40%	0
Urban Wood Waste	64,225	0.5	45%	0.91

[a]Bone dry, i.e., zero-percent moisture.
[b]Moisture content in GREET is inferred from truck cargo capacity, which is stated on a BD-basis; MC derived in the study (L. McCreery, personal communication, October 16, 2020).
[c]As-received
[d] Compare to 1.37 gal/AR ton in Zhang, 2015.

Kingsley (2008) examined the energy inputs required for biomass production from commercial logging operations and forest residue collection based on surveys of 5 major contractors operating in the Northeast states and found that most of the energy use was from diesel fuel (Table 13). The level of activity was estimated to be similar for large-scale logging and selective forest thinning, given that the feedstock was relatively large diameter (3 to 6 inches). Westbrook (2006) found that 0.83 gallons of diesel were used per ton of 1 to 4-inch dbh 50% moisture-content pine plantation slash produced into chips. Of this total, 0.41 gal/ton powered the felling, skidding and loading, and 0.40 gallons the chipping. Energy use for reforestation is not accounted for in this Study, as the emissions associated with this activity are beyond the System Boundary Diagram (Figure 8), and are associated with the commercial logging operations.

Table 13. Diesel Inputs for Forestry Harvesting and Estimates for Forest Products Mill Operations

Activity	Forest Residue	Forest Products Mill Waste	Units
Felling & Skidding	0.6	0	gal/AR ton
Landing, yarding, sorting, handling	0.25	0.25	gal/AR ton
Chipping	0.42	0.42	gal/AR ton
Totals	1.27	0.67	gal/AR ton
	2.31	1.22	gal/BD ton
	294,326	155,274	Btu/BD ton

Source: Kingsley, 2008. Numerous assessments examine diesel inputs, for example, see: Zhang, 2015; Northwest Advanced Renewables Alliance, 2016; Whittaker, 2016, Martinkus, 2017; and ANL, 2019.

The energy requirements for processing forest residue specified by Kingsley (2008) correspond to about twice the GREET values for forest residue (
Table 12). Kingsley's energy requirements for forest product mill waste are comparable to those in GREET for clean pine and willow.

The appropriate energy inputs for the life cycle analysis are 100% diesel for the feedstock harvesting and collection and transport. New pellet mills tend to be equipped with electric-powered motors for operating the mechanical equipment while yard equipment is diesel-fueled. Drying energy for the pelletizing process tends to be provided by natural gas or biomass. The energy inputs for pelletizing operations are therefore a combination of diesel fuel, electricity, and biomass or natural gas.

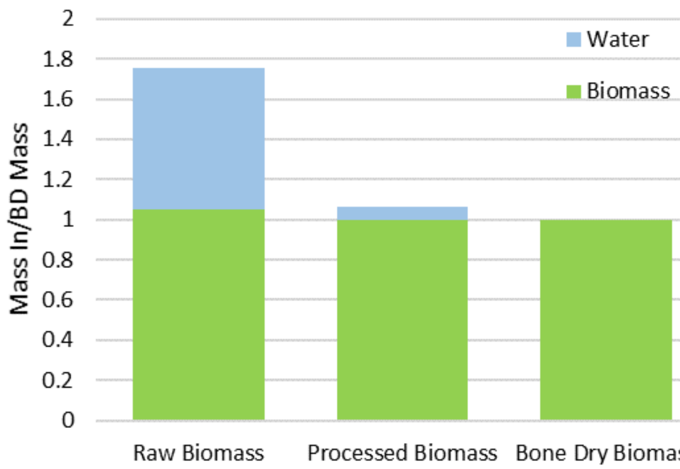

Figure 13. Relative moisture content of different states of woody biomass.

Moisture content of biomass varies depending on biomass type and is an important input parameter in the energy calculations for wood pelletization (Appendix A, Figure 13). The wood pelletization production process requires energy to dry biomass feedstock to a production-acceptable level. Prior to pelletization, feedstock is stored on-site, and typically loses some moisture during that storage timeframe. Drying energy is additionally applied to dry feedstock to the level required by pelletization equipment on the basis of 1,800 Btu (HHV) per pound of water removed. Pellet production from dried feedstock is assumed to be the same across different feedstocks.

Alternative Fates.

In this section, the emissions-relevant alternative fates of woody biomass sources when they are not manufactured into wood pellets or wood chips, is presented in relation to the five reference systems presented in Figure 8. The source of woody biomass feedstock can be classified into two main categories: wood residue and harvested trees. According to the RFS, in order to use harvested trees from tree plantations for bioenergy purposes, the biomass must be obtained from non-federal lands (

Table **4** and Table 5). The issues associated with these alternative fates are similar, and largely related to the production of GHG via decomposition of woody biomass in-situ or in a landfill, or via wild fire. The trees planted for pulp are the exception.

Reference System 1: Forest Residue to Decomposition/Wildfire

In this scenario, residues left in forests following implementation of forest management practices, such as thinning and selective harvesting, become a source of unquantified GHG, primarily carbon dioxide while in an aerobic environment, and once exposed to an anaerobic environment, decompose to methane and nitrous oxide (California Air Resources Control Board, 2018; EPA, 2006; IPCC, 2000; Pier and Kelly, 1997). Forest residues may also ignite through controlled burns or wildfires and emit a wider range of GHG and PM. The range of emissions impacts modeled for this bioenergy scenario include net carbon neutral or decomposition as described above.

Reference System 2: Forest Product Mill Waste to Decomposition/Landfill

Saw dust and mill waste that accumulates in piles, either on-site, or at a landfill, and similarly as discussed above, becomes a source of unquantified GHG, primarily carbon dioxide while in an aerobic environment, and decomposing to methane and nitrous oxide once exposed to an anaerobic environment (Whittaker et al., 2016; CARB, 2019). The range of emissions impacts modeled for this bioenergy scenario include net carbon neutral or decomposition as described above.

Reference System 3: Urban Wood Waste to Decomposition/Landfill:

Wood waste associated with urban tree-trimming, as well as clean pallets and dunnage[15] is sent to landfills where it decomposes, primarily to carbon dioxide while in an aerobic environment, and to methane once exposed to an anaerobic environment. Landfills typically exhibit an 80% capture efficiency with recovery and flaring of landfill gas. The range of emissions impacts modeled for this bioenergy scenario include credit for 80% LFG capture under the California LCFS versus an uncontrolled landfill with 100% emissions.

Reference System 4: Fire Hazard Reduction/Insect-Killed Standing Dead Trees to Decomposition or Wildfire

Woody material in forests that are damaged due to factors including disease, insect infestations and extended drought can lead to considerable fuel loads that either decompose and produce carbon dioxide and/or methane and nitrous oxide, or are ignited through controlled burns or wildfires and emit a wider range of GHG and PM. The range of emissions impacts modeled for this bioenergy scenario include net carbon neutral, or decomposition of combustion as described above, based on GREET data, which includes biomass combustion values that are on the low end of emissions (e.g., see: Weber and Stocks, 1998; Kasischke & Bruhwiler 2002; and Springsteen et al., 2011).

[15] Wood used in crate blocking for shipping.

Reference System 5: Pulp Wood Planted Trees to Pulp and Paper/Wood Products

Softer woods such as poplar, willow and pine, and smaller diameter material are typically sourced from tree plantations for pulp and paper products and for power production, although biomass power demand Is declining relative to the growth of other renewable sources. By design, tree plantations are meant to be actively managed and harvested, and lack the diverse structure and function of natural forests. Left unmanaged, these plantations can become overcrowded, creating high fuel loads and risk for disease and fire. Left unburned in-situ, dead woody biomass decomposes, producing carbon dioxide in an aerobic environment and methane and nitrous oxide in an anaerobic environment. The range of emissions impacts modeled for this bioenergy scenario include net carbon neutral or lost electric power as a debit. As well, the alternative fate to paper products is associated with the impact of indirectly effecting the conversion of land to tree farms.

Wood Chips and Pellets Transport Parameters

Feedstock and product transport distances can vary greatly and are site-specific. In this Study, two phases of transport were modeled: distance travelled by truck from the feedstock source to a chipping or pelleting plant, and distance travelled by truck and/or train from the chipping or pelleting plant to market. Feedstock truck transport was estimated using an 18-ton heavy-duty truck moving feedstocks with respective moisture contents (as-received/green ton basis) and yielded a similar energy intensity input (Btu/dry ton-mi) as the GREET default inputs.

For all Reference Systems, it was assumed that feedstocks are chipped and stored in-situ until sold/used, and therefore no transport distance to a wood chipping mill is modeled. For the UWW scenario, the tree trimming entity owns the emissions for hauling the chips to the central repository from which they are sold. Transport distances to pelletizing plants (

Table **14**) were modeled based on data in GREET (ANL, 2019) and Steering Committee best professional judgement (L. McCreery, personal communication, October 16, 2020). To model emissions associated with transport to market, a 50-mile distance was used for wood chips. Relative to wood pellets, wood chips have lower energy content per same volume, and are heavier due to the extra moisture content and less-dense packing structure, therefore they are typically shipped shorter distances than wood pellets. Due to the higher energy and market values for pellets, a 250-mile transport distance, via truck, was used to model transport emissions from the pellet plant to market for all scenarios except the Pulp Wood Planted Trees. For this scenario, transport to market was represented as a 250-mile distance by train (also a proxy for barge transport) with an additional 50-mile transport by truck.

Table **14** presents direct input parameters (upper segment of table) and calculated emission parameters (lower part of table) for all transport scenarios relevant to the wood pellet pathway. Detailed model results are included in Appendix A.

Electric Power Generation

GHG emissions are calculated using GREET model (ANL, 2019) upstream emission factors and the U.S. resource mix (U.S. Avg Mix) with two exceptions. For Reference System 4 (Fire Hazard Reduction/Insect-Killed Standing Dead Trees), which occurs primarily in western U.S. states, the WECC energy resource mix provided the basis for the upstream power generation emissions, and for Reference System 5 (Pulp Wood Planted Trees), which occurs primarily in the southeastern U.S., the SERC mix was used (Figure 14).

Table 14. Woody Biomass Feedstock Parameters for Transport to Pelletizing Plants

Transportation Factor	**Value or Type**
Transportation Mode	Truck
Fuel	Diesel
Cargo Capacity (ton)	25
Moisture Content (% of total wt)	25-50%[a]
Fuel Economy To Destination (mi/gal)	6.22
Fuel Economy Return Trip (mi/gal)	9.20
Fuel Energy Content (Btu/gal)	128,450
Energy Consumption To Destination (Btu/mi)	20,651
Energy Consumption Return Trip (Btu/mi)	13,962
Energy Intensity To Destination (Btu/ton-mile)	1,181
Energy Intensity Return Trip (Btu/ton-mile)	798
One-way Transport Distance (mile)	50 - 112.5[b]
GHG Emissions (gCO_2/ton-mile)	
GREET 1.8c	78,195
GREET1_2019	78,153

[a] 50% for Forest Residue and Pulpwood Planted Trees Chip feedstocks, 45% for Urban Wood Waste feedstock, 40% for Forest Products Mill Waste feedstock, 25% for Fire Hazard Reduction/Insect-Killed Standing Dead Tree Feedstock (L. McCreery, personal communication, October 16, 2020).

[b] 50 miles for Forest Products Mill Waste, and Urban Wood Waste, 90 miles for Fire Hazard Reduction/Insect-Killed Standing Dead Tree feedstocks (L. McCreery, personal communication, October 16, 2020); 112.5 miles for Forest Residue and 60 miles for Pulp Wood Planted Trees (average of willow and poplar for central and distributed processes) (ANL, 2019).

Figure 14. North American Electric Reliability Corporation Regions[16].
Source: North American Electric Reliability Corporation

2.3.2 Heating Oil and Natural Gas Upstream Emissions

Consumption of heating oil and natural gas for space and water heating are common practice. The purpose of this Study is to analyze the environmental impacts of current fossil fuels and their renewable alternatives (wood pellets and wood chips).

In this Study, the emission factors of diesel were used for heating oil (Table 13). The GHG emissions of diesel are divided into two groups, upstream emissions which is from crude oil to diesel and emissions resulted from burning the fuel. The GREET model estimates the emissions from crude oil to petroleum fuels based on the complexity of the oil refineries in different regions of the U.S. Among other parameters the GHG emissions from a refinery are directly related to the density of crude oils measured in API gravity. Crude oils that are light (higher degrees of API gravity or lower density) tend to require less intensive processing which results in lower GHG emissions. Similarly, natural gas has upstream emissions resulting from extraction and delivery of natural gas and emissions from burning natural gas (Table 15).

[16] Electricity mix in this study is based on NERC regions which are identified in GREET1_2019 and subsequent versions. Note that fuel policies such as the RFS reference older versions of GREET and the GHG calculations for the California LCFS are based on eGRID regions.

Table 15. GREET Upstream Emissions for Heating Oil and Natural Gas

	GREET1_2019				GREET_1.8c			
	Natural gas		**Heating oil**		**Natural gas**		**Heating oil**	
$gCO_2e/MMBtu$	Upstream Emissions	Fuel Burning	Upstream Emissions	Fuel Burning	Upstream Emissions	Fuel Burning	Upstream Emissions	Fuel Burning
VOC	10.320	2.540	7.657	0.800	5.827	1.557	7.683	1.173
CO	31.994	22.210	12.773	20.867	8.010	16.419	12.219	16.686
NO_x	40.003	36.400	26.523	53.860	22.825	57.607	41.532	82.225
PM10	0.473	3.507	1.790	8.122	0.878	3.206	8.042	42.530
PM2.5	0.421	3.507	1.502	5.473	0.521	3.206	3.237	38.000
SO_x	11.551	0.269	9.983	0.542	11.573	0.269	19.855	8.038
BC[a]	0.132	0.579	0.261	0.547				
OC[b]	0.151	1.501	0.445	1.368				
CH_4	219.231	1.060	111.644	0.198	196.356	1.100	103.396	0.180
N_2O	1.416	0.750	0.230	0.918	0.087	1.100	0.233	0.390
CO_2	6,066	59,367	13,527	78,163	5,258	59,379	14,416	78,169
CO_2 (w/ C in VOC & CO)	6,149	59,410	13,571	78,199	5,288	59,410	14,459	78,199
GHG	13,101	59,640	16,981	78,448	10,223	59,765	17,113	78,319

[a] Black Carbon, this pollutant is a contribution to global warming and counted in GREET but is not part of the analysis for the RFS2.
[b] Organic Carbon

2.3.3 Heating Value of Fuels

The heating value of biomass materials is based on the higher heating values in GREET with an adjustment for the moisture content of the delivered biomass fuel assuming 6% hydrogen content in the biomass. Note that the LHV in GREET is on a bone-dry basis[17]. Equation 1 takes into account the moisture content of each fuel, the LHV formula from van Loo (2002) which is consistent with studies on drying requirements for biomass fuels (Gebreegziabher, 2013).

$$LHV = HHV \times (1-MC) - 2.44(MC) - 2.44 \times (\%H) \times 8.936 \times (1-MC) \text{ in MJ/kg} \quad (1)$$

[17] Adjusting the LHV values in GREET for moisture content results in similar LHV values for non-dry wood. However, some of the LHV/HHV ratios are inconsistent with equation 1; so, this formula was applied to all of the woody biomass materials in this Study.

Table 16. Heating Values of Biomass Materials

Fuel/Scenario	Higher Heating Value		LHV Pellets (6% MC)		Lower Heating Value for Chips		
	Btu/ton	MJ/kg	MJ/kg	Btu/ton	Moisture	MJ/kg	MMBtu/ton
Willow[a]	16,524,000	19.22	16.69	14,347,343			
Poplar[a]	17,062,000	19.84	17.27	14,853,063			
Clean Pine[a]	17,062,000	19.84	17.27	14,853,063			
Forest Residue[a]	17,906,000	20.82	18.20	15,646,423	50%	8.54	7.34
Fire Hazard Reduction[b]	17,906,000	20.82	18.20	15,646,423	25%	14.02	12.06
Urban Wood Waste	18,400,000	21.40	18.74	16,110,783	45%	9.95	8.55
Pulp Wood	17,484,000	20.33	17.74	15,249,743	50%	8.29	7.13
Mill Waste	17,484,000	20.33	17.74	15,249,743	40%	10.44	8.97

[a] Fuel property data from GREET provide the basis for biomass in this Study

[b] Refers to Fire Hazard Reduction/Insect-Killed Standing Dead Trees Bioenergy Scenario.

3. LIFE CYCLE GHG EMISSIONS

Life cycle GHG emissions were calculated for a range of feedstock sources and drying options for biomass pellets and wood chip fuel. The GHG emissions from woody biomass pathways are discussed in the following section followed by the life cycle GHG emissions from comparable fossil fuels.

3.1 Wood Pellets and Chips LCA

The GHG emissions of wood pellets and wood chips produced from various sources, including, forest products mill waste, forest residue, urban wood waste, fire hazard reduction/insect-killed standing dead trees, and pulp wood planted trees, were estimated using the data discussed in Section 2. For combustion emissions, the combusting wood pellets/chips are treated on a carbon neutral basis. The biogenic CO_2 emissions resulting from burning of wood pellet/chips were recently removed from the atmosphere and will be captured when biomass is grown sustainably or when the alternative fate results in decomposition to CO_2. Therefore, only methane and nitrous oxide emissions contribute to direct GHG emissions from combustion, based on the pollutants counted under the RFS2.

The GHG emissions results for pellets are presented in

Table **17**. The table shows the steps of the feedstock collection, processing, transport and combustion with a total for biomass and natural gas based drying. For biomass drying energy, the emissions include the full life cycle of wood chips as the energy source in the subsequent table. Natural gas drying energy includes the well to burner emissions based on the GREET model.

The total with 100% avoided emissions is also shown. While the alternative fate is not always 100% of the avoided emissions shown here the range illustrates the potential effect which shows that the avoided emissions from decomposing wood or burning can be as large as those from the pellet production and combustion.

Similarly, Table 18 shows the life cycle emissions for wood chip fuel. Figure 15 illustrates the relative contributions of each stage of production to the total CI for the wood pellets and wood chips. The utilization of wood chips and pellets, and their efficiency was not further examined in this Study, for example, the moisture content of pellets and wood would affect the potential energy recovery in the heating applications.

Table 17. GHG Emissions of Wood Pellets[a]

GHG (gCO_2e/MJ)	Forest Products Mill Waste	Forest Residue	Urban Wood Waste	Fire Hazard Reduction[b]	Pulp Wood Planted Trees
Collection & Transportation					
Farming	0	0	0	0	0.24
Collection	0	1.47	0.69	0.98	2.27
Transportation	0.97	2.56	1.07	1.36	1.40
Pelletizing Plant					
Diesel	0.38	0.37	0.36	0.37	0.38
Electricity	3.56	4.34	4.21	3.12	2.50
Natural Gas	7.11	11.29	9.44	2.57	11.31
Biomass	0.36	0.91	0.54	0.16	1.29
Transportation to Market	0.41	0.40	0.38	2.87	2.94[c] or 0.41[d]
Biomass Combustion[g]	1.96	1.96	1.96	1.96	1.96
Total Biomass Drying	7.64	11.44	9.22	10.89	13.0 or 10.4
Total Natural Gas Drying	14.39	22.38	17.33	13.23	23.27
100% Avoided Fate[e]	Compost	Burning	Compost	Burning	N/A
Total Biomass Drying	-21.4	-3.36	-19.06	-4.55	
Total Natural Gas Drying	-14.7	7.01	-10.95	-2.13	
Total Biomass Drying, Rail Transport					10.44
Total Natural Gas Drying, Rail Transport					20.73

[a]Emissions are on a net carbon neutral basis assuming that biogenic CO_2 is removed from the atmosphere with no storage effect. There the biogenic uptake and reforestation as well as changes in forest growth are not show here.

[b]Refers to Fire Hazard Reduction/Insect-Killed Standing Dead Trees Bioenergy Scenario

[c]Truck Transport

[d]Rail Transport [e] see details in Appendix A

Table 18. GHG Emissions of Wood Chips

GHG (g CO_2e/MJ)	Forest Products Mill Waste	Forest Residue	Urban Wood Waste	Fire Hazard Reduction[a]	Pulp Wood Planted Trees
Collection & Transportation					
Farming	0	0	0	0	1.01
Collection	0	1.59	0.68	0.97	2.45
Transportation	0	0	0	0	0
Chipping Plant					
Diesel	0.26	0.32	0.27	0.19	0.33
Transportation to Market	1.00	1.22	1.05	0.74	1.26
Burning Emissions	1.96	1.96	1.96	1.96	1.96
Total	3.22	5.09	3.96	3.86	7.00
100% Avoided Fate	Compost	Burning	Compost	Burning	N/A
Total Drying	-26.71	-12.34	-23.86	-12.05	

[a]Refers to Fire Hazard Reduction/Insect-Killed Standing Dead Trees Bioenergy Scenario.

While the pelletization stage provides the greatest contribution to the wood pellet CI, diesel used for in-situ chipping diesel and biomass combustion account for the majority of the wood chip CI. The GHG emissions of wood chips are 2 to 8 times lower than those of wood pellets, making wood chips a comparatively low carbon intensity fuel for the given market distance range. Two main factors account for the lower emissions associated with wood chips: lower energy consumption during wood chipping compared to wood pelletization (particularly drying energy); and shorter transport distance to market. The emissions shown for pellet transport to market represent a worst-case scenario as they are based on truck rather than on more fuel-efficient rail transport. The Pulp Wood Planted Tree Scenario is an exception, for which transport was modeled both by truck and by train (which also serves as a proxy for barge transport that may transpire in that region).

Figure 15 illustrates the relative contributions of wood chips and wood pellets to respective fuel CIs under the five bioenergy scenarios modeled in this Study. In addition to providing a visualization of the relative contributions to biomass fuel CI, as discussed above, this figure depicts the emissions avoided under alternative fates, and the net emissions associated with each scenario, e.g., the sum of emissions resulting from the chipping/pelleting process and those associated with the avoided alternative fates, including diversion from decomposition, landfilling, and wildfire (see colored bars below the x-axis zero line). Were these alternative fates not displaced by biomass fuel production, the GHG emissions for each scenario would represent the values at the top of each bar in Figure 15. Avoided emissions resulting from decomposition in a landfill or a composting system (-29 g CO_2e/MJ), as well as from open field burning or wildfire (-15 g CO_2e/MJ) have significant potential to reduce GHG emissions.

The representation of alternative fates in this Study warrants several caveats. First, the level of avoided landfill emissions portrayed in this Study represents a conservative estimate, for a landfill that is capturing 75% of landfill gases, however, some landfills operate with little or no capture of landfill gas. In such cases, the avoided emissions would be much greater than represented in this Study. Secondly, this Study is not accounting for the full cost of wildfires which can cause considerable damage to ecosystem services, beyond GHG emissions. Lastly, the effect of pulp wood tree planted feedstock, directed to either biomass fuel, or paper products, could cause an indirect effect of land conversion to more tree planting. Depending on the harvesting schedule, this could result in carbon neutral or positive emissions. Directing pulp wood tree planted feedstock to fuel, either as pellets or chips, could divert resources from electric power generation, however, this is less likely to be an issue due to the increasingly available sources of alternative renewable power. An argument could also be made that diverting such biomass from pulp and paper products could result in indirect emissions associated with an increasing need for secondary recycling to provide the necessary feedstock. Alternatively, this situation could induce more efficient use of paper resources and the production and use of electronic media.

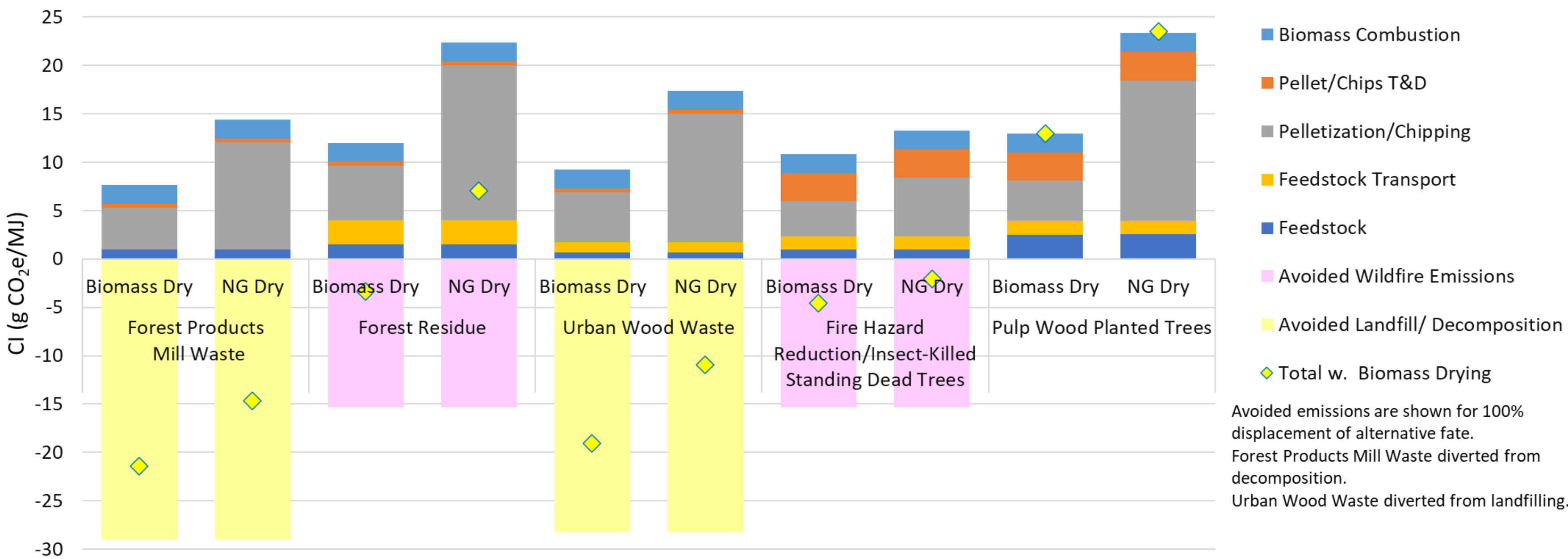

Figure Footnotes:
T&D refers to transport and drying.
CI of electric power for pelleting depends on the region selected in assumption tables.
Avoided emissions for methane production would be higher for uncontrolled landfills and lower for biomass that is applied for landscaping or agricultural soil amendment.

Figure 15. Life cycle GHG emissions from biomass pellets.

Figure Footnotes:
T&D refers to transport and drying.
Wood chips are used as a process fuel without drying.
Avoided emissions for methane production would be higher for uncontrolled landfills and lower for biomass that is applied for landscaping or agricultural soil amendment.
Fire hazard reduction is associated with insect-killed standing dead trees
Feedstock transport is zero since wood chips are hauled directly to end use customer.

Figure 16. Life cycle GHG emissions from wood chips.

3.2 Heating Oil and Natural Gas LCA

The GHG emissions of natural gas and heating oil as two major fuels for heating were calculated using GREET1_2019 and GREET_1.8c and shown in Table 19. Note that the emissions listed in Table 19 include both upstream emissions and stove emissions. Natural gas has a lower carbon intensity (CI) than heating oil, and its use for space heating has been increasing relative to heating oil.

Table 19. GHG Emissions of Heating Oil and Natural Gas

	GREET1_2019		GREET_1.8c	
	Natural Gas	**Heating Oil**	**Natural Gas**	**Heating Oil**
Upstream Life Cycle (gCO_2e/MMBtu)	13,101	16,981	10,223	17,113
Fuel Combustion (gCO_2e/MMBtu)	59,640	78,448	59,765	78,319
Total (gCO_2e/MMBtu)	72,741	95,429	69,988	95,432
Total (gCO_2e/MJ)	68.95	90.45	66.34	90.45

3.3 Scenario Analysis

After conducting the LCA for the baseline scenario, in which fossil fuels such as heating oil and natural gas are used for heating, and for the bioenergy scenarios, in which woody biomass are converted to wood pellets/chips and the energy used for heating, the CI of each case was compared[18] (Figure 17). The CI of natural gas and heating oil is much higher than their renewable alternatives. Thus, replacing heating oil and natural gas with wood pellets or wood chips can significantly reduce GHG emissions.

Figure 17 illustrates the cradle to boiler emissions and the avoided emissions associated with each woody biomass feedstock relative to the emissions associated with heating oil and natural gas. Comparing only the life cycle boiler to displaced fossil fuel emissions demonstrates a three to thirty-fold reduction, depending on which scenarios are compared. Accounting for the avoided emissions in the respective bioenergy scenarios results in GHG emission reductions of at least 66%, and up to 117.5 g CO_2e/MJ. Note that not collecting forest residues, and insect-killed standing trees may increase the risk of wildfire. Therefore, for the forest residue and fire hazard reduction/insect-killed standing trees bioenergy scenario, it is reasonable to not account for biomass combustion emissions, since the aforementioned increase the risk of wildfire and generates emissions equal to or greater than those. In this case, the CI of wood pellets/chips would be even lower than current estimates presented in this Study.

[18] The scope of this Study did not include comparing efficiencies of converting various fuel sources to useable energy.

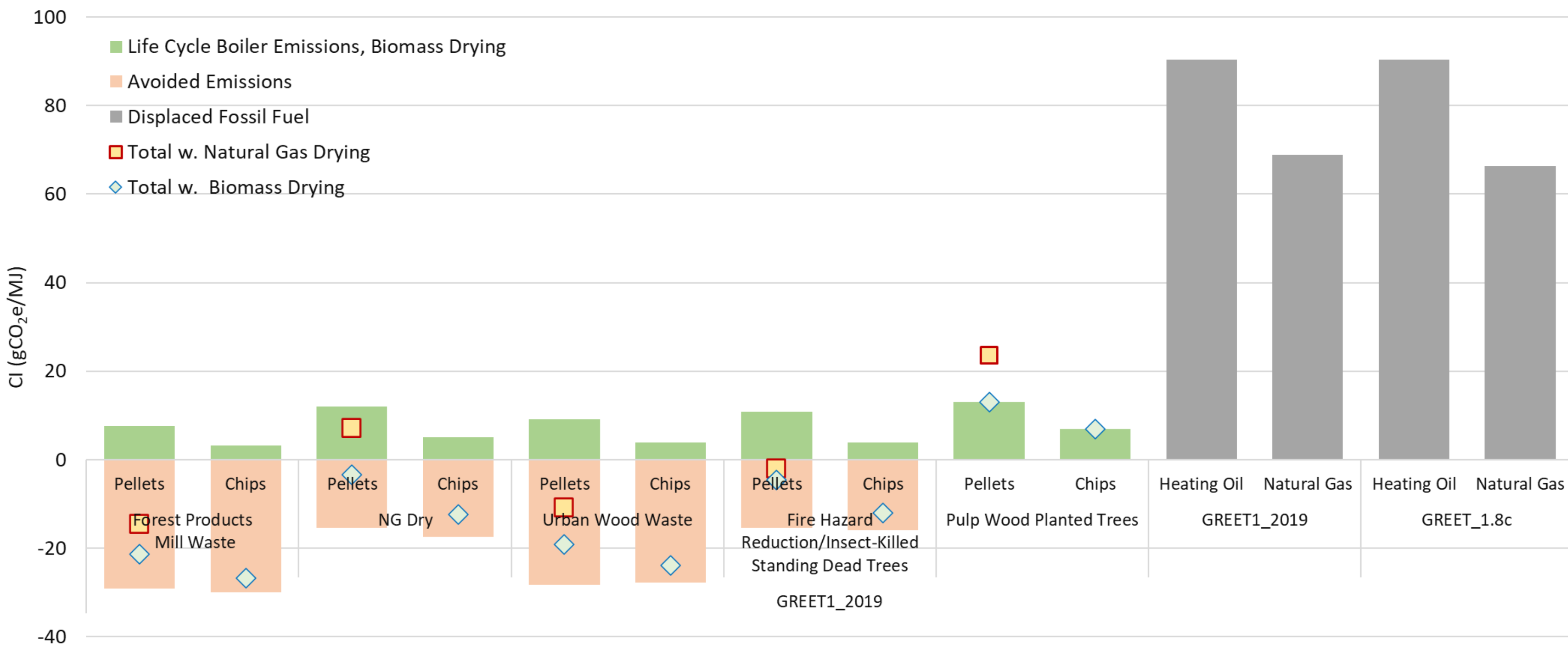

Figure Footnotes:

CI of electric power for pelleting depends on the region selected in assumption tables.
Wood chips are used as a process fuel without drying.
Avoided emissions for methane production would be higher for uncontrolled landfills and lower for biomass that is not landfilled.
The range of transport emissions is reflected in the pulp wood planted trees case with 100% truck transport for the NG case and truck/rail transport in the biomass case. Rail and barge transport would result in similar transport emissions.

Figure 17. CI of heating oil, natural gas and their renewable alternatives.

4. Carbon Credit Programs

GHG credit programs provide an opportunity to monetize the emission savings associated with the use of biomass. To date the most significant programs, include the federal Renewable Fuel Standard, the European Fuel Quality Directive, the California Low-Carbon Fuel Standard, and voluntary credit programs. The potential value of biomass fuel in these programs is examined here.

4.1 California Low Carbon Fuel Standard

In 2009 the California Air Resource Board approved the LCFS regulation to reduce the CI of transportation fuel used in California by at least 10 percent by 2020 from a 2010 baseline (Figure 18). The LCFS requires biofuel developers to measure the CI of their biofuel since the LCFS credit is based on the difference between the CI of biofuel and CI of baseline fossil fuel and varies over time based on market demand. The LCFS sets annual CI standards, or benchmarks, which reduce over time, for gasoline, diesel, and the fuels that replace them. The LCFS also requires that the biofuel is used in the transportation sector. Using biomass-generated electricity to charge electric vehicles and earn LCFS credits is potentially an option. The power must be generated in California to generate credits for electric vehicle (EV) operation in the state.

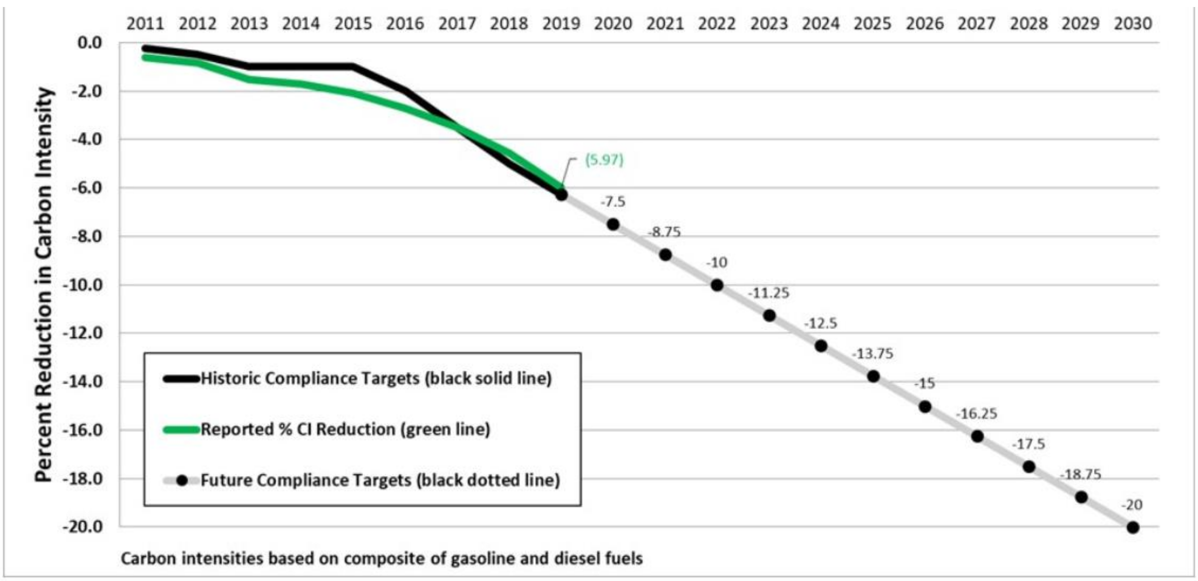

Figure 18. Performance targets for the California Low Carbon Fuel Standard.
Source: California Air Resources Control Board, 2020b.

While process heat is not treated as a transportation fuel under the LCFS, the use of biomass that displaces natural gas as process heat in a fuel pathway would increase LCFS credit generation. For example, if a biodiesel plant that uses 15,000 MMBtu/month of natural gas switched to using wood pellets that have a CI of 12 g CO_2e/MJ, the facility would reduce GHG emissions by 823 tonnes[19] CO_2e per month, and increase credit revenue by $164,000 at a value of $12.13/MMBtu. This revenue would vary with credit price. Recent LCFS credit price history is shown in Figure 19.

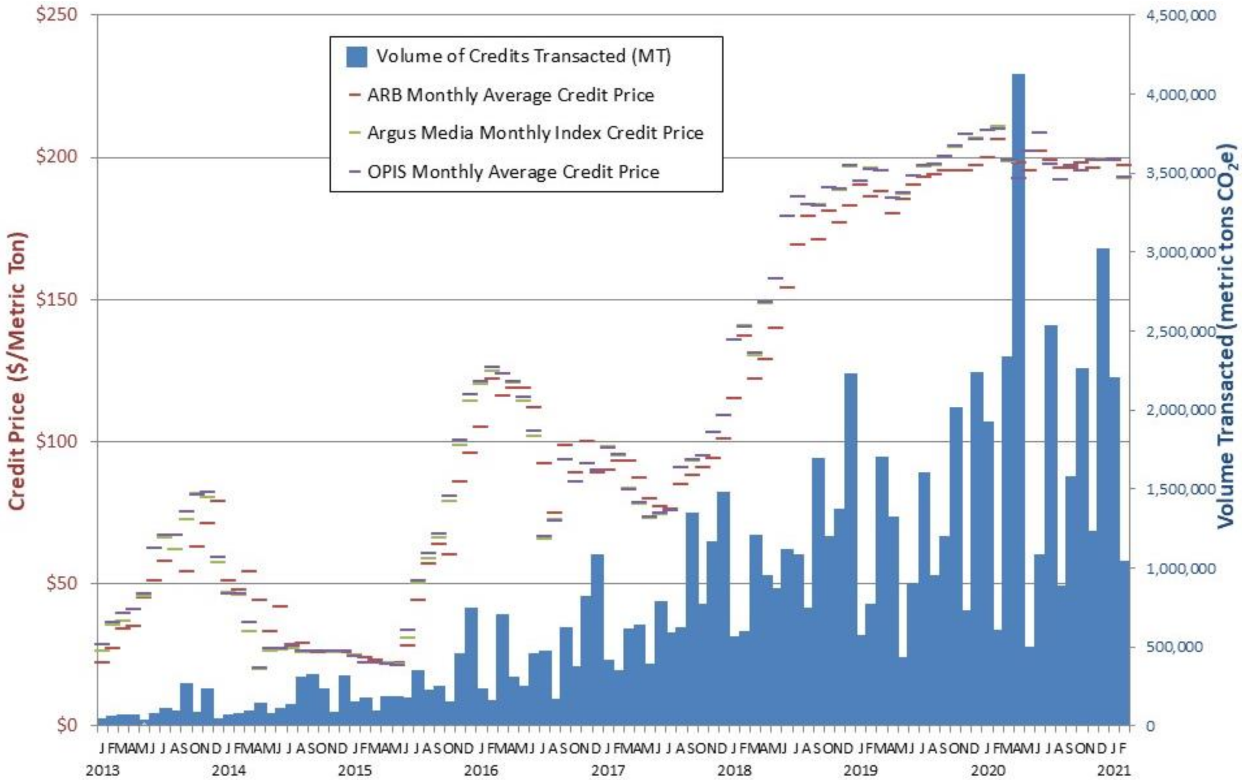

Figure 19. Price per ton for credits generated by the California Low Carbon Fuel Standard.
Source: California Air Resources Board, 2020b

4.2 Voluntary Credit Programs

Voluntary carbon markets provide an opportunity for entities that are unable to reduce their emissions to purchase carbon credits from verified suppliers to offset their emissions. The revenues collected are used to finance carbon reduction projects. Voluntary credit buyers are often driven by certain considerations such as safeguarding their reputation, ethics, and corporate social responsibility (CSR). The value of GHG reductions in voluntary markets is typically below $10/tonne of GHG emissions (Zwick, 2020) compared to approximately $190/tonne for the LCFS, which aims to motivate change in the transportation sector.

4.3 Renewable Fuel Standard

To date the RFS has enabled credit generation for heating oil used to generate heat to warm buildings or other facilities where people live, work, recreate, or conduct other activities. This heating application is similar to the many for biomass thermal energy. A consistent energy analysis for biomass thermal energy under the RFS is examined here. If biomass based thermal

[19] Change in CI (69.5-12) g/MJ × 1055.055/1,000,000*$190/tonne = $11.5/MMBtu savings. 15,000 MMBtu, HHV × 0.903 (LHV/HHV) × 60,700 g CO_2e/MMBtu, LHV = 823 tonne GHG.

energy were included under the RFS2, it could generate a D3 RIN, valued in this Study at $1.50/RIN (Figure 20). For 1 MMBtu on an HHV-basis or 77,000 Btu on an LHV-basis, this would generate 12 RINs or $312 per ton of biomass (dry basis[20]).

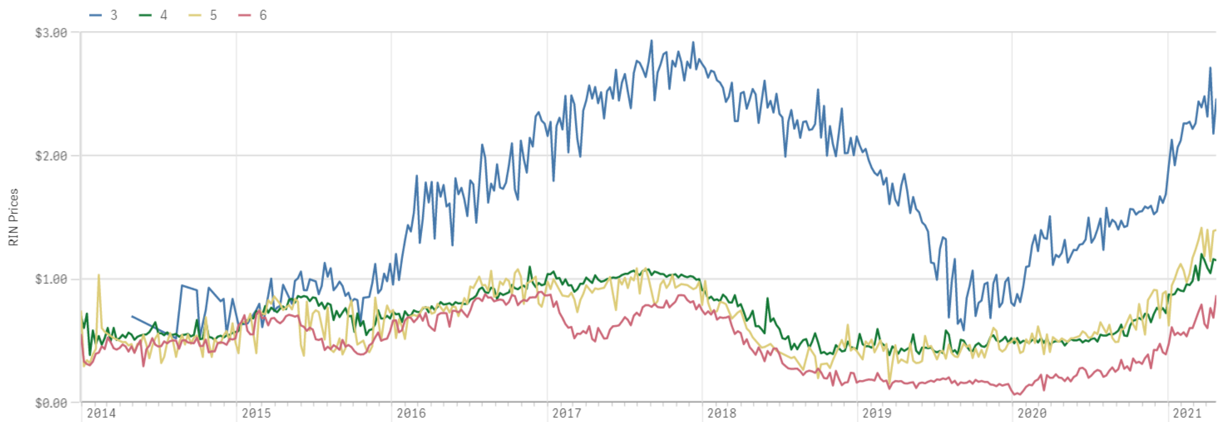

Figure 20. Value of renewable identification number (RIN) credits generated under the Renewable Fuel Standard.
Source: EPA, 2020

[20] The RIN equivalence factor is determined on an LHV-basis. 16 MMBtu/ton/ 77,000 = 208 RIN/ton or $312/ton

Table 20 illustrates the relative value of woody biomass fuel under the RFS, as a heating fuel, and under the LCFS, as a process fuel. This example is based on recent market values for the RFS and the LCFS, and illustrates an approximate $82 valuation difference. This comparison demonstrates that even if a pathway were not approved under the RFS, the LCFS potentially provides significant benefit for displacing natural gas as a process heat fuel for a fuel production facility[21]. Even if these biomass fuels do not meet a specific end-use RFS requirement such as space heating, the potential to generate LCFS credits, which are of comparable value to RINs provides a viable opportunity to valorize wood pellets and wood chips to another market.

[21] The LCFS Tier1 calculators provide an opportunity to utilize biomass as process heat fuel, with approval subject to California Air Resources Board review.

Table 20. Comparison of Valuation of Woody Biomass Fuel as Heating Fuel Under the RFS and as Process Fuel Under the LCFS

RFS Valuation		
Application	Heating fuel	
RIN Value	\$1.50	/D3 RIN
Energy per RIN	77,000	Btu, LHV
RIN/BD ton	208	
RIN Value	\$312	/ton
LCFS Valuation		
Application		
LCFS Credit	\$190	/tonne CO_2e
Biomass LHV	16.08	MMBtu/BD ton, LHV
LCFS Baseline	92	g CO_2/MJ
CI	12	g CO_2/MJ
GHG Savings	1.22	tonne GHG
LCFS Value	\$231.64	/BD ton

5. Conclusions

In this study, the possibility of adding thermal conversion of biomass for heating to RFS was assessed. Heating oil and natural gas are two major sources of energy for space heating. Wood pellets and wood chips are two renewable substitutes for heating oil and natural gas. Wood pellets and wood chips are made from various waste sources such as lumbermill waste, forest residue, fire hazard reduction and salvaged material including insect-killed standing dead trees, and urban wood waste that would otherwise generate GHGs either through the process of decomposition or burning. LCA results showed that the CI of wood pellets/chips from all biomass sources considered in this study was significantly lower than that of fossil heating oil and natural gas (without considering the conversion efficiencies), indicating that wood pellets/chips are a promising alternative for heating oil and natural gas.

Since wood pellets/chips are made from pulpwood and waste biomass such as lumbermill waste and forest residue, and they have a significantly lower CI compared to heating oil and natural gas, it would be consistent with the prior pathways approved under the RFS, if EPA would reevaluate the RFS and consider creating a pathway for thermal conversion of biomass from federal and non-federal lands as heating energy.

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Appendices

Appendix A. Life Cycle Inventory (LCI) and Life Cycle Analysis (LCA)

Note: BD indicates bone-dry; Yellow cells indicate reference values; white cells indicate calculated values; blue cells indicate capability to toggle category. Two LCA tables are listed for each Bioenergy Scenario to represent both biomass and natural gas as drying fuels for wood pellets. For the Pulp Wood Planted Trees Bioenergy Scenario two additional LCA tables represent transport to market by truck or by rail as a proxy for barge transport.

LCI, Forest Products Mill Waste			
Collection & Transportation to Pelletizing/Chipping Plant		**Pellets**	**Chips**
Feedstock Moisture Content	%	40%	40%
Distance[a]	mile	50	0
Processing - diesel	gal/ton	0	0
Transportation Mode	-	Truck	Truck
Pelletizing/Chipping Plant			
Dry Matter Yield	ton BD product/ton BD feedstock	0.95	1
Feed to Product Ratio, AR	AR ton/ton product	1.649	1.000
Biomass Heating Value, HHV	MMBtu/BD ton	17.48	17.48
Heating Value of Pellet/Chip, LHV	MMBtu/delivered ton	15.25	8.97
Moisture Content of Biomass Fuel	%	6%	40%
Diesel	gal/ton	0.5	0.2
Electricity	kWh/ton	120	0
Biomass	MMBtu/ton	1.72	0
Transportation to Market			
Distance	mile	250	50
Transportation Mode	-	Train	Truck
Drying Requirement Moisture of feed before pelletizing		12%	40%
Mass before drying		1.667	1.667
Mass after drying ton/BD ton		1.136	1.667
Mass of water dried off (lb/BD ton)		1061	0

[a]Zero collection energy required for biomass waste material at the mill.

LCA, Forest Products Mill Waste									
	Wood Pellets, Biomass Drying			Wood Pellets, NG Drying			Wood Chips		
Life Cycle CI (g CO_2e/	ton Pellet	MMBtu	MJ	ton Pellet	MMBtu	MJ	ton chips	MMBtu	MJ
Feedstock Collection & Transportation									
Transportation	15,623	1,025	0.97	15,623	1,025	0.97	0	0	0.00
Collection	0	0	0	0	0	0	0	0	0.00
Fuel Processing									
Diesel	6,129	402	0.38	6,129	402	0.38	2,452	273	0.26
Electricity, U.S. Avg	57,300	3,757	3.56	57,300	3,757	3.56	0	0	0
Drying Fuel	5,853	384	0.36	114,399	7,502	7.11	0	0	0
Transportation- Pelletizing Plant to Market									
Transportation	6,523	428	0.41	6,523	428	0.41	9,474	1,056	1.00
Biomass Combustion	31,514	2,067	1.96	31,514	2,067	1.96	18,544	2,067	1.96
Total	122,942	8,062	7.64	231,488	15,180	14.39	30,470	3,395	3.22
Avoided Emissions									
Composting	-467,239	-30,639	-29.04	-467,239	-30,639	-29.04	-283,326	-31,573	-29.93
Total with 100% Avoided Emissions	-344,296	-22,577	-21.4	-235,751	-15,459	-14.65	-252,856	-28,177	-26.71

LCI, Forest Residue			
Collection & Transportation to Pelletizing/Chipping Plant		**Pellets**	**Chips**
Feedstock Moisture Content	%	50%	50%
Distance	mile	112.5	0
Processing - diesel	gal/AR ton	1	1
Transportation Mode	-	Truck	Truck
Pelletizing/Chipping Plant			
Dry Matter Yield	ton BD product/ton BD feedstock	0.95	1
Feed to Product Ratio, AR	AR ton/ton product	1.979	1.000
Biomass Heating Value, HHV	MMBtu/BD ton	17.91	17.91
Heating Value of Pellet/Chip, LHV	MMBtu/delivered ton	15.65	7.34
Moisture Content of Biomass Fuel	%	6%	50%
Diesel	gal/ton	0.5	0.2
Electricity	kWh/ton	150	0
Biomass	MMBtu/ton	2.81	0
Transportation- Pelletizing Plant to Market			
Distance	mile	250	50
Transportation Mode	-	Train	Truck
Drying Requirement Moisture of feed before pelletizing		12%	50%
Mass before drying		2.000	2.000
Mass after drying ton/BD ton		1.136	2.000
Mass of water dried off (lb/BD ton)		1727	0

LCA, Forest Residue									
	Wood Pellets, Biomass Drying			Wood Pellets, NG Drying			Wood Chips		
Life Cycle CI (g CO_2e/	ton Pellet	MMBtu	MJ	ton Pellet	MMBtu	MJ	ton chips	MMBtu	MJ
Feedstock Collection & Transportation									
Transportation	42,183	2,696	2.56	42,183	2,696	2.56	0	0	0.00
Collection	24,317	1,554	1.47	24,317	1,554	1.47	12,288	1,674	1.59
Fuel Processing									
Diesel	6,129	392	0.37	6,129	392	0.37	2,452	334	0.32
Electricity, U.S. Avg	71,624	4,578	4.34	71,624	4,578	4.34	0	0	0.00
Drying Fuel	15,065	963	0.91	186,306	11,907	11.29	0	0	0.00
Transportation- Pelletizing Plant to Market									
Transportation	6,523	417	0.40	6,523	417	0.40	9,474	1,291	1.22
Biomass Combustion	32,334	2,067	1.96	32,334	2,067	1.96	15,166	2,067	1.96
Total	198,175	12,666	12.00	369,417	23,610	22.38	39,379	5,366	5.09
Avoided Emissions									
Slash Pile Burning	-253,702	-16,215	-15.37	-253,702	-16,215	-15.37	-134,948	-18,388	-17.43
Total with 100% Avoided Emissions	-55,527	-3,549	-3.36	115,715	7,396	7.01	-95,569	-13,022	-12.34

LCI, Urban Wood Waste			
Collection & Transportation to Pelletizing/Chipping Plant		**Pellets**	**Chips**
Feedstock Moisture Content	%	45%	45%
Distance	mile	50	0
Processing - diesel	gal/AR ton	0.5	0.5
Transportation Mode	-	Truck	Truck
Pelletizing Plant			
Dry Matter Yield	ton BD product/ton BD feedstock	0.95	1
Feed to Product Ratio, AR	AR ton/ton product	1.914	1.000
Biomass Heating Value, HHV	MMBtu/BD ton	18.40	18.40
Heating Value Wood Pellets, LHV	MMBtu/delivered ton	16.11	8.55
Moisture Content Biomass Fuel	%	0%	45%
Diesel	gal/ton	0.50	0.20
Electricity	kWh/ton	150	0
Biomass	MMBtu/ton	2.22	0
Transportation- Pelletizing Plant to Market			
Distance	mile	250	50
Transportation Mode	-	Train	Truck
Drying Requirement Moisture of feed before pelletizing		12%	45%
Mass before drying		1.818	1.818
Mass after drying ton/BD ton		1.136	1.818
Mass of water dried off (lb/BD ton)		1364	0

LCA, Urban Wood Waste									
	Wood Pellets, Biomass Drying			Wood Pellets, NG Drying			Wood Chips		
Life Cycle CI (g CO_2e/	ton Pellet	MMBtu	MJ	ton Pellet	MMBtu	MJ	ton chips	MMBtu	MJ
Feedstock Collection &									
Transportation	18,132	1,125	1.07	18,132	1,125	1.07	0	0	0.00
Collection	11,759	730	0.69	11,759	730	0.69	6,144	718	0.68
Fuel Processing									
Diesel	6,129	380	0.36	6,129	380	0.36	2,452	287	0.27
Electricity, U.S. Avg	71,624	4,446	4.21	71,624	4,446	4.21	0	0	0.00
Drying Fuel	9,262	575	0.54	147,084	9,130	8.65	0	0	0.00
Transportation- Pelletizing Plant to Market									
Transportation	6,523	405	0.38	6,523	405	0.38	9,474	1,107	1.05
Biomass Combustion	33,293	2,067	1.96	33,293	2,067	1.96	17,678	2,067	1.96
Total	156,722	9,728	9.22	294,544	18,282	17.33	35,748	4,179	3.96
Avoided Emissions									
Composting	-480,631	-29,833	-28.28	-480,631	-29,833	-28.28	-251,129	-29,356	-27.82
Total with 100% Avoided Emissions	-323,908	-20,105	-19.06	-186,086	-11,550	-10.95	-215,382	-25,177	-23.86

LCI, Fire Hazard Reduction/Insect-Killed Standing Trees			
Collection & Transportation to Pelletizing/Chipping Plant		**Pellets**	**Chips**
Feedstock Moisture Content	%	25%	25%
Distance	mile	90	0
Processing - diesel	gal/ton	1	1
Transportation Mode	-	Truck	Truck
Pelletizing Plant			
Dry Matter Yield	ton BD product/ton BD feedstock	0.95	1
Feed to Product Ratio, AR	AR ton/ton product	1.319	1.000
Biomass Heating Value, HHV	MMBtu/BD ton	17.91	17.91
Heating Value of Pellet/Chip, LHV	MMBtu/delivered ton	15.65	12.06
Moisture Content of Biomass Fuel	%	6%	25%
Diesel[a]	gal/ton	0.5	0.2
Electricity	kWh/ton	150	0
Biomass	MMBtu/ton	0.64	0
Transportation- Pelletizing Plant to Market			
Distance	mile	250	50
Transportation Mode	-	Truck	Truck
Drying Requirement Moisture of feed before pelletizing		12%	25%
Mass before drying		1.333	1.333
Mass after drying ton/BD ton		1.136	1.333
Mass of water dried off (lb/BD ton)		394	0

[a] Best professional judgement (Study Steering Committee, 2020)

LCA, Fire Hazard Reduction/Insect-Killed Standing Trees									
	Wood Pellets, Biomass Drying			Wood Pellets, NG Drying			Wood Chips		
Life Cycle CI (g CO_2e/	ton Pellet	MMBtu	MJ	ton Pellet	MMBtu	MJ	ton chips	MMBtu	MJ
Feedstock Collection &									
Transportation	22,498	1,438	1.36	22,498	1,438	1.36	0	0	0.00
Collection	16,211	1,036	0.98	16,211	1,036	0.98	12,288	1,019	0.97
Fuel Processing									
Diesel	6,129	392	0.37	6,129	392	0.37	2,452	203	0.19
Electricity, WECC	51,430	3,287	3.12	51,430	3,287	3.12	0	0	0.00
Drying Fuel	2,609	167	0.16	42,491	2,716	2.57	0	0	0.00
Transportation- Pelletizing Plant to Market									
Transportation	47,369	3,027	2.87	47,369	3,027	2.87	9,474	786	0.74
Biomass Combustion	32,334	2,067	1.96	32,334	2,067	1.96	24,920	2,067	1.96
Total	178,579	11,413	10.82	218,462	13,962	13.23	49,134	4,074	3.86
Avoided Emissions									
Wildfire Risk	-253,702	-16,215	-15.37	-253,702	-16,215	-15.37	-202,422	-16,786	-15.91
Total with 100% Avoided Emissions	-75,123	-4,801	-4.55	-35,241	-2,252	-2.13	-153,288	-12,711	-12.05

LCI, Pulp Wood Planted Trees			
Collection & Transportation to Pelletizing/Chipping Plant		**Pellets**	**Chips**
Feedstock Moisture Content	%	50%	50%
Fertilization	g N/BD ton	2,000	2,000
Distance	mile	60	0
Processing - diesel	gal/ton	1.5	1.5
Transportation Mode	-	Truck	Truck
Pelletizing Plant			
Dry Matter Yield	ton BD product/ton BD feedstock	0.95	1
Feed to Product Ratio, AR	AR ton/ton product	1.98	1.000
Biomass Heating Value, HHV	MMBtu/BD ton	17.48	17.48
Heating Value of Pellet/Chip, LHV	MMBtu/delivered ton	15.25	7.13
Moisture Content of Biomass Fuel	%	6%	50%
Diesel	gal/ton	0.5	0.2
Electricity	kWh/ton	150	0
Biomass	MMBtu/ton	2.81	0.00
Transportation- Pelletizing Plant to Market			
Distance	mile	250	50
Transportation Mode	-	Truck	Truck
Drying Requirement Moisture of feed before pelletizing		12%	50%
Mass before drying		2.000	2.000
Mass after drying ton/BD ton		1.136	2.000
Mass of water dried off (lb/BD ton)		1727	0

LCA, Pulp Wood Planted Trees									
	Wood Pellets, Biomass Drying			Wood Pellets, NG Drying			Wood Chips		
Life Cycle CI (g CO_2e/	ton Pellet	MMBtu	MJ	ton Pellet	MMBtu	MJ	ton chips	MMBtu	MJ
Feedstock Collection & Transportation									
Transportation	22,498	1,475	1.40	22,498	1,475	1.40	0	0	0.00
Collection	36,476	2,392	2.27	36,476	2,392	2.27	18,432	2,586	2.45
Farming	3,820	251	0.24	3,820	251	0.24	7,560	1,061	1.01
Fuel Processing									
Diesel	6,129	402	0.38	6,129	402	0.38	2,452	344	0.33
Electricity, SERC	40,256	2,640	2.50	40,256	2,640	2.50	0	0	0.00
Drying Fuel	20,736	1,360	1.29	186,306	12,217	11.58	0	0	0.00
Transportation- Pelletizing Plant to Market									
Transport Truck	47,369	3,106	2.94	47,369	3,106	3	9,474	1,329	1.26
Biomass Combustion	31,514	2,067	1.96	31,514	2,067	1.96	14,730	2,067	1.96
Total	208,798	13,692	12.98	374,367	24,549	23.27	52,647	7,386	7.00

LCA, Pulp Wood Planted Trees, Rail Transport						
	Wood Pellets, Biomass Drying			Wood Pellets, NG Drying		
Life Cycle CI (g CO_2e/	ton Pellet	MMBtu	MJ	ton Pellet	MMBtu	MJ
Feedstock Collection & Transportation						
Transportation	22,498	1,475	1.40	22,498	1,475	1.40
Collection	36,476	2,392	2.27	36,476	2,392	2.27
Farming	3,820	251	0.24	3,820	251	0.24
Fuel Processing						
Diesel	6,129	402	0.38	6,129	402	0.38
Electricity, SERC	40,256	2,640	2.50	40,256	2,640	2.50
Drying Fuel	20,736	1,360	1.29	186,306	12,217	11.58
Transportation- Pelletizing Plant to Market						
Transport Train	6,523	428	0.41	6,523	428	0
Biomass Combustion	31,514	2,067	1.96	31,514	2,067	1.96
Total	167,952	11,013	10.44	333,522	21,871	20.73