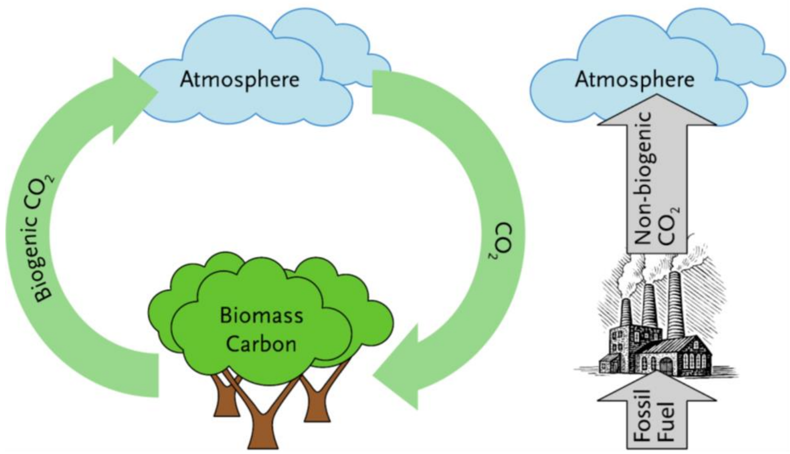

Biomass – Accounting Principles, Alternative Fates, and Verification

LCA.8192.224.2024
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DISCLAIMER

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TERMS AND ABBREVIATIONS

ABA	Annual Basis Accounting
ANL	Argonne National Laboratory
AR	As Received, weight includes moisture
ARB	Air Resources Board
BD	Bone dry
Btu	British Thermal Unit
BUC	Biogenic Uptake Credit
CA	California
CA PUC	California Public Utilities Commission
CARB	California Air Resources Board
C-BREC	California Biomass Residue Emissions Characterization
CCS	Carbon Capture Sequestration
CEMS	Continuous Emissions Monitoring Systems
CFS	Clean Fuel Standard
CHP	Combined Heat and Power
CI	Carbon intensity
CNG	Compressed Natural Gas
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
CORRIM	Consortium for Research on Renewable Industrial Materials
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CPUC	California Public Utilities Commission
ECCC	Environment and Climate Change Canada
EF	Emission Factors
EISA	Energy Independence and Security Act
EPA	U.S. Environmental Protection Agency
FAO	Food and Agriculture Organization
FSC	Forest Stewardship Council
g CO_2e	Grams of carbon dioxide equivalent
GHG	Greenhouse Gas
GPS	Global Positioning System
GREET	The Greenhouse gas, Regulated Emissions, and Energy use in Transportation Model
GTAP-BIO	Global Trade Analysis Project- Biofuels
GWP	Global Warming Potential
HF	Hydrogen Fluoride
HHV	Higher Heating Value
ICAO	International Civil Aviation Organization
IEA	International Energy Agency
iLUC	Indirect Land Use Change

IPCC	Intergovernmental Panel on Climate Change
ISCC	International Sustainability and Carbon Certification
LCA	Life Cycle Analysis or Life Cycle Assessment
LCI	Life Cycle Inventory
LCFS	Low Carbon Fuel Standard
LHV	Lower Heating Value
LPG	Liquified Petroleum Gases
LUC	Land Use Change
MC	Moisture Content
MJ	Megajoule
MMBtu	Million Btu
MSW	Municipal Solid Waste
MW	Mega Watt
mw	Molecular Weight
NG	Natural gas
NMHC	Non-methane Hydrocarbons
NPP	Net Primary Productivity
N_2O	Nitrous oxide
NO_x	Oxides of nitrogen
NWL	Natural Working Lands
NZ ETS	New Zeeland Emission Trading Scheme
OR CFS	Oregon Clean Fuel Standard
PCDD/F	Polychlorinated dibenzo-p-dioxin / Furan
PM	Particular Matter
RIA	Regulatory Impact Analysis
RFS	Renewable Fuel Standard
RSB	Roundtable on Sustainable Biomaterials
SAF	Sustainable Aviation Fuel
SFI	Sustainable Forestry Initiative
SOC	Soil Organic Carbon
UCO	Use Cooking Oil
USDA	United States Department of Agriculture
UWW	Urban Wood Waste
VOC	Volatile Organic Compound
WA CFS	Washington Clean Fuel Standard
WWF	World Wildlife Foundation

EXECUTIVE SUMMARY

The California Air Resources Board's failure to provide adequate guidance on the treatment of waste and residual biomass under the Low Carbon Fuel Standard (LCFS) undermines efforts to utilize natural and working lands effectively, hindering climate goals and wildfire risk mitigation. This includes guidance on the both biogenic carbon accounting for biomass and the characterization of biomass types and certification schemes. Clear guidance and support for waste biomass utilization can unlock substantial opportunities to reduce emissions, promote sustainable land management, and mitigate wildfires, advancing California's climate agenda.

This paper explores the challenges and opportunities associated with waste biomass under the California LCFS, and presents a comprehensive framework for determining appropriate accounting methods based on specific types of biomasses, conversion processes, and end-uses.

Five distinct categories of biomass are analyzed: energy crops, crop wastes, forest residues, urban landscaping residues, and construction and demolition waste. Each category exhibits unique characteristics and alternative fates that significantly impact carbon exchanges throughout the biomass lifecycle. Understanding these implications proves crucial for accurately representing the greenhouse gas (GHG) emissions reductions linked to biofuel production and utilization.

Energy Crops	**Crop Wastes**	**Forest Residues**	**Urban Landscaping Residues**	**C&D Waste**
Crops that are grown specifically for their energy content. ○Switchgrass ○ Miscanthus ○ Willow	Residues from agricultural crops. ○Corn stover ○ Wheat straw ○ Rice straw	Waste materials from forestry operations. ○Tree trimmings ○ Slash ○Stumps	Waste materials from urban landscapes. ○ Grass clippings ○ Yard waste	Waste materials from construction and demolition activities.

Figure S.1. Biomass Categories and Examples

To overcome the multifaceted challenges tied to waste biomass, the paper proposes a series of immediate actions that the CARB can take to advance the utilization of biomass-derived fuels under the LCFS. These actions are as follows:

Action 1: Develop a Near-Term Solution for Biogenic Carbon Accounting
CARB should actively develop a near-term solution for biogenic carbon accounting that enables future development. This solution should apply to biomass from forest residues, crop residues, forest slash, and thinnings. CARB should adhere to the carbon-neutral framework provided by the GREET modeling system, ensuring that these biomass sources contribute to California's carbon neutrality goals.

Action 2: Create a Tier 1 Calculator Framework
CARB should establish a Tier 1 calculator framework specifically designed for converting biomass into synthetic fuels, ethanol, hydrogen, and compressed natural gas (CNG). This framework will provide a standardized approach to accurately account for the carbon emissions associated with different conversion processes.

Action 3: Establish a Temporary Fuel Pathway Code for Carbon Neutrality
To support carbon neutrality, CARB must set up a temporary fuel pathway code with a safety margin. This code should apply to biomass fuels derived from different sources and conversion technologies. By setting a safety margin, CARB allows for any uncertainties in measuring carbon neutrality while still ensuring rigorous emissions reductions. This temporary code provides a flexible and adaptive approach to incentivize the use of biomass-derived fuels.

Action 4: Introduce a Temporary Fuel Pathway Code for Biomass Fuels and CCS
To further support carbon neutrality, CARB should introduce a temporary fuel pathway code tailored to biomass fuels and their production in conjunction with carbon capture and storage (CCS) technologies. This code would enable the inclusion of biomass-derived fuels that have undergone CCS, ensuring their emissions are effectively reduced or even sequestered. By incorporating CCS into the fuel pathway code, CARB can promote the deployment of advanced technologies that maximize carbon mitigation potential.

Action 5: Provide an Initial 10-Year Implementation Period
CARB should offer an initial 10-year implementation period based on carbon-neutral biomass, allowing for a safety margin. This implementation period accounts for the complexities and uncertainties surrounding biomass utilization and ensures a smooth transition for stakeholders. By providing a reasonable timeframe, CARB fosters confidence and stability in the biomass-derived fuels market, encouraging investment and innovation.

Action 6: Establish Biomass Verification Guidelines
In the latest proposed changes to the LCFS regulation, CARB has taken steps to explicitly include certain waste biomass categories. However, changes were made without stakehold engagement and an understanding of the nuances in the waste biomass industry. CARB should undertake the following actions to develop comprehensive biomass verification guidelines:

1. Define categories of biomass feedstocks, including thinnings and slash, agricultural residue, energy crops, and urban waste. This clear categorization enables accurate

assessment and consistent monitoring of different biomass sources, ensuring transparency and reliability in the verification process.

2. Review existing verification protocols and align them with the requirements of the LCFS program. CARB should conduct a thorough evaluation of current verification protocols, considering factors such as the inclusion of thinning and slash materials and the compatibility with relevant regulatory frameworks like the RFS. Additionally, alignment with recognized forestry certification schemes, such as the Sustainable Forestry Initiative (SFI) and the Forest Stewardship Council (FSC), should be ensured to enhance the credibility and integrity of the verification process.

In addition to these immediate actions, the paper highlights the importance of organizing workshops to enhance understanding and collaboration on biogenic carbon neutrality issues and residual biomass utilization. CARB should coordinate a residual biomass to energy/LCFS workshop, bringing together key stakeholders, such as academic institutions like UC Davis, state agencies, forestry development companies, environmental groups, and verification bodies. Additionally, CARB should actively participate in a third-party/wood utilization workshop, held in Sacramento, to foster collaboration and knowledge sharing among relevant experts.

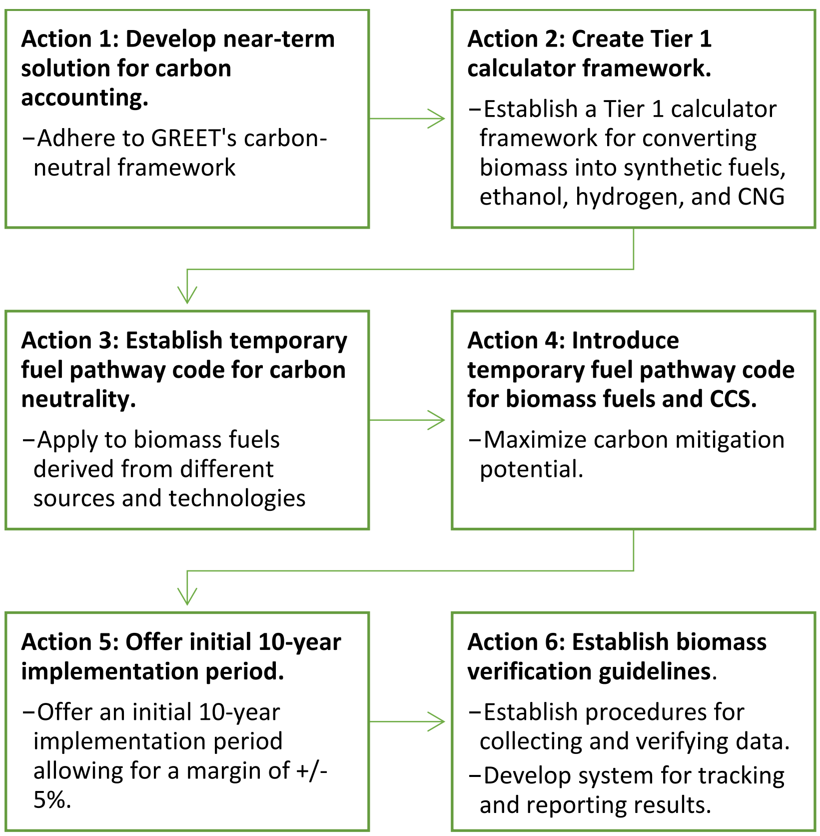


Figure S.2. Summary of Action Items

The following review supports these recommended action items through a comprehensive overview of the literature on biomass to energy. The review includes information on the properties of biomass, the alternative fate of biomass, biomass conversion processes, biogenic accounting in other regulated programs, and data sources for biomass emissions factors. This review provides a foundation for the development of policies and regulations for the utilization of biomass-derived fuels under the California LCFS.

1. Introduction

Achieving the State of California's goal[1] of carbon neutrality by 2045 requires a multifaceted approach to minimize greenhouse gas (GHG) emissions from sources and maximize their removal in sinks. Potential scenarios to accomplish this are described in reports (Baker, et al., 2020), and are under development through efforts including the California Air Resource Board's 2022 Scoping Plan (CARB, 2022a; CARB, 2022b).The transformation of energy systems and management of natural and working lands (NWL) is critical to reducing GHG emissions and mitigating the effects of climate change under these scenarios.

The California Air Resources Board (CARB) has the opportunity to bolster the effectiveness of its climate policies by aligning the goals of its scoping plan with existing policies, namely the California Low Carbon Fuel Standard (LCFS), and by providing clear guidance to developers on policy implementation. The LCFS is a powerful tool for reducing greenhouse gas (GHG) emissions in California's transportation sector. It incentivizes the consumption of low-carbon alternative fuels while reducing the use of conventional gasoline and diesel through the generation of billions of dollars' worth of credits and deficits each year. Alternative fuels producers receive credits under the LCFS based on the GHG reductions they achieve, as determined by a life cycle assessment (LCA) and verified by third-party reviewers.

CARB has fallen short of aligning the goals of the scoping plan with LCFS regulation and guidance in one key area: next-generation biomass-derived fuels. While CARB's 2022 scoping plan aims to mobilize private finance to invest in biomass management to reduce wildfire threats and spur innovation, the agency has failed to provide developers with guidance on how biomass feedstocks will be verified and accounted for under the LCFS. As a result, developers face obstacles when attempting to utilize biomass feedstocks in their fuel production processes.

To mobilize private finance, developers need clarity on how carbon emissions from biomass-derived feedstocks will be accounted for and verified under the LCFS. Biomass feedstocks differ fundamentally from fossil feedstocks in their ability to sequester CO_2 on time scales relevant to global climate change (EPA, 2011). However, when biomass or biologically based materials combust or decompose, carbon dioxide (CO_2) and other gases are released. Therefore, accounting for CO_2 emissions originating with biomass feedstocks – referred to as biogenic CO_2 - requires a framework for considering the scientific and technical issues surrounding tracking emissions through the biomass carbon cycle (EPA, 2011).

The lack of guidance on biogenic emissions is not without cause. Since the emergence of biomass-derived fuels, scientists have debated how carbon sequestered through photosynthesis and burned during combustion should be accounted for in well-to-wheels (WtW) life cycle assessments. Despite this debate, regulations in the US and abroad have defined accounting and verification frameworks for biomass-derived fuels, allowing their

[1] Established by California Executive Order, B-55-18, signed by former Governor Jerry Brown.

proliferation under policies aimed at reducing GHG emissions. This paper aims to review the current biogenic carbon accounting approaches and provide a framework for determining appropriate accounting methods for specific types of biomass, conversion processes, and end-uses.

To facilitate this, the paper examines five categories of biomass: energy crops, crop wastes, forest residues, urban landscaping residues, and construction and demolition waste. Each category of biomass has unique properties, alternative fates, and uses that significantly impact carbon exchanges throughout its lifecycle. Understanding these implications is critical to accurately represent biomass feedstocks' GHG emissions reductions associated with biofuel production and use. In the next section, we'll provide examples of each biomass category, and their respective properties and uses, as shown in Figure 1.1.

Figure 1.1. Examples of biomass types by category

The report is structured into multiple sections, each of which explores a different aspect of biomass and its conversion into energy. The initial section provides a comprehensive overview of biomass, including its sources, composition, and properties. Subsequently, various methods for assessing the impact of biomass on greenhouse gas emissions are discussed. This is followed by an exploration of alternative applications of biomass. Additionally, the report examines the emissions generated during biomass collection and presents different approaches for verifying the sustainability of biomass. The report further provides recommendations for accounting for biogenic emissions and offers specific suggestions for policymakers. For a visual representation of the paper's organization, refer to Figure 1.2.

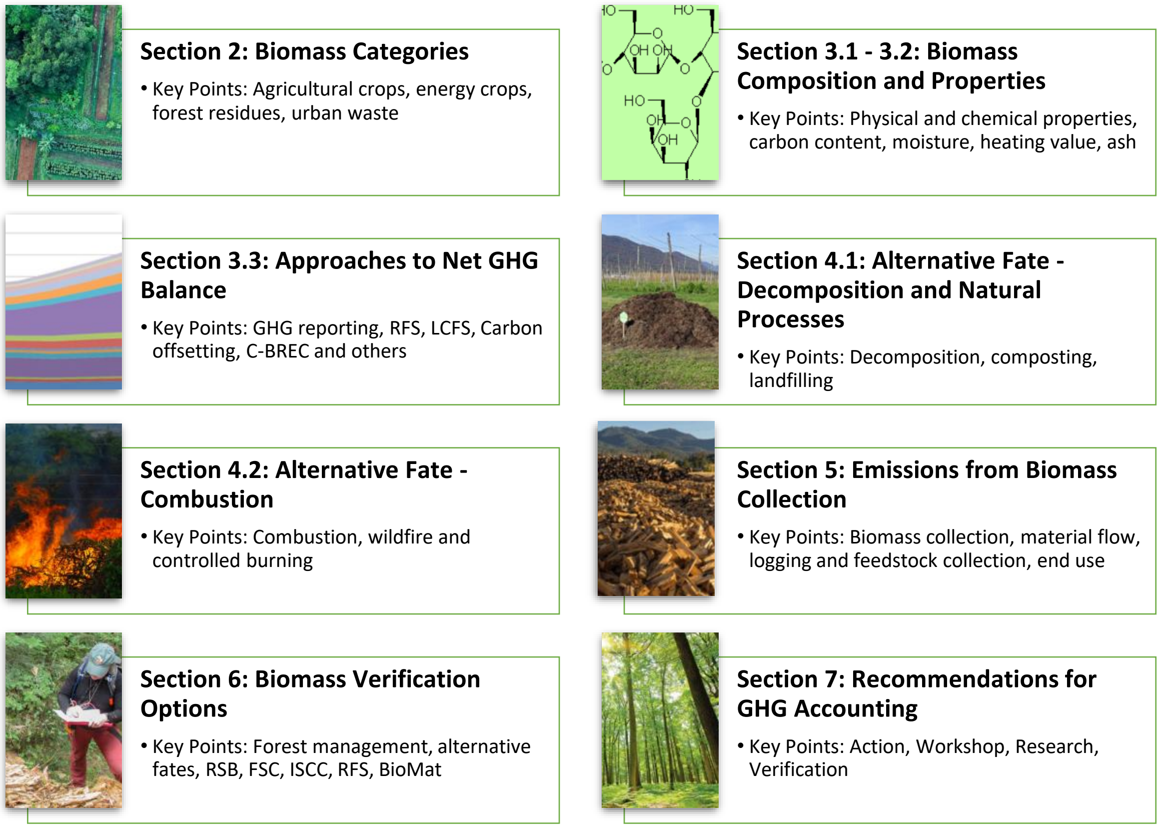


Figure 1.2. Organizational structure of the report

1.1 Objectives

Developers seeking to invest in infrastructure and technology for producing low-carbon next generation biomass-derived fuels face several significant challenges. These include a lack of guidance on how the net carbon balance of biomass will be assessed under California's LCFS regulation, the need to educate CARB staff on the specific alternative fate of their particular biomass feedstock, and the uncertainty around what CARB will require for verification of biomass-derived feedstocks.

This paper aims to address each of these challenges by:

1) Providing insights into the net carbon balance of different types of biomass
2) Describing the alternative fates of biomass based on category, location, and collection practices
3) Reviewing current verification schemes and options for each biomass category and location.
4) Recommending actions that would provide an immediate path forward for developers seeking to invest in low-carbon next-generation biomass derived fuels.

The following subsections further describe each of these objectives.

1.1.1 Addressing the net carbon balance of biomass

The net carbon balance of biomass refers to the difference between the amount of carbon emitted by biomass feedstocks and the amount of carbon sequestered through photosynthesis. It is a critical factor that must be considered when assessing the environmental impact of biomass-derived fuels.

The absence of a defined policy by CARB addressing the net carbon balance of biomass feedstocks under the LCFS has significant implications for developers of biomass derived fuels. When seeking funding for their projects, developers must provide financial projections that include expected credit generation under the LCFS. Under the LCFS, credit generation is directly linked to GHG emission reductions, which are determined by CARB-approved accounting principles. However, with no clear guidelines on accounting for biomass, developers cannot accurately project credit generation and may find it challenging to secure funding for their projects.

To address this challenge, we aim to provide insights on the net carbon balance of biomass, including its full lifecycle from production, processing, to end use. Given the complex nature of the issue, we have conducted an extensive literature review to gather information from a range of sources, including academic papers, policy documents, and industry reports. We have also reviewed the approach to net carbon balance in regulated programs, such as those used to certify the sustainability of bioenergy products. By examining the factors that can affect the net carbon balance of biomass, including biomass type, production and processing methods, and end use of the bioenergy product, we aim to provide a comprehensive understanding that could help CARB make a policy decision on this critical issue.

1.1.2 Describing the alternative fate of biomass derived feedstocks

The counterfactuals or alternative fates of biomass are the potential outcomes for a particular biomass type if it were not used for bioenergy. These alternative fates, such as food production for energy crops, are essential in determining the effect of a biomass feedstock on the net carbon balance. It is important to compare a bioenergy system to scenarios that would have occurred had the biomass not been utilized, as a bioenergy system does not exist in a vacuum.

CARB needs to provide a framework for understanding the alternative fates of specific biomass categories in order to facilitate investment in low-carbon next-generation biomass-derived fuels. The alternative fate of a biomass feedstock is highly dependent on factors such as biomass type, location, and farming or collection practices. For instance, woody biomass feedstocks collected from California forests to mitigate forest fire risk would have otherwise emitted carbon during a wildfire event, while woody biomass feedstocks collected from managed The South Eastern U.S. forests could increase net carbon sequestration by diverting resources to healthy trees.

To understand the alternative fates of different biomass types, we have conducted a literature review and interviewed biomass-derived fuel developers. Our findings provide generalizations that could be helpful for CARB in understanding the alternative fate of various biomass categories and locations.

1.1.3 Verification Schemes for Biomass-Derived Feedstocks

Verification of biomass-derived feedstocks is critical to ensuring that they meet sustainability standards and are aligned with the alternative fate framework. To comply with LCFS regulations, CARB will require verification of all steps in the supply chain, from cultivation to processing, trade, and transport of biomass-derived fuels. However, the lack of guidance from CARB on how biomass-derived feedstocks will be verified poses a significant hurdle for developers seeking to invest in low-carbon next-generation biomass-derived fuels.

Fortunately, several certification schemes currently exist that allow for the certification of the complete supply chain of biomass-derived fuels. Many foresters in the U.S. are already required to gain certification under one or more of these schemes. For example, the Forest Stewardship Council (FSC) and the Sustainable Forestry Initiative (SFI) offer certification programs for sustainable forestry practices. The Programme for the Endorsement of Forest Certification (PEFC) is a global certification scheme that recognizes sustainable forest management.

In addition, the U.S. Renewable Fuel Standard (RFS) has worked with developers to certify biomass-derived feedstocks. The RFS requires that renewable fuel producers register with the Environmental Protection Agency (EPA) and provide documentation showing that their feedstocks meet the greenhouse gas (GHG) reduction and sustainability criteria set by the EPA. The strategies used under the RFS may inform possible strategies under the CA LCFS.

This paper aims to provide detailed descriptions of current biomass verification schemes, including a comparison of different aspects of each certification scheme. By examining existing certification programs, the paper aims to help developers navigate the complex landscape of biomass verification and provide recommendations for CARB on how best to verify biomass-derived feedstocks under the CA LCFS.

1.1.4 Providing a Path Forward for Investment in Low-Carbon Biomass-Derived Fuels

The issues surrounding biomass-derived fuels are complex and have been the subject of ongoing scientific and policy debate. However, it is essential to address these issues in order to promote the development of alternative fuels and support California's goals for reducing greenhouse gas emissions and mitigating the risks of wildfires and natural resource loss.

Inaction on the part of CARB and other stakeholders could hinder progress in this area, which would ultimately undermine efforts to achieve important environmental goals. Given the urgency of the situation, it is critical that CARB take immediate steps to address the challenges related to biomass-derived fuels.

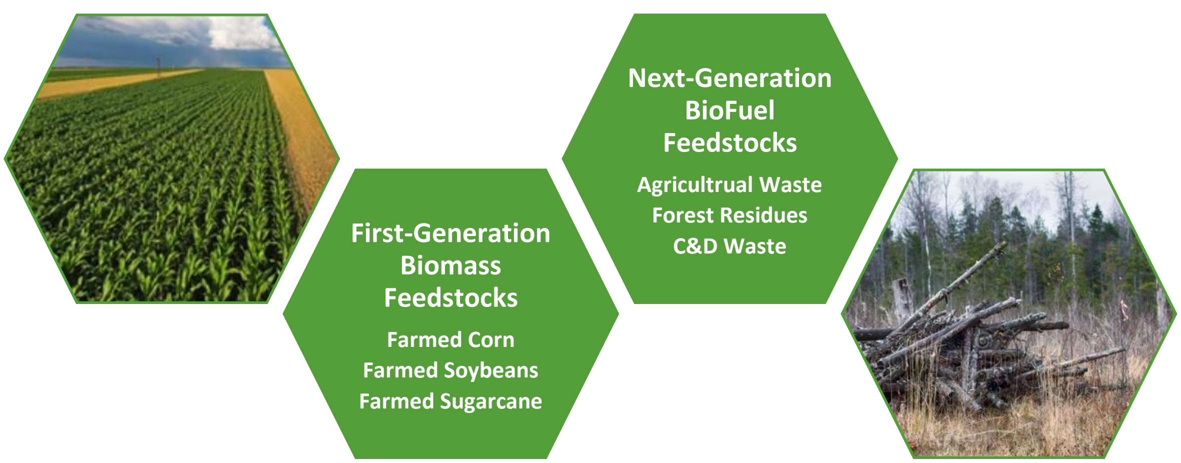
The paper concludes by offering recommendations that are designed to provide a practical and actionable path forward for developers seeking to invest in low-carbon next-generation biomass-derived fuels. By taking these steps, CARB can remove barriers for developers seeking to invest in low-carbon alternative fuels.

2. BACKGROUND

Biomass-derived fuel has a long history, with roots dating back to ancient civilizations' use of vegetable oils for lighting. The interest in using biomass feedstocks for transportation fuel resurged in the 1970s during the energy crisis, with countries like Brazil and the US investing in biofuels as a way to reduce their dependence on foreign oil.

Today, biofuels are an essential part of the renewable energy mix in the United States. Both federal and statewide policies exist to incentivize biofuel production. For instance, the Renewable Fuel Standard (RFS) is a national policy that requires a specific volume of biofuels to be blended into the transportation fuel supply each year. Additionally, statewide programs like California's Low Carbon Fuel Standard (LCFS) require a certain reduction in greenhouse gas emissions from transportation fuels each year. Biofuels are an important way to achieve this reduction, with alternative fuels producers receiving credits for GHG reductions based on a life cycle assessment (LCA).

First-generation biofuels were made from crops like corn and soybeans, but there has been a significant shift towards next-generation biofuels that use non-food feedstocks like agricultural waste and forest residues. This shift is due to concerns about using food crops for fuel and the need to reduce the carbon intensity of transportation fuels. Using agricultural waste and forest residues to produce biofuels can create a more sustainable and circular supply chain. Additionally, it reduces the amount of waste sent to landfills, creates new revenue streams for farmers and foresters, and helps to mitigate the risk of wildfires by removing excess biomass from forests.



2.1 The Carbon Cycle & Biomass-Derived Feedstocks

Understanding the carbon cycle is crucial in developing an accounting framework for both first-generation and next-generation biomass-derived fuels. Biogenic and non-biogenic greenhouse gas (GHG) emissions are key components in this accounting framework. While both bio-based and fossil-based materials emit CO_2 during combustion, bio-based materials also remove CO_2

from the atmosphere through photosynthesis (Figure 2.1). Carbon sequestration is the process of capturing and storing carbon from the atmosphere, and it can occur through natural or artificial processes such as biological, geological, or technological carbon sequestration.

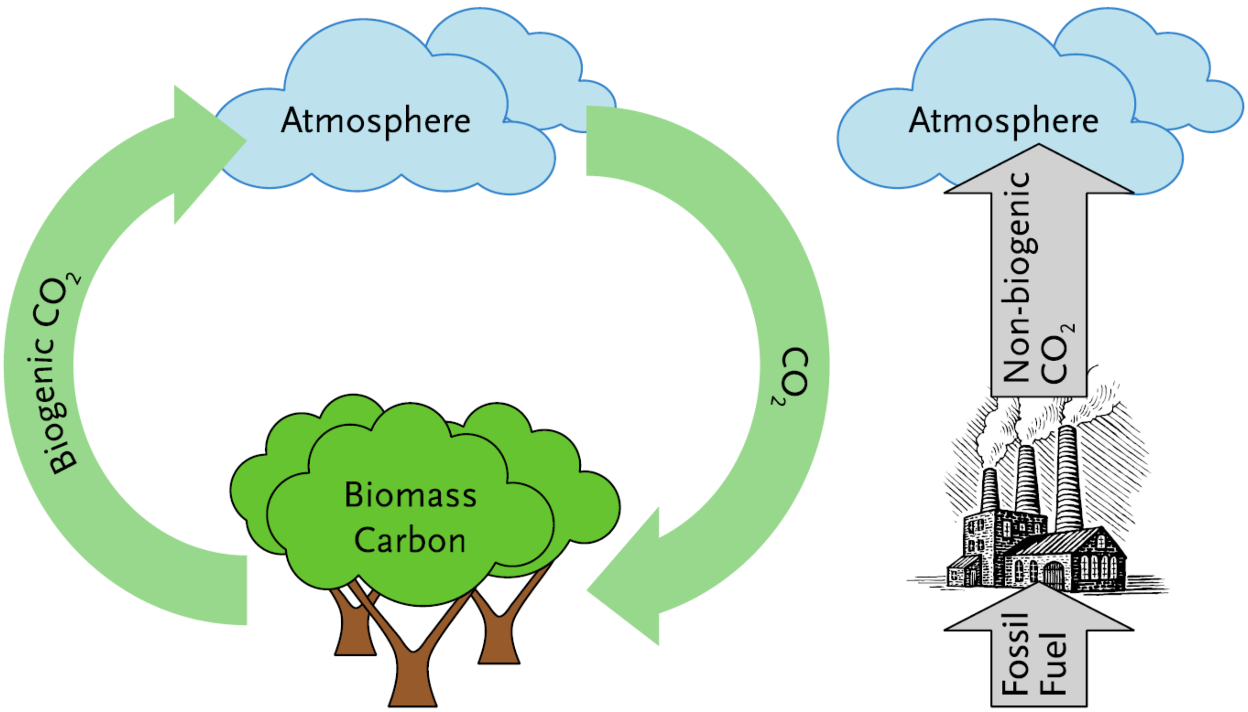


Figure 2.1. Biogenic and Non-biogenic Sources of CO_2 to the Atmosphere.
Source: IEA, 2018[2]

During the growth phase of vegetation, a certain amount of biogenic carbon is taken up from the atmosphere. The sequestered carbon is distributed in the soil, soil ecosystem, and various parts of the plant or tree. However, some of this carbon is also released back into the atmosphere through respiration and other interactions. Figure 2.2 illustrates the major exchanges of biogenic carbon that take place during plant growth. The carbon sequestered in the form of soil and underground biomass is assumed not to change considerably over longer time-periods. The aboveground biomass left on the field is assumed to subsequently decompose aerobically, releasing roughly the same amount of carbon back into the atmosphere as was absorbed (some of which may be converted into microbial biomass).

[2] IPCC distinguishes between the slow domain of the carbon cycle, where turnover times exceed 10,000 years, and the fast domain (the atmosphere, ocean, vegetation and soil), vegetation and soil carbon have turnover times in the magnitude of 1– 100 and 10– 500 years, respectively. Fossil fuel transfers carbon from the slow domain to the fast domain, while bioenergy systems operate within the fast domain.

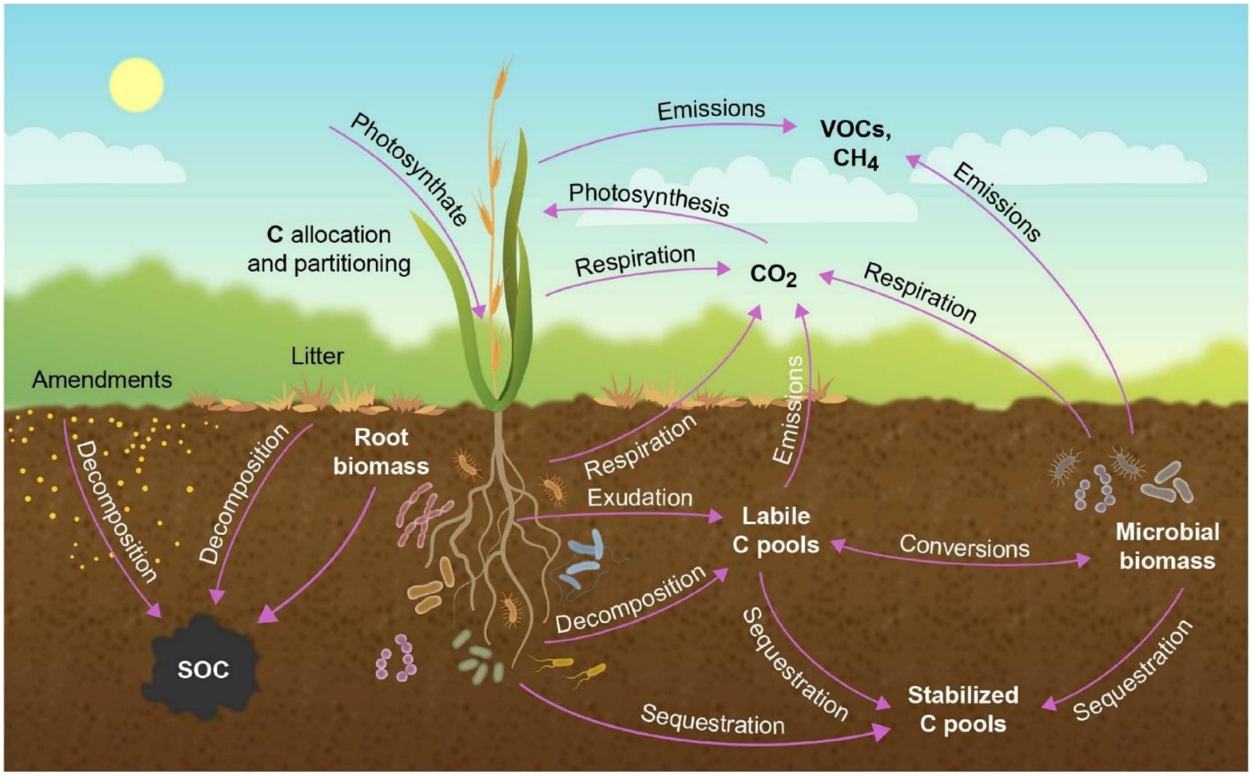


Figure 2.2. Carbon flux during crop farming.

2.1.1 Time Accounting

Time accounting for biomass feedstocks is particularly important because of the difference between biogenic and fossil CO_2 emissions. Fossil fuels were formed over millions of years and are extracted and consumed in a single pulse, resulting in a large and immediate release of carbon into the atmosphere. In contrast, biomass feedstocks can be grown and harvested on much shorter timescales, and carbon sequestration and emissions are distributed over time.

Different types of biomass feedstocks have different growth and harvesting cycles, which also affects the timing of carbon emissions and sequestration. For example, corn can be grown and harvested on an annual cycle, while woody biomass harvested from managed forests may take 20-50 years to regrow. Waste biomass feedstocks may have a timing related to the seasonality of harvesting a food crop, but the alternative fate of decomposition may take place over months or years.

In order for CARB to accurately account for the carbon emissions and sequestration associated with biomass-derived feedstocks, it is important to take into account these different timeframes and understand how they relate to global warming potential (GWP).

Global Warming Potential (GWP) Time Horizon

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 1 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 (Washington Administrative Code, 2022) 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).

Table 1 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. (IPCC AR4, 2007; IPCC AR5, 2013).

Table 1. Global Warming Potential of GHG Pollutants

IPCC Assessment	**AR6[c]**		**AR5[a]**		**AR4[b]**	
GWP Time Horizon	100	20	100	20	100	20
CO_2	1	1	1	1	1	1
CH_4	30	83	30[a]	85	25[a]	72
N_2O	273	273	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, et al., 2013)
[b] Fourth IPCC Assessment report published in 2007 (IPCC AR4, 2007)
[c] Sixth IPCC Assessment report published in 2022 (IPCC AR6, 2022)

2.1.2 Biomass Sources

The source of biomass is a crucial factor that influences the carbon emissions of a bioenergy system over its lifetime. Various variables such as the growing period, plant species, climate, and management practices can have a significant impact on the biogenic carbon accounting of biomass. Therefore, it is essential to consider these factors while assessing the carbon footprint of biofuels.

To facilitate the understanding of biogenic carbon accounting, this report categorizes biomass-derived feedstocks into five main categories: energy crops, crop wastes, forest residues, urban landscaping residues, and construction and demolition waste. Each of these categories is introduced in the following sections. These categories are referenced throughout the report as each is examined for biogenic accounting methodology, alternative fate, and verification options.

Five distinct categories of biomass are analyzed: energy crops, crop wastes, forest residues, urban landscaping residues, and construction and demolition waste. Each category exhibits unique characteristics and alternative fates that significantly impact carbon exchanges throughout the biomass lifecycle. Understanding these implications proves crucial for accurately representing the greenhouse gas (GHG) emissions reductions linked to biofuel production and utilization.

Energy Crops	**Crop Wastes**	**Forest Residues**	**Urban Landscaping Residues**	**C&D Waste**
Crops that are grown specifically for their energy content.	Residues from agricultural crops.	Waste materials from forestry operations.	Waste materials from urban landscapes.	Waste materials from construction and demolition activities.
○Switchgrass ○ Miscanthus ○ Willow	○Corn stover ○ Wheat straw ○ Rice straw	○Tree trimmings ○ Slash ○Stumps	○ Grass clippings ○ Yard waste	

Figure 2.3. Biomass Categories and Examples

2.1.3 Energy Crops

Energy crop biomass is derived from dedicated crops grown primarily for use as biofuels, such as corn, sugarcane, and soybean. These crops are typically annual, meaning they are planted and harvested within a single growing season. In the case of corn, for example, the crop is typically planted in the spring, harvested in the fall, and processed into ethanol or other biofuels. The carbon accounting for energy crop biomass feedstocks is typically based on the assumption that the carbon absorbed during plant growth is returned to the atmosphere relatively quickly upon combustion or decay, and that the crops are replanted annually or within a few years.

Farmed trees are another type of energy crop biomass, which are considered short-rotation crops. These include species such as willow and poplar, which are harvested in shorter timeframes and smaller in diameter than trees used for timber and other traditional uses. Poplar is generally grown in Mid-Atlantic and Southeastern regions of the US. Willow is a cold-tolerant species, and is grown in the Upper-Midwest and Northeastern regions of the US (Jackson, 2021). These crops can be harvested and processed for use as bioenergy on a cycle ranging from one to ten years, depending on the species and management practices used.

2.1.4 Crop Waste and Residue

Crop residues are an inevitable byproduct of agricultural production and represent a substantial source of biomass feedstocks for the production of biofuels and other bio-based products. Crop residues can be classified into three categories: primary residues, secondary residues, and tertiary residues. Primary residues are directly removed from the field after harvest, such as straw and stover. Secondary residues are generated during processing, such as bagasse and molasses from sugarcane processing. Tertiary residues are residues left on the field after harvest, such as root systems and plant debris.

While crop residues have traditionally been viewed as a waste product and left to decompose, they offer a significant opportunity to provide sustainable, low-carbon alternatives to fossil fuels.

2.1.5 Forest Waste and Residue

Forest wastes and residues come from two main sources: sustainable forest management practices and wildfire mitigation. Forest residues are a vital component of sustainable forest management practices. When trees are grown for commercial purposes such as timber, forest residues are generated through pre-commercial thinning operations and harvest practices. Pre-commercial thinning involves the removal of rows of trees in order to decrease competition for sunlight, water, and soil resources, and enhance growth rate and desired log quality. The frequency of thinning depends on the species, site productivity, desired final product, and local market conditions. During harvest operations, limbs, tree tops, and trees considered to have either poor form or health are also culled.

Both pre-commercial thinning and harvest residues are stored in slash piles, which are either left to decompose in-situ or are burned to facilitate reseeding. The decomposition process is a form of unmanaged composting. If left unmanaged, the decomposition process can result in significant greenhouse gas emissions, primarily methane.

Forest waste from wildfire mitigation is another source of biomass feedstock. Wildfires can pose a significant threat to communities and ecosystems, and forest management practices often include measures to mitigate the risk of wildfires. These measures can include thinning of overgrown forests and removal of dead or diseased trees. The resulting forest waste can be used as a feedstock for bioenergy production, as well as for other purposes such as soil amendment or animal bedding.

It is important to note that the use of forest residues must be managed properly to avoid unintended negative consequences, such as soil depletion and habitat destruction.

2.1.6 Urban Landscaping Residues

Urban landscaping residues refer to the organic material that is generated from maintenance activities of parks, golf courses, and residential areas such as pruning, mowing, trimming, and fall cleanup. These residues can be used as a feedstock for next-generation biofuels, which can reduce dependence on fossil fuels and contribute to lower carbon emissions.

Right-of-way management is a significant source of urban landscaping residues. Roadsides, highways, and utility rights-of-way generate significant amounts of organic material from regular maintenance activities. Landscaping waste from parks and golf courses also contribute to the overall availability of urban landscaping residues. These materials are typically collected and transported to landfills, which not only leads to higher costs for municipalities but also results in greenhouse gas emissions. Utilizing these materials as a feedstock for next-generation biofuels not only provides an alternative to landfills but also contributes to the development of a circular economy.

2.1.7 Construction and Demolition Waste

Construction and demolition (C&D) waste is another potential source of biomass feedstock for next-generation biofuels. C&D waste includes materials such as wood, concrete, and metals that are generated from construction and demolition activities. One example of C&D waste that can be used for bioenergy production is railway ties. Railway ties are typically made from treated wood, which contains chemicals such as creosote that can make it difficult to dispose of. However, by converting railway ties into biofuels, the energy content of the wood can be harnessed and the environmental impact of disposal can be minimized. In addition, wood pallets, which are commonly used in shipping and storage, can also be a potential feedstock for biofuels. These pallets are often discarded after a single use and can contribute to the waste stream. By using wood pallets as a feedstock, their energy content can be harnessed while reducing waste.

2.2 The Alternative Fate of Biomass

The alternative fates, also known as counterfactuals, of biomass refer to the possible outcomes of a particular biomass type if it had not been utilized for bioenergy. Accurately accounting for the net carbon balance of a biomass feedstock requires considering these alternative fates. This means that a biobased product or bioenergy system must be compared to scenarios that would have occurred if the biomass had not been used.

Figure 2.4 presents examples of possible alternative fates for various types of biomass feedstock. For example, crops such as corn, sugarcane, and soybean could be utilized as agricultural products, either for direct consumption or as ingredients in food processing, if not used for biofuel production. Similarly, crop residues such as corn stover, sugarcane straw, and rice straw could be left for in-situ decay. Lumber and farmed trees like willow and poplar could be utilized to produce commercial products like paper, pulp, and pellet fuel if not used for biofuel production.

Ultimately, the full life cycle GHG emissions of a biomass feedstock are highly dependent on its alternative fate. A full life cycle assessment compares the emissions that occur in a bioenergy system to the emissions that would have occurred if the bioenergy system did not exist, taking into account the various alternative fates of the biomass feedstock.

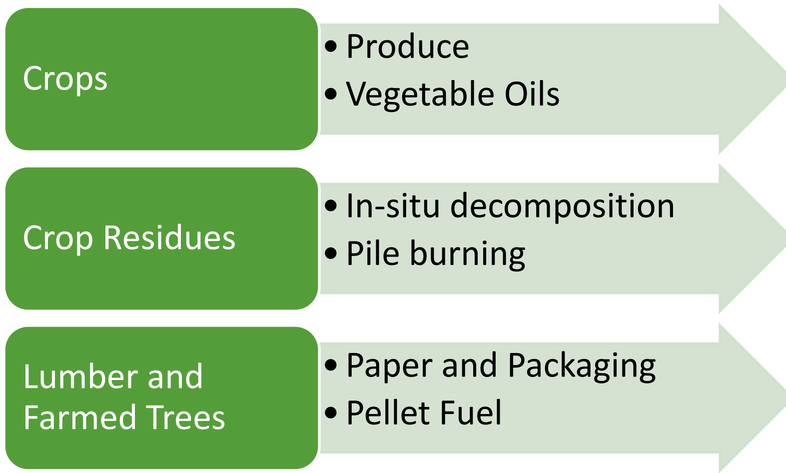


Figure 2.4. Possible alternative fates of biomass if not used for bioenergy.

Land Use Change (LUC) and Indirect Land Use Change (iLUC)

Land use change (LUC) and indirect land use change (iLUC) refer to the potential changes in land use patterns that may result from the production of biofuels. LUC occurs when land previously used for other purposes, such as agriculture or forestry, is converted into biofuel crop production. iLUC occurs when biofuel crop production displaces existing agricultural or forestry land, resulting in the conversion of other land, such as forests or grasslands, into new agricultural or forestry land to meet the displaced demand for food or other products. The potential for LUC and iLUC to occur and their associated greenhouse gas emissions must be considered when evaluating the net carbon balance of a particular biofuel feedstock and its alternative fates.

CARB has provided guidance on performing a comprehensive lifecycle analysis for biomass feedstocks in relation to land use change (LUC) and indirect greenhouse gas (GHG) emissions. This includes providing a LUC analysis by either performing a LUC analysis using GTAP-BIO coupled with the AEZ model to derive a feedstock-fuel specific LUC value, or demonstrating through robust data and analysis that the available LUC value of the LCFS regulation (shown in Table 2 below) is applicable to the feedstock sourced from a particular country or new US-based feedstock.

CARB guidance further states to provide a comprehensive LUC report summarizing model parameters used in the model including elasticities, baseline year, and the magnitude of biofuel demand, and all modeling assumptions should be clearly stated.

Table 2. Land Use Change (LUC) emission for use in CA LCFS Regulation

Biofuel	LUC (gCO_2/MJ)
Corn Ethanol	19.8
Sugarcane Ethanol	11.8
Soy Biomass-Based Diesel	29.1
Canola Biomass-Based Diesel	14.5
Grain Sorghum Ethanol	19.4
Palm Biomass-Based Diesel	71.4

It is worth noting that this guidance pertains to all biomass-derived feedstocks, regardless of category. Developers may argue that there is no LUC or iLUC emissions associated with biomass waste and residue feedstocks. This is because these feedstocks are typically generated as byproducts or waste from existing land uses, such as agriculture, forestry, or manufacturing processes, and therefore do not require additional land use or land conversion. However, CARB may still require a full evaluation of potential LUC and iLUC for these feedstocks to comply with LCFS regulation.

2.3 Properties of Biomass

Biomass feedstock properties have a significant impact on the emissions of a bioenergy system throughout its lifecycle. These properties affect combustion characteristics, efficiency, and emission factors used in the system's calculations. For instance, carbon content, heating value, and moisture content can affect biomass's effectiveness as a fuel in bioenergy systems. In addition to these, other properties such as ash content, bulk density, and particle size distribution can also affect the combustion and handling of biomass. Materials with high heating value and carbon content are usually more cost-effective and efficient to use as fuel, while high moisture content can decrease biomass heating value and make it harder to handle and transport. The following subsections examine and summarize the key biomass properties and their impact on the carbon balance.

2.3.1 Biomass Composition

The composition of biomass fuels is associated with a multitude of physical forms, but for nearly all plant species, the main structural cell wall components are cellulose, hemicellulose and lignin (Klass, 1998). Cellulose is the major structural polymer of a plant cell wall, while hemicellulose serves to strengthen the cell wall and interact with lignin, which provides flexibility and strength (see Figure 2.5 for the spatial arrangement of cellulose, hemicellulose and lignin).

The properties of biomass will be determined largely by their proportion of cellulose, hemicellulose and lignin. Lignin has a relatively high carbon content, however its structural properties are less favorable for use as carbon fiber, while cellulose has a lower carbon content, but more beneficial structure (Bengtsson, 2019). Cellulose content of biomass ranges from 9% to 80%, while hemicellulose content ranges from 10% to 50%, and lignin content ranges from 10% to 50% (Xu & Li, 2017). The percentages of each cell component for select biomass types are shown in Table 3.

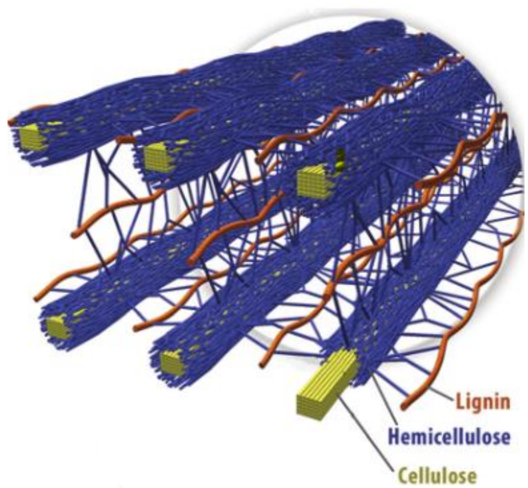


Figure 2.5. Spatial arrangement of cellulose, hemicellulose, and lignin in the cell wall of biomass. Source: (Brandt, Grasvik, Hallet, & Welton, 2013).

Table 3. Percentage of cellulose, hemicellulose and lignin content in select biomass types. Source: (Blaschek & Ezeji, 2022)

Biomass Type	Cellulose	Hemicellulose	Lignin
Hardwood	40-50	24-40	18-25
Softwood	45-50	25-35	25-35
Corn cobs	45	35	15
Grasses	25-40	35-50	10-30
Wheat Straw	33-40	20-25	15-20
Rice Straw	40	18	5.5

Calculating Emissions from Carbon Content

The proportion of cellulose, hemicellulose, and lignin in biomass determines the carbon content, which serves as a bases for calculating carbon emissions. However, other factors, such as moisture content and ash contamination, can also impact the actual emissions that occur.

For example, wood with a carbon content of 45 % would contain 450 g carbon per kg, or if fully oxidized it would emit 1,650 g of CO_2. However, if the wood contains 30% moisture, it would only contain 315 g carbon and emit 1,154 g CO_2. Since the effort the track biogenic carbon depends both on the emissions from and use as well as the alternative fate, establishing the range in carbon content of biomass helps clarify their contribution to the net carbon balance.

Physical Properties

Physical properties of biomass can significantly impact its suitability for use in various bioenergy applications. For example, electrical conductivity is an important physical property, as biomass with high electrical conductivity may be more suitable for use in fuel cells or other energy conversion devices. Particle density is another property that can be important in bioenergy, as biomass with high particle density may be more energy-dense, meaning that it contains more energy per unit of weight or volume. This can be beneficial for certain bioenergy applications, such as the production of biofuels. The shape of biomass particles can also affect their flowability and handling characteristics, which can be important in certain bioenergy processes. For example, biomass with irregular or elongated shapes may be more difficult to handle and may require additional processing steps to prepare it for use in bioenergy systems. Finally, the thermal conductivity of biomass can affect its ability to transfer heat, which can be important in certain bioenergy applications such as the production of biochar or the use of biomass for thermal energy production. Biomass with high thermal conductivity may be more efficient at transferring heat than biomass with low thermal conductivity. Physical properties of biomass are summarized in Table 4 which was obtained from Wiebren De Jong's chapter in Biomass as a Sustainable Energy Source for the Future (De Jong & Ruud, 2014).

Table 4. Physical properties of solid biomass and their possible effects in processing

Physical property	Effect
Bulk density	Logistics (storage, transportation, handling)
Electrical conductivity	Microwave processing, particle cleaning via electrostatic precipitation (ash), or fine particulate matter repulsion by plants, e.g., *sea buckthorn* (tinyurl.com/luyld2g)
Hygroscopy	Logistics (storage, transportation, handling)
Particle density[a]	Conversion processes (e.g., segregation)
Particle porosity[a]	Formation of fines in processing, intraparticle heat and mass transfer impacted and so conversion
Particle shape (distribution)	Storage behavior (dimension/shape of a heap, bridging in bunkers, self-ignition), transportation (conveying) characteristics, mass and heat transfer behavior in conversion processes
Particle size (distribution)	Storage behavior (dimension/shape of a heap, bridging in bunkers, self-ignition), transportation (conveying) characteristics, mass and heat transfer behavior in conversion processes
Thermal conductivity	Physicochemical processing (heat transfer)

Chemical Properties

Chemical properties of biomass are listed in Table 5. These were also abstracted from de Jong report Biomass as a Sustainable Energy Source for the Future (De Jong & Ruud, 2014).

The elemental properties of biomass refer to the amounts of different elements present in the biomass, such as hydrogen (H), oxygen (O), nitrogen (N), and potassium (K). These elements can affect the energy content and reactivity of the biomass, as well as other properties such as its density and nutritional value. For example, biomass that is high in hydrogen may be more reactive and have a higher energy content, while biomass that is high in oxygen may be less reactive and have a lower energy content.

Fixed carbon refers to the carbon present in biomass that is not volatilized during pyrolysis or combustion. The fixed carbon content of biomass can be used to predict its energy content and behavior during bioenergy processes. Biomass with a high fixed carbon content may be more energy-dense and may be more suitable for use in certain bioenergy applications.

Ultimate analysis is used to determine the elemental composition of biomass. This information can be used to calculate the energy content of the biomass and predict its behavior during various bioenergy processes.

Similarly, proximate analysis involves the determination of the major chemical components of biomass, including the percentages of moisture, ash, volatile matter, and fixed carbon present. This information can be used to predict the behavior of biomass during processes such as combustion and fermentation, and can also be used to compare the quality of different biomass feedstocks. Table 5 shows the elements in solid biofuels and their effect in energy conversion.

Table 5. Elements in solid biofuels and their possible main effects in energy conversion processes

Element	Effect
C, carbon	Heating value, possible emission of CO, Generation of CO_2 emissions
H, hydrogen	Heating value
O, oxygen	Heating value (negatively impacting)
N, nitrogen	Emission of NO, NO_2 (together termed NO_x), and N_2O
Cl, chlorine	Emission of HCl and polychlorinated dibenzo-p-dioxin/furan (PCDD/F), causing corrosion and catalyst poisoning
S, sulfur	Emission of SO_2, SO_3 (both named SO_x), causing corrosion and catalyst poisoning
F, fluorine	Emission of HF, causing corrosion
K, potassium	Corrosion, ash melting, ash utilization, aerosol formation
Na, sodium	Corrosion, ash melting, ash utilization, aerosol formation
Mg, magnesium	Ash melting, ash utilization, deposits formation
Ca, calcium	Ash melting, ash utilization, deposits formation
P, phosphorus	Ash utilization, deposits formation
Trace elements	Emissions, ash utilization, aerosol formation

2.3.2 Feedstock Properties

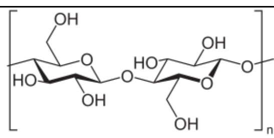
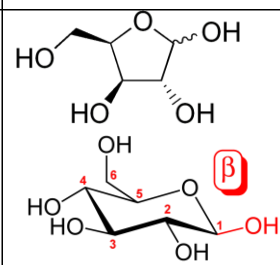
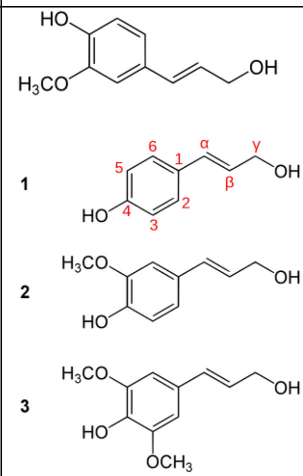
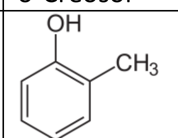
Feedstock properties are crucial when considering the life cycle emissions of a biomass feedstock to fuel system. Carbon content, moisture content, and heating value are some of the important properties to consider. Carbon content plays a significant role in determining the greenhouse gas emissions associated with its production and use. Moisture content impacts the efficiency of biofuel production and combustion. High moisture content can increase the energy required for drying and decrease the heating value of the feedstock. Heating value measures the energy that can be obtained from the feedstock when burned, and it affects the efficiency and cost-effectiveness of biofuel production. Below, we describe how each of these properties is related to the carbon balance of a biomass to biofuel system.

Carbon Content

Accurate modeling of the carbon content of biomass is crucial to understanding the role of plant carbon sequestration on the carbon balance of an energy system. The most widely used canonical value of the carbon content of biomass is 50% on a dry matter basis, which is calculated from an average molecular formula of $CH_{1.44}O_{0.66}$, which has a composition of about 50% carbon, 6% hydrogen, 44% oxygen, and trace amounts of metals (Ma, et al., 2017). However, the actual carbon content of biomass can vary drastically depending on the biomass category. Carbon content and other specific properties can be found in different Data sources, those are explained with more detail in Section 2.1.

The carbon content of biomass depends on its composition which is primarily cellulose, hemicellulose, and lignin as well as ash and moisture. Carbon content is consistent across species with the same chemical formula; however, carbon content varies in each material. Cellulose is a biologically well-defined material with a carbon content of 44.4%, however the other components of biomass consist of several different structures each with their own chemical formula and carbon content. Table 6 shows example structures for biomass components with an example carbon content calculated based on the typical formula. The range of carbon content based on literature values is also shown. Additionally, biomass contaminated with ash will have a lower carbon content than samples that aren't contaminated. As an example of the range of carbon content in biomass, Table 6 shows the carbon content and heating value for some woody biomass (hard wood, soft wood and waste) from different sources.

Table 6. Biomass Components Structure and Carbon Content

Component	Cellulose	Hemicellulose	Lignin	Tar and Pitch
Formula	$(C_{12}H_{20}O_{10})_n$	$(C_5H_{10}O_5)_m$	$(C_9H_{10.2}O_{3.4})_m$	$(CH_3)C_6H_4(OH)$ o-Creosol
Structure[a]				
% Carbon	44.58%[a] 44.4%[b]	40.0%[a] 25%-35%[c]	62.5%[a] 60%-65%[b]	77.7%[a] 64%-75%[d]

[a] Carbon content show for example structure. Range based on literature values
[b] Carbon Fibers from Lignin-Cellulose Precursors: Effect of Stabilization Conditions, (Bengtsson, 2019).
[c] Of dry wood. *Biomass as a Sustainable Energy Source for the Future*. (De Jong & Ruud, 2014).
[d] Analysis and Conceptual Model of its Structure. (Pasa, Carazza, & Otani, 1997)
Typical lignin from Le, 2017.
Coniferol Alcohol $HO(CH_3O)C_6H_3CH{=}CHCH_2OH$
PubChem shows... $C_{18}H_{13}N_3Na_2O_8S_2$

Calculating Carbon Content in Woody Biomass

Estimating the quantity of carbon in woody biomass may seem straightforward, as carbon makes up approximately half of the dry weight of wood. However, it is important to consider several factors that can significantly impact the accuracy of these estimates. For example, the moisture content and density of the wood can affect the weight of the wood, and therefore the amount of carbon present. In addition, the chemical composition of the wood, including the types and amounts of carbohydrates, lignin, and other compounds present, can impact the accuracy of carbon estimates. Careful consideration of these factors is essential for accurately estimating the carbon content of wood.

The moisture content of woody biomass can significantly affect its weight and must be taken into account when calculating its dry weight. Carbon makes up about half of the dry weight of woody biomass. To determine the dry weight of a given volume of wood, it is necessary to divide its weight by the sum of one and the moisture content, expressed as a decimal.

For example, kiln-dried lumber usually has a moisture content of around 15%. This means that the weight of the wood is 15% greater than if it were completely dry. To calculate the dry weight of kiln-dried wood, you would need to divide its weight by 1.15.

It's important to accurately calculate the dry weight of woody biomass because it determines the amount of carbon that can be derived from it. Accurately calculating the dry weight of woody biomass helps to determine the amount of carbon that can be derived from it and, in turn, the amount of carbon dioxide that will be released when it is burned. To ensure the validity of data on the carbon content of woody biomass found in databases (as outlined in Section 3.3), database developers must explicitly provide information on the moisture content of the biomass.

Table 7 presents data on the carbon content and heating value of several different biomass feedstocks, including forest residue, willow, poplar, pine, hemlock, miscanthus, switchgrass, and corn stover. The carbon content of these feedstocks ranges from 44.8% to 53.0%, while their higher heating values (HHV) and lower heating values (LHV) vary from 14.4 to 22.9 mmBtu/ton and 16.8 to 24.2 MJ/kg, respectively.

Torrefaction is a thermal treatment process used to convert biomass into a more energy-dense material. By removing some of the oxygen, torrefaction increases the carbon content of the biomass, resulting in a higher energy density and reduced transportation costs. It's worth noting, however, that torrefaction requires energy inputs and therefore has its own carbon footprint, which would need to be considered in a full LCA.

Table 7. Carbon Content and Heating Value

Feedstock	Source	Carbon Content (%)	HHV (mmBtu /ton)	LHV (mmBtu /ton)	HHV (MJ/kg)	LHV (MJ/kg)	Carbon Factor (g CO_2/kg)
Forest Residue	C-BREC	n/a	n/a	n/a	n/a	n/a	n/a
	GREET	50.3%	17.9	17.3	20.8	20.1	65,595
	PHYLLIS[a]	50.2% - 56.1%	22.2 - 22.9	20.9 - 21.6	23.4 - 24.2	22.0 - 22.8	81,252 - 84,036
Willow	C-BREC	49.6%	18.3		19.3		67,038
	GREET	48.7%	16.5	15.4	19.2	17.9	60,532
Willow torrefied	PHYLLIS	51.8% - 53.0%[b]	20.4 - 20.8	19.2 - 19.6	21.5 - 22.0	20.2 - 20.7	74,658 - 76,306
Poplar	C-BREC	n/a	n/a	n/a	n/a	n/a	n/a
	GREET	50.1%	17.1	15.9	19.8	18.5	62,503
Lignin from poplar	PHYLLIS	51.2% - 53.0%	20.3 - 21.0	19.2 - 19.6	21.5 - 22.2	20.2 - 20.9	74,475 - 77,076
Pine	C-BREC	49.3%	19.1		20		69,786
Clean Pine	GREET	50.1%	17.1	15.9	19.8	18.5	62,503
bark, pine	PHYLLIS	52.3% - 53.9%	19.4 - 19.9	18.2 - 18.7	20.4 - 21.0	19.2 - 19.7	70,921 - 73,046
Hemlock	C-BREC	49.7%	19.0		20.0		69,456
	GREET	n/a	n/a	n/a	n/a	n/a	n/a
Western hemlock	PHYLLIS	50.4% - 51.5%	19.0 - 19.4	17.8 - 18.2	20.1 - 20.5	18.8 - 19.2	69,603 - 71,178
Miscanthus	C-BREC	n/a	n/a	n/a	n/a	n/a	n/a
	GREET	47.6%	16.4	15.3	19.0	17.8	59,994
	PHYLLIS	47.9% - 50.3%	18.0 - 19.0	16.9 - 17.8	19.1 - 20.0	17.9 - 18.8	66,196 - 69,529
Switch Grass	C-BREC	n/a	n/a	n/a	n/a	n/a	n/a
	GREET	46.6%	15.6	14.4	18.1	16.8	57,085
	PHYLLIS	47.8% - 53.2%	17.1 - 19.0	15.9 - 17.7	18.0 - 20.1	16.8 - 18.7	62,569 - 69,603
Corn Stover	C-BREC	44.8%	17.8		19		65,170
	GREET	46.7%	15.8	14.7	18.3	17.1	57,785
	PHYLLIS	46.8% - 49.3%	17.2 - 18.1	16.0 - 16.8	18.1 - 19.1	16.9 - 17.8	62,862 - 66,196

[a] Source: https://phyllis.nl/

[b] Carbon content is higher in this case because is willow torrefied. The maximum value of carbon content in natural woody biomass is around 51%. Bark may also have a higher carbon content as the material is exposed to natural degradation.

Moisture

The moisture content of biomass is the quantity of water existing within the biomass, expressed as a percentage of the total material's mass. Moisture content of biomass in natural conditions (without any further processing) varies enormously depending on the type of biomass, ranging from less than 15% in cereals straw to more than 90% as in algae biomass. (Sanchez, Curt, Robert, & Fernandez, 2019).

Water is generally held in biomass in two ways - either as a free liquid and vapor that is contained in the cell cavities, or as a molecule that is bound within the cell walls. Moisture content tends to vary widely with biomass species, age, geographic locations and genetic differences. It also varies between different anatomical fractions of the same plant and throughout the year (Biomass Chemistry, 2022).

Presenting a carbon balance on a moisture free basis helps avoid errors in CO_2 emissions.

Woody biomass moisture content can vary from 5% to approximately 60% depending on the conditions of the wood at harvest and the ambient atmospheric moisture as well as the duration of storage of the material. Many biomass conversion processes require feedstocks with specific moisture content which is achieved by drying the feedstock with process energy.

There are several ways to determine the moisture content in woody biomass, including the dry basis and wet basis methods. The wet basis method, also known as the green or wet basis method, is one of the most common. In this method, the moisture content in the wood is expressed as a percentage of the total weight of the wood, including both the dry wood material and the water (Govett, Mace, & Bowe, 2010).

The moisture content of biomass is critical in converting it to energy systems, as it affects the heating value. As the moisture content increases, the heating value of the biomass decreases, sometimes significantly. This means that the higher the moisture content, the greater the difference between the high heating value (HHV) and the low heating value (LHV), and the less total energy will be available, as shown in Figure 2.6. In order to obtain consistent estimates of carbon content, it is important to consistently measure biomass on the same moisture basis.

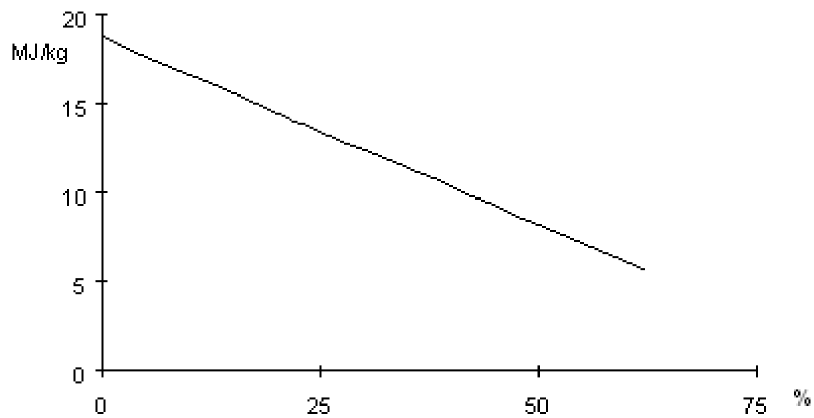


Figure 2.6. Effect of moisture (wet basis) on heating value[3].

Heating Value

The heating value of biomass measures the amount of thermal energy stored in the material. Heating values can be measured as either the high heating value (HHV) or the low heating value (LHV). The HHV includes the sensible heat of vaporization of water during combustion, while the LHV excludes this heat. These values are typically expressed in units of energy per unit of mass, such as megajoules per kilogram (MJ/kg) or kilojoules per kilogram (kJ/kg). The HHV measures the total amount of heat produced by combustion, while the LHV represents the amount of heat that is actually available for capture and use during the combustion process (FAO, 2022b). The heating values of biomass are often expressed on a dry basis, as a significant amount of energy is required to remove moisture from woody biomass feedstocks. The HHV ranges from 19 to 22 MJ/kg, while the LHV ranges from 16 to 20 MJ/kg.

The heating value of biomass materials in GREET is based on the HHV, with an adjustment for the moisture content of the delivered biomass fuel. This calculation assumes that the biomass contains 6% hydrogen. It is important to note that the LHV in GREET is calculated on a bone-dry basis. Equation 2 takes into account the moisture content of each fuel and uses the LHV formula from van Loo (2002), which is consistent with studies on the drying requirements for biomass fuels (Gebreegziabher, Oyedun, & Hui, 2013).

$$LHV = HHV \times (1-MC) - 2.44(MC) - 2.44 \times (\%H) \times 8.936 \times (1-MC) \text{ in MJ/kg} \quad (2)$$

Table 8 presents a summary of HHV and LHV from GREET for some types of biomass that this study took in consideration including woody waste, hard wood and soft wood.

3 https://www.fao.org/3/j0926e/J0926e06.html

Table 8. Heating Values of Biomass Materials

Fuel	Higher Heating Value		Lower Heating Value[b]	
	Btu/ton	MJ/kg	MJ/kg	Btu/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
Urban Wood Waste	18,400,000	21.40	18.74	16,110,783
Lumber Mill Waste	17,484,000	20.33	17.74	15,249,743

[a] Fuel property data from GREET provide the basis for biomass in this Study
[b] 6% Moisture Content

Ash

Ash is defined as the inorganic content of biomass. It can be introduced during harvest and process, or exist naturally as biogenic material inside of plant tissues. The sum of all of the ash sources generally yields an ash content of roughly 0.1% for debarked wood chips, or as high as 26% for rice husks (Tao, Geladi, Lestander, & Xiong, 2012). Ash content increases as ash is introduced during harvesting, often from solid incorporated during collection. The carbon content of ash is usually low, typically less than 1%, and thus significant ash contamination can lower the overall carbon content of biomass. Additionally, ash is of interest to bioenergy producers because of the abrasive wear and tear that it causes on processing equipment.

2.1 Biomass Conversion Processes

The biomass conversion process will determine the feedstock to biofuel pathway. There are several technologies available for converting biomass into energy, each with its own advantages and disadvantages. The most common biomass conversion processes include thermal conversion, biochemical conversion, and thermochemical conversion. Here, we provide a brief overview of each of the biomass conversion processes, including the types of biomass that are most suitable for each process, as well as the advantages and disadvantages of each.

2.1.1 Thermochemical conversion

Thermochemical conversion is a process that involves the use of heat and chemical reactions to break down biomass into a range of products, including biofuels, biochemicals, and bioplastics. There are several sub-processes that fall under the umbrella of thermochemical conversion, including combustion, pyrolysis, gasification, and liquefaction (Zafar, 2021). A simplified overview of the thermochemical conversion process is show in Figure 2.7. The following subsections then explain each process in detail.

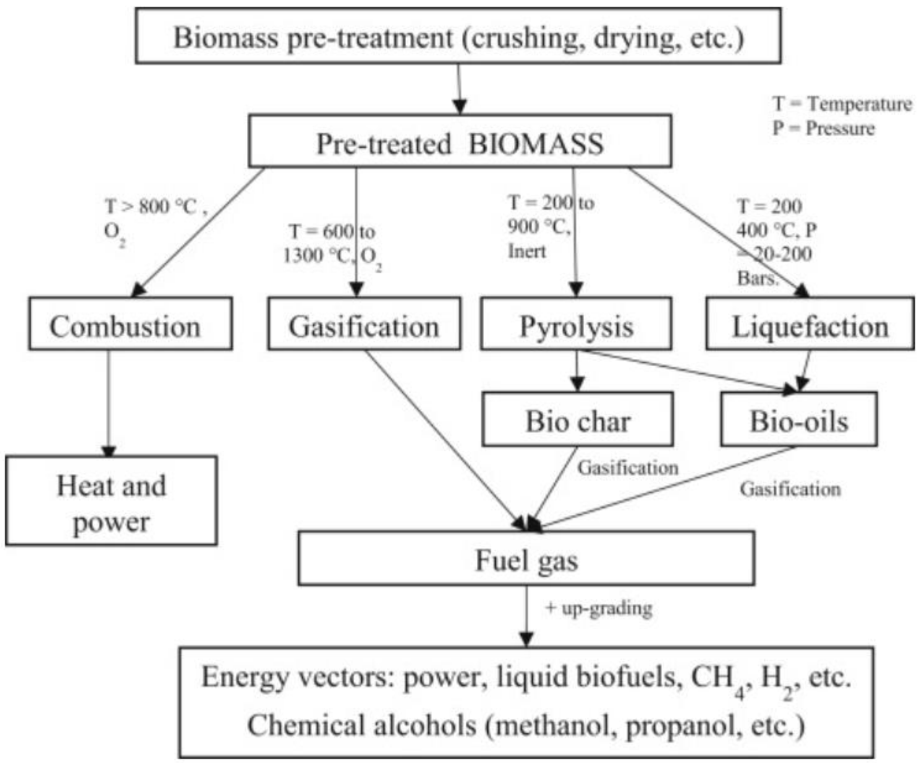


Figure 2.7. Overview of main thermochemical process. Source: (Ram & Kumar, 2021).

2.1.2 Combustion

Biomass combustion has been utilized for centuries to produce heat and electricity from a variety of organic materials, including wood, agricultural residues, and municipal waste. Today, biomass combustion continues to be an important technology for bioenergy production.

The efficiency of biomass combustion depends on a variety of factors, including the type and moisture content of the biomass, the type of combustion technology used, and the end use of the energy produced. In general, dry and dense biomass materials, such as wood pellets or briquettes, are more efficient for combustion than wet or low-density materials, such as grass or straw.

The moisture content of the biomass should be kept as low as possible to minimize the energy required for drying and to maximize the efficiency of the combustion process. To prepare the biomass for combustion, it is first heated and dried to remove moisture. Once all moisture has been removed, the biomass is heated to a temperature above 800°C in the absence of oxygen for pyrolysis to occur (see Figure 2.7). During this process, the biomass is broken down into simpler chemical compounds, such as hydrogen, carbon monoxide, carbon dioxide, methane, and other hydrocarbons. In the end, char and volatile gases are formed, which continue to react independently. The volatile gases require oxygen in order to achieve complete flame combustion, resulting in the production of mostly carbon dioxide and water. The solid char also burns, producing carbon monoxide and carbon dioxide.

There are several types of technologies available for biomass combustion, including grate boilers, fluidized bed boilers, and co-fired boilers. Grate boilers are the most common type of biomass boiler, and they operate by burning the biomass on a grate, similar to a coal-fired boiler. Fluidized bed boilers operate by suspending the biomass in a bed of hot air, allowing for more efficient combustion. Co-fired boilers are designed to burn both biomass and fossil fuels. Co-Firing can only occur in conjunction with coal fired power production. As this is being phased out, there are limited opportunities to co-fire biomass wastes to produce power.

2.1.3 Liquefaction

In the context of bioenergy, liquefaction is a process that converts biomass into a liquid form. The main goal of this process is to produce liquid products that can be used as transportation fuels, heating fuels, or raw materials for industrial processes. The conversion of biomass into liquid products is often associated with a higher value addition compared to alternative processes, such as carbonization and gasification.

There are two main approaches to liquefaction: direct liquefaction and indirect liquefaction (see Figure 2.8). Direct liquefaction is a process that converts biomass or other organic matter directly into liquid products, such as transportation fuels or chemicals, through a chemical reaction, while indirect liquefaction is a process that converts biomass or other organic matter into an intermediate product, such as syngas or bio-oil, which is then further processed into the desired liquid products. Each process is described in further detail below.

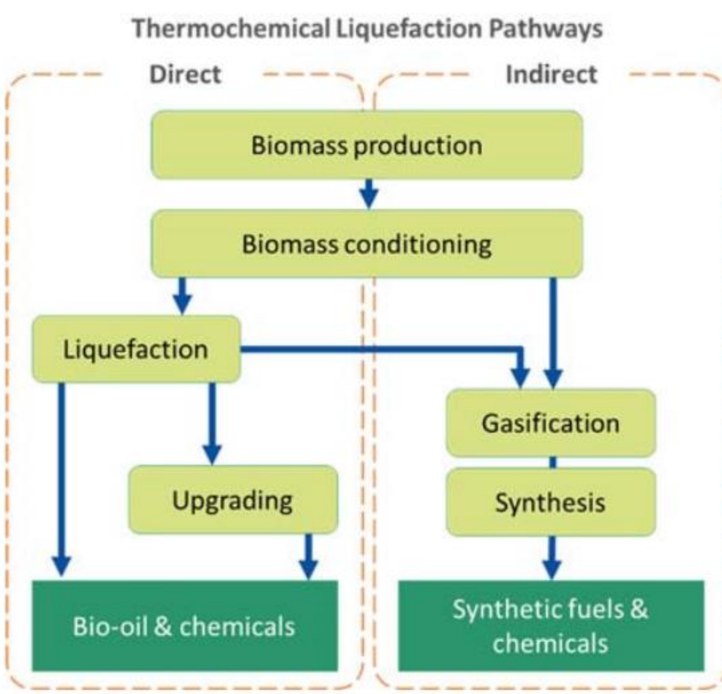


Figure 2.8. Difference between direct liquefaction and indirect liquefaction via gasification. Source: (Funke & Dahmen, 2020).

Direct Liquefaction

The direct liquefaction of biomass refers to the conversion biomass into bio-oil, and the main technologies are hydrolysis fermentation and thermodynamic liquefaction.

There are two types of thermodynamic liquefaction pyrolysis liquefaction and hydrothermal liquefaction (Zhang, et al., 2019). Bio-oil, which is also regarded as pyrolysis oil or pyrolytic oil, could be obtained from both of these two methods. As shown in the literature, bio-oil is the extremely complex substance and composed of hundreds of organic compounds, e.g., alkanes, aromatic hydrocarbons, phenol derivatives, ketones, esters, ethers, sugars, amines, and alcohols. The pyrolyze bio-oils could be directly burned in boilers, or upgraded to produce valuable fuels and chemicals using the following methods: Extraction, emulsification, esterification/alcoholysis, supercritical fluids, hydrotreating, catalytic cracking, and steam reforming (Zhang, et al., 2019).

Indirect Liquefaction

The indirect liquefaction refers to the Fischer–Tropsch (F-T) process using the syngas of biomass as the raw material to produce the liquid fuel, including methyl alcohol, ethyl alcohol, and dimethyl ether (Zhang, et al., 2019).

Indirect liquefaction technology, which is divided into two stages. The first stage is a thermochemical gasification process. In this process, the syngas is produced after the raw material reacts with air or steam. In the syngas, the primary substances are CO, CO_2, H_2, and H_2O. The second stage is the well-established Fischer–Tropsch (F–T) process (Apanel & Johnson, 2004). During the F–T process, the mixture would be used to produce a range of chemicals, including methyl alcohol, dimethyl ether, and ethyl alcohol, while there is little research on the higher alcohols derived from the biomass syngas (Zhang, et al., 2019).

2.1.4 Gasification

Gasification of biomass offers the most efficient means of conversion of biomass feedstocks into useful products as the entire content of the feedstock is converted into syngas instead of only the cellulosic fraction which is the case with some cellulosic biofuels conversion processes.

2.1.5 Pyrolysis

Pyrolysis of biomass converts woody biomass into a liquid and gas products with the liquids being unstable needing further processing after production. Pyrolysis oils can be hydro-processed into hydrocarbon products but requires high pressure hydro-processing and consumption of large volumes of H2 yielding products that are not conventional fuels but can be co-processed with crude in a conventional refinery at some level of co-feeding.

2.2 Data Sources

A lifecycle assessment (LCA) of biomass involves evaluating the environmental impacts of biomass energy systems over their entire lifecycle, from raw material extraction to disposal or reuse. Conducting an LCA requires accurate and comprehensive data on the chemical and physical properties of the biomass being examined. There are several sources that can provide this type of data, including:

1. Journal articles: Case studies published in scientific journals may provide detailed information on the properties of specific biomass types. These articles can be a valuable source of data for researchers conducting an LCA.
2. Life cycle biomass to energy models: Some models, such as the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model, include data on the properties of different biomass types. This data can be extracted and used in an LCA.
3. Biomass property databases: There are several databases dedicated to biomass properties, Phyllis and The Bioenergy Knowledge Discovery Framework (KDF). These databases can provide a wide range of data on the chemical and physical properties of different biomass types, including information on energy content, moisture content, and ash content.

In the following section, we examine several sources for data on the chemical and physical properties of biomass

2.2.1 GREET and LCA Models

GREET

The **G**reenhouse gases, **R**egulated **E**missions, and **E**nergy use in **T**ransportation (GREET) is a comprehensive analytical tool designed to assess the life-cycle impacts of various vehicle technologies, fuels, products, and energy systems.

One of the key features of the GREET model is its ability to model emissions of traditional greenhouse gases (GHGs), including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), as well as criteria pollutants from transportation fuels. The model uses global warming potential (GWP) values to aggregate these GHG species emissions into a single carbon dioxide equivalent (CO_2e) result. Volatile organic compounds (VOCs) and carbon monoxide (CO) are also accounted for in the model, in their fully oxidized forms as CO_2 (Life Cycle Associates LLC, 2020).

In addition to its GHG emissions modeling capabilities, the GREET model also includes life cycle inventory (LCI) data for a variety of biomass types, including energy crops, grasses, and woody biomass. This data can be used to assess the environmental impacts of different biomass energy systems and can be disaggregated to reveal underlying assumptions on biomass properties (see Table 7). This data can be particularly useful for policymakers and other stakeholders looking to evaluate the sustainability of different biomass energy systems.

C-BREC

The California Biomass Residue Emissions Characterization (C-BREC) model is a tool designed to assess the environmental and public health impacts of using residual biomass from California's forests for energy generation. Developed by the California Energy Commission, the model aims to reduce the state's reliance on fossil fuels and decrease the vulnerability of its electricity system to the impacts of climate change. The C-BREC model can also be used to evaluate the sustainability of other biomass energy systems, such as biofuel production (Carman, et al., 2021).

The C-BREC model is implemented using the R programming language and can be accessed using an online web tool. To use the model, users must specify certain key characteristics, including the location of the residue generation, the type of forestry or agricultural activity being conducted, the location of the residue use, and the counterfactual fate of unremoved biomass (e.g., piled, scattered, burned). Other key supply chain characteristics, such as post-harvest treatment and end-use technology, must also be specified.

The C-BREC model relies on a range of data sources to input biomass properties and assess the environmental and public health impacts of biomass energy generation in California. These data sources include:

1. The CONSUME model for wildfire risk: This model is used to assess the potential risks associated with wildfire events and the likelihood of such events occurring. By considering these risks, the C-BREC model can provide a more accurate assessment of the overall sustainability of biomass energy generation in California.
2. Biomass inventory data: The C-BREC model uses data on the quantity and quality of biomass residues available for energy generation. This includes data on the types and amounts of biomass residues generated from different forestry and agricultural activities, as well as data on the physical and chemical properties of these residues.
3. Emissions data: The C-BREC model uses data on greenhouse gas emissions associated with different stages of the biomass energy generation process. This includes emissions from the production, transportation, and end-use of biomass residues.

By considering a range of factors and data sources, the model allows for the assessment of the environmental and public health impacts of biomass energy generation, as well as the potential risks associated with such activities.

2.2.2 CONSUME

CONSUME is a database developed by the USDA Forest Service that is used to assist resource managers in planning for wildland fire events, such as prescribed burns and wildfires. It uses fuel loadings, fuel moisture, and other environmental factors to predict fuel consumption, pollutant emissions, and heat release (Ottmar & Prichard, 2022). The emissions species considered in the CONSUME model include CO, CO_2, CH_4, and non-methane hydrocarbons (NMHC) (Carman, et al., 2021).

Although CONSUME was not specifically designed to calculate the carbon content in biomass, it is possible to estimate carbon content using CONSUME data, as shown in Table 9. The table shows that the carbon content for selected woody materials, such as slash, lodgepole, and hardwood, is consistent with expected values. However, the carbon content for Western pine is significantly lower, at 24.66%, compared to the expected range of 45%-49%. The extent of the use of emission factors in CONSUME should be examined as the Western pine data appear to be represented on a 50% moisture basis. Table 10 provides a clear comparison between the values obtained from all sources. Figure 2.9 presents a graphical representation of the GHG emissions reported by CONSUME for the selected biomass materials used to calculate the carbon content discussed in Table 9.

Table 9. Emission Factors and Calculation of Carbon Content from CONSUME (Prichard S. O., 2019)

Specie	*Emissions (g/kg)*				%C	GHG (g/kg)	Fully Oxidized to CO_2
	CO	CO_2	CH_4	NHMC			
Slash Smolder	540	1402	190.0	4.9	49.09%	2137.1	1799.9
Slash Flaming	167	1693	57.5	2.5	49.58%	1919.3	1817.8
Lodgepole Smoldering	333	1486	182.5	5.6	47.58%	2006.1	1744.6
Lodgepole Flaming	104	1701	37.5	2.1	48.55%	1843.9	1780.2
Hardwoods Flaming	107	1695	55.0	3.0	48.57%	1859.9	1781.0
Western Pine Flaming[a]	95	832	36.1	1.6	24.66%	964.7	904.1

[a] GHG emission factors for western pine appear to be for material with 49.3% carbon and 50% moisture.

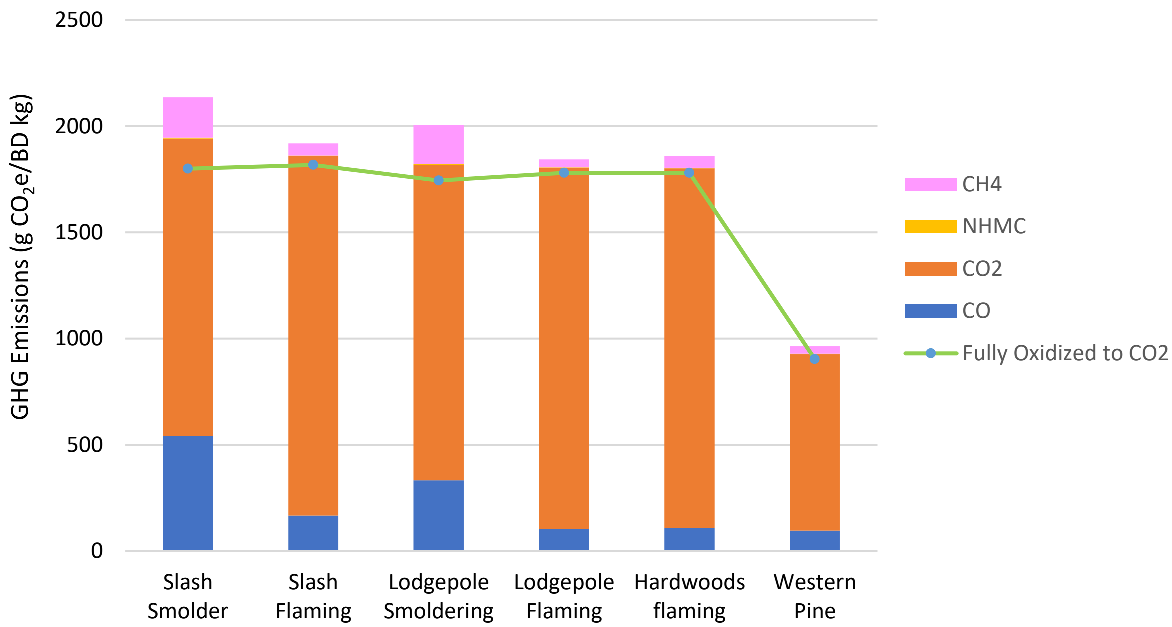


Figure 2.9. GHG emissions by CONSUME.

C-BREC has been used in conjunction with the CONSUME model to estimate emissions from pile burns, prescribed burns, and wildfire (Carman, et al., 2021). However, the fact that the difference in carbon content for Western pine between CONSUME and C-BREC is greater than 20% raises points to potential challenges in identifying carbon content and GHG emissions which warrants examining the causes of such differences and underlying assumptions. Comparing the results of the CONSUME model with those from other sources, such as satellite observations or ground-based measurements may provide insight to accurate and reliable estimates of carbon content and GHG emissions.

Table 10. Carbon content in Pine

Material	Source	Carbon content (%)
Pine	C-BREC	49.3%
Clean Pine	GREET	50.1%
Bark, Pine	PHYLLIS	52.3% - 53.9%
Western Pine Flaming	CONSUME	24.66%

2.2.3 PHYLLIS

The Phyllis database is a comprehensive resource that provides detailed information on the chemical and physical properties of woody biomass feedstocks (European Commission, 2013). Developed by the University of Ghent in Belgium, Phyllis is a valuable resource for researchers conducting a lifecycle assessment (LCA) of biomass energy systems. By accessing the data provided by Phyllis, researchers can gather a wide range of information on the properties of different biomass materials, including:

1. Classification codes: Each data record in Phyllis includes a unique ID number and classification codes that can be used to identify the type of biomass material being examined.
2. Ultimate analysis: The ultimate analysis data in Phyllis includes information on the carbon, hydrogen, oxygen, nitrogen, sulfur, chlorine, fluorine, and bromine content of the biomass material. This data is provided in weight percent for dry material, dry and ash-free material, and as-received material.
3. Proximate analysis: The proximate analysis data in Phyllis includes information on the ash content, water content, volatile matter content, and fixed carbon content of the biomass material. This data is provided in weight percent for dry and as-received material.
4. Calorific value: Phyllis provides data on the calorific value of different biomass materials, expressed in mega-joules per kilogram.
5. Metal content: The data in Phyllis includes information on the metal content of different biomass materials, including data on alkali metal content.
6. Composition of the ash: Phyllis provides data on the composition

The Phyllis database allows users to select a classification scheme for the biomass materials being examined and view the samples in the database through an interactive tree structure. The samples are grouped according to the chosen classification scheme and can be searched using sample names, classification groups, and sample IDs. The tree structure highlights the search results and allows users to show or hide different groups of data by clicking the header. When possible, the database converts dry values to dry and ash-free and as-received values for certain properties, displaying all three values side-by-side. Figure 2.10 provides an example of the database for forest waste from South Africa, demonstrating the interactive tree structure and the range of data available (TNO, 2020).

ID-number	#3121
Material	Forest waste
Classification	CEN/TS 14961 classification ‣ Solid biofuels ‣ Woody biomass ‣ Wood processing industry
	ECN Phyllis classification ‣ untreated wood
	NTA 8003 classification ‣ [100] hout ‣ [110] vers hout ‣ [114] dunningshout
Country	South Africa
Production date	2007-08-21
Submitter organisation	ECN (Netherlands)

Values

Property	Unit	Value ar	dry	daf	Std dev	Det lim	Lab	Date	Method	Remarks
▼ Main biomass properties										
▼ Proximate analysis										
Moisture content	wt%	56.80	← Edit						CEN/TS 14774-1,2,3	
Ash content at 550°C	wt%	1.25	2.90						CEN/TS 14775	
▼ Ultimate analysis (macroelements)										
Carbon	wt%	22.94	53.10	54.69					CEN/TS 15104	
Hydrogen	wt%	2.68	6.20	6.39					CEN/TS 15104	
Nitrogen	wt%	0.48	1.11	1.14					CEN/TS 15104	
Sulphur	wt%	0.03	0.07	0.07					CEN/TS15289	
Total (with halides)	wt%	84.18	63.38	62.29					Calculated	
▼ Heating value										
Net calorific value (LHV)	MJ/kg	7.29	20.09	20.69					CEN/TS 14918	
Gross calorific value (HHV)	MJ/kg	9.26	21.44	22.08						

Figure 2.10. Forest waste database (TNO, 2007).

2.3 Representation and Reporting of Emission Factors (EFs)

Emissions factors (EF) are a tool used to estimate the amount of greenhouse gases or other pollutants emitted during a specific activity or process. They are typically expressed as the amount of emissions per unit of activity, such as kilograms of emissions per unit of energy produced or per unit of fuel consumed. These factors can be used to calculate the total emissions resulting from a specific activity or process by multiplying the emissions factor by the amount of activity or fuel consumed.

Emissions factors are usually presented in terms of mass per unit of activity, such as kilograms of emissions per megajoule of energy produced. However, they may also be presented in other units, such as grams of emissions per mile traveled for transportation fuels.

Emissions factors can be derived from a variety of sources, including measurements taken during controlled laboratory experiments, field studies, or estimates based on engineering models. The accuracy and reliability of emissions factors may vary depending on the data sources used to calculate them. It is therefore important for researchers to carefully consider the quality and relevance of the data sources used to calculate emissions factors in order to ensure the accuracy of their estimates.

3. THE NET GREENHOUSE GAS BALANCE OF BIOMASS

The most straightforward assumption regarding the net carbon balance for biomass in a bioenergy system is that of neutrality, which suggests that the carbon sequestered during photosynthesis is equal to the carbon emitted during combustion, is a commonly used approach in conducting life cycle assessments (LCAs) for bioenergy systems. However, this assumption is being widely debated among the scientific community (Wiloso, Heijungs, Huppes, & Fang, 2016). Bio-based materials can cause removals and emissions that impact atmospheric CO2 concentrations, even on short timescales. On longer timescales, it is essential to determine whether a bio-material system leads to a net gain in the biosphere carbon stock before considering the system carbon neutral.

While models may include the assumption that CO_2 will eventually be re-sequestered as forest regrowth, or that residues would have been emitted later by decay or wildfire, the timing of near-term climate impacts versus long-term recovery is an ongoing debate (Buchholz, Hurteau, Gunn, & Saah, 2016). The debate surrounding the biogenic carbon neutrality assumption centers around the fact that accepting this assumption can overlook the true carbon impact of a bioenergy system. Therefore, understanding the carbon balance as it relates to a particular biomass type, location, and alternative fate is crucial in facilitating the use of biomass in the CA LCFS regulation. The following subsections examine categories of GHG accounting, analytical approaches to net carbon balance, and how other policies and regulations account for biogenic carbon under their framework.

3.1 Categories of GHG Accounting

Several approaches exist to quantify the life cycle of carbon in biomass. The approach implemented will depend on the purpose of the study, the time period under examination, and underlying assumptions regarding the characteristics of the biomass under consideration and its alternative fates. The treatment of indirect land use change (iLUC) emissions in relevant programs, models, and studies is also examined.

Many LCA programs, models, and studies treat biogenic carbon in biomass from various sources as carbon-neutral[4]. Carbon neutrality refers to the life cycle of biogenic material. Photosynthesizing organisms, such as plants, fix carbon from the atmosphere as they grow, and when such biomass decays or combusts, an equivalent amount of carbon is released to the

[4] Carbon neutrality is implemented in many different ways in GHG calculations. In corn ethanol pathways, for example, biogenic carbon is treated as neutral, with no carbon accounted for in either the tailpipe emissions nor the life cycle, however, in the GREET model (on the Results Tab), the positive tailpipe emissions are represented with a biogenic uptake credit factored into the well-to-tank phase. In the case of forest residue to ethanol, and biomass to power pathways, the GREET model accounts for the positive emissions from fuel combustion and the negative biogenic carbon uptake. This approach is sometimes referred to as Totality of Emissions accounting. Landfill gas is similarly accounted for. Regardless of the accounting method, the biogenic uptake or avoided CO_2 from combustion balances the CO_2 in the end-use.

atmosphere. Thus, over an entire life cycle, such biomass can be considered carbon-neutral. Two accounting approaches that are typically employed to represent carbon neutrality for biomass-based products are described below.

Carbon Neutral Approach

The Carbon Neutral approach is applied in numerous policy initiatives and modeling systems. In this approach, the emissions caused by bio-based materials in the combustion phase are equal to those removed during photosynthesis, and are therefore not included in the carbon intensity calculations for a product life cycle.

This Approach assumes that: 1) there is no time-lag associated with emissions relative to the preceding biogenic carbon uptake, and 2) the biomass embodied in the bio-based materials will grow back within the time period under consideration. When the time elapsed between biomass growth and biofuel combustion is relatively short, or when "waste" residues from managed forests or lumbermill operations, that would otherwise either decay in-situ, or burn as a result of prescribed or wild fires, are being utilized, this carbon-neutral assumption is defensible. In the case of non-waste forestry-derived feedstocks, however, the growth period of the woody biomass is significantly longer than annual agricultural or bioenergy crops. The assumption of carbon neutrality is therefore considered to be weaker due to the relatively longer timeframe in which decay and combustion may occur.

Biogenic Uptake and Credit Approach

The Biogenic Uptake and Credit (BUC) approach is a variation of the Carbon Neutral approach in which the biogenic uptake and credit are explicitly accounted for. In the BUC approach, all of the CO_2 emitted from vehicle fuel use and process emissions is accounted for in the GHG emissions and biogenic carbon uptake is treated as a credit. The BUC approach can be considered a variation of the Carbon Neutral approach because the biogenic uptake credit is equivalent to the biogenic emissions over a product's lifetime. The BUC approach is used in models and product LCA standards, including the U.S. EPA Inventory (EPA, 2022b), and the European Product Life Cycle Reporting Standard (Bhatia, et al., 2011).

3.1.2 Temporal Accounting

Time-accounting approaches are analytical methods that aim to capture the temporal dynamics of biogenic carbon flows throughout a bioenergy system's life cycle. These approaches seek to account for the carbon sequestration that occurs during the growth phase of the biomass, as well as the carbon emissions that arise from the bioenergy system's operation, whether from combustion or decomposition. Additionally, these methods consider the carbon storage that occurs in long-lived bio-based products.

Several time-accounting approaches have been developed, each with its own strengths and limitations. For example, some approaches utilize models that estimate the timing and rate of carbon sequestration and emissions from different parts of the bioenergy system, while others utilize empirical data to estimate the carbon flows. Some approaches incorporate carbon dynamics over a range of time horizons, from short-term to long-term, while others focus on specific time periods.

Because biomass to biofuel systems sequester and emit carbon on timescales relevant to global climatic change, understanding the temporal dynamics of biogenic carbon flows can inform policy decisions.

3.2 Treatment of Biogenic Carbon in Regulated Programs

The treatment of biogenic carbon in regulated programs is an important factor to consider when making policy decisions for GHG reduction programs. In Table 11, we can see a summary of the treatment of biogenic carbon in various regulated programs. Among them, eight programs consider biogenic carbon as carbon neutral. The EPA U.S. Inventory is the only program that requires that carbon and biogenic carbon be reported separately (EPA, 2022b). Several of these programs are discussed in further detail in the following sections with an analysis of their treatment of biogenic carbon in woody and other biomass materials, either as feedstocks or fuels.

Table 11 illustrates a variety of regulatory programs spanning federal, state and international entities, as well as a variety of feedstocks including biomass forest and crop residues, and the GHG accounting treatment for each program. With the exception of the LCFS CCS protocol, each of these programs identifies biomass as being carbon neutral, either using a Carbon Neutral or BUC approach. These programs and nuances in the associated GHG calculations are described briefly below.

The treatment of biogenic carbon is either on a neutral basis such that CO_2 from combustion and biogenic uptake are not counted in emission factors or a biogenic uptake credit which corresponds to the carbon in biomass is part of the calculation. Note that the

Table 11. Treatment of Biogenic Carbon in Regulated Programs

Program	Citation	Approach	iLUC	Biomass Feedstock
EPA RFS	(EPA, 2010)	Carbon Neutral	0	Forest Thinnings, Slash
EPA RFS	(EPA, 2011)	Carbon Neutral	0	Corn stover
EPA U.S. Inventory	(EPA, 2022b)	Reports Biogenic Separately [a]	0	Biomass
CA LCFS Biomass Residue[b]	(CARB, 2009a)	Carbon Neutral – positive emission with uptake credit	TBD	Forest Residue
CA LCFS Crop Residue[b]	CARB 2015a, 2015b (CARB, 2014; CARB, 2009b)	Carbon Neutral	0	Corn Stover, Wheat Straw, Sugarcane Straw
CA LCFS CCS Protocol	(CARB, 2018b)	Fully oxidized carbon in fuel or defer to CA-GREET	0	Wood and Wood Residuals
CA LCFS Grid Avg Power	(CARB, 2018c)	Carbon Neutral – positive emission with uptake credit	0	NA
CA LCFS Biomass Energy Crop [b]	(CARB, 2009a)	TBD	TBD	Farmed Trees
CA LCFS Crop-derived feedstock	(CARB, 2023)	Carbon neutral with requirement to analyzed indirect emissions.	TBD	Biomass
CA RPS	(CA PUC, 2009)	Carbon Neutral	0	Biomass
Canada CFS[d]	(ECCC, 2020)	Carbon Neutral	0	Biomass
EU REDII	(EU, 2021)	Carbon Neutral	0	Biomass
NZ ETS	(NZ ETS, 2021)	Carbon Neutral	0	Forest Biomass
RTFO	(RTFO, 2021)	Carbon Neutral	0	Biomass
RenovaBio	(RenovaBio, 2017)	Carbon Neutral	0	Biomass
CORSIA	(Prussi, et al., 2021)	Carbon Neutral	0	Forest Residue
CORSIA	(Prussi, et al., 2021)	Carbon Neutral	-5.2 g/MJ	Farmed Poplar

[a]Requires annual emissions for applicable categories to be reported separately for biogenic and non-biogenic.
[b]CA LCFS pathways were preliminary and never used for credit generation.
[c] Emission factors in the CCS protocol reflect fully oxidized carbon as CO_2 without reference to any biogenic uptake credit other than providing CA-GREET as an alternative source of emission factors.
[d]Canada CFS is in pre-publication.

3.2.1 EPA RFS

The Renewable Fuel Standard (RFS) was enacted by the United States Congress in 2005 under the Energy Policy Act to reduce GHG emissions. Renewable fuel categories under the RFS include biomass-based diesel, cellulosic biofuel, advanced biofuel, and total renewable fuel. The policy was extended in 2007 to increase long term goals for total renewable fuel use, explicitly define renewable fuels, and include waiver authorities.

Several fuel pathways are identified under the RFS. A fuel pathway is a combination of the fuel's feedstock, the fuel's specific product process, and the fuel's end type. Approved pathways meet certain emissions reduction criteria established by the EPA. Example of feedstocks that exist in approved pathways include crop residue, forest slash, pre-commercial thinnings and tree residue, switchgrass, miscanthus, energy cane, *Arundo donax*, *Pennisetum purpureum*, separated yard waste; biogenic components of separated municipal solid waste (MSW), cellulosic components of separated food waste, and cellulosic components of annual cover crops. Any process that converts cellulosic biomass to fuel can be considered for approval under the RFS.

To determine if a fuel meets the criteria for an approved pathway, the fuel's lifetime emissions are compared to that of a baseline fossil fuel. The analysis of a fuel's lifetime emissions is based on the GREET model which applies the same biogenic carbon accounting method discussed in Section 4.1. The EPA has adopted the carbon balance approaches from the GREET model for its treatment of biomass (EPA, 2010).

3.2.2 Greenhouse Gas Reporting

Greenhouse gas emissions are reported in national inventories, including the United States' (EPA, 2020), as well as many programs designed to reduce overall GHG emissions from different sectors of society, including programs targeting the transportation sector, such as the California Cap-and-Trade Program, the California Low Carbon Fuel Standard (CA LCFS), the Oregon Clean Fuel Standard (OR CFS), the Washington Clean Fuel Standard (WA CFS), and the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). Numerous models and "carbon footprint calculators" have also been developed to quantify the carbon intensity of products, entities, and processes, including lifestyles. This section describes the different carbon accounting approaches employed in such inventories, programs, and tools, with a focus on the treatment of biogenic carbon.

EPA

The EPA characterizes GHG emissions using two complementary programs – the Greenhouse Gas Reporting Program (GHGRP) and the Inventory of U.S. Greenhouse Gas Emissions and Sinks (Inventory). The Inventory is updated annually based on GHGRP reporting. The GHGRP requires fuel and industrial gas suppliers, and other large[5] sources of GHG emissions in the United States to report their facility-level GHG emissions annually in accordance with the Code of Federal Regulations Title 40 Part 98 (C.F.R. Title 40, 2009). GHG emissions are estimated using methodologies consistent with IPCC guidelines for key categories that have been prioritized

[5] Approximately 7,600 facilities that emit over 25,000 metric tonnes of CO_2e per year report their annual emissions. Agricultural and land-use sectors are not required to report their emissions.

based on the relative proportion of a national inventory that they represent (IPCC, 2006a). The Inventory provides a high-level national accounting of GHG emissions based on the finer-resolution facility-level data reported in the GHGRP. Emissions are accounted for both with and without uncertainty, and with and without contributions from land use, land-use change and forestry (LULUCF). Including uncertainty and LULUCF, the 2020 Inventory included 47 source categories that accounted for 95.9% of the total emissions (EPA, 2022b). The top 5 contributing categories included road transport-related fuel combustion, coal-fired electricity generation, net carbon stock change from forest land remaining forest land, gas-fired electricity generation, gas-fired industrial combustion. Net carbon fluxes from changes in biogenic carbon reservoirs are accounted for in the estimates for LULUCF.

The GHGRP addresses biogenic CO_2 separately from other emissions sources, as this excerpt describes:

> *For facilities, except as otherwise provided in paragraph (c)(12) of this section, report annual emissions of CO_2, CH_4, N_2O, each fluorinated GHG (as defined in § 98.6), and each fluorinated heat transfer fluid (as defined in § 98.98) as follows.*
>
> *(i) Annual emissions (excluding biogenic CO_2) aggregated for all GHG from all applicable source categories, expressed in metric tons of CO_2e calculated using Equation A-1 of this subpart. For electronics manufacturing (as defined in § 98.90), starting in reporting year 2012 the CO_2e calculation must include each fluorinated heat transfer fluid (as defined in § 98.98) whether or not it is also a fluorinated GHG.*
>
> *(ii) Annual emissions of biogenic CO_2 aggregated for all applicable source categories, expressed in metric tons.*
>
> *(iii) Annual emissions from each applicable source category, expressed in metric tons of each applicable GHG listed in paragraphs (c)(4)(iii)(A) through (F) of this section.*
> *(A) Biogenic CO_2.*
> *(B) CO_2 (excluding biogenic CO_2).*

Here, biogenic CO_2 emissions are clearly reported separately from non-biogenic emissions sources (WRI, 2005). This Regulation does not, however, address the reporting of biogenic CO_2 uptake nor removals.

CA Inventory and Cap-and-Trade Program

The California Cap-and-Trade Program, established by CARB in 2012, pursuant to Assembly Bill 32, is a market-based emissions trading system that establishes a declining cap on emissions over time and distributes tradeable credits under the cap. This program applies to emissions economy-wide and covers approximately 80 percent of the State's GHG emissions. Entities[6] in

[6] Covered entities are those that emit 25,000 or more metric tonnes of CO_2e/year. Approximately 450 entities report to CARB annually via the Mandatory Reporting Regulation (MRR).

CA that generate emissions through their activities, for example electricity generation, manufacturing, or fuel refining, must comply with the program by purchasing credits or allowances in an amount equal to the level of their emissions. As the cap declines annually, so do the number of overall credits available, and therefore emissions.

The Compliance Offsets Program is a component of the CA Cap-and-Trade Program that issues Offset Credits to qualifying projects that reduce or sequester GHGs in compliance with CARB Compliance Offset Protocols. Offset credits represent verified GHG emissions reductions or removal enhancements from sources that are not obligated in the Cap-and-Trade Program and may be purchased by obligated parties to satisfy a small[7] percentage of their overall compliance obligation.

3.2.3 California Low Carbon Fuel Standard (LCFS)

The LCFS has several examples of the treatment of biogenic carbon from biomass. Biomass-based electric power is part of the electricity mix for power generation. In addition, several fuel pathways have been published for both woody biomass and crop residue-based pathways. CARB has at least four different programs that address woody biomass as a feedstock, each of which is framed, and reports emissions slightly differently. In order to demonstrate CARB's treatment of biogenic carbon under the LCFS, pathway output from CCS, biomass power, woody biomass, and crop residue is discussed below.

Carbon Capture and Sequestration (CCS) Protocol

The CCS Protocol under the LCSF does not explicitly state a biogenic carbon credit for biofuels (CARB, 2018c). The CCS refers to the CA-GREET model as the primary source of emissions factors, and refers to Appendix E from the CCS (see Table 12) as a secondary source of emissions factors. Note that in Table 12 only positive emissions factors for biomass-derived fuels are listed, and no credits assigned to the biomass. The protocol refers to the emission factors are presumably the approach defined in CA-GREET:

> *"GHG emissions from fuel combustion and electricity use must be determined using emission factors available in CA-GREET. If an emission factor for a particular fuel is not available in CA-GREET, applicants must refer to combustion emission factors in Tables E1-E3 in Appendix E (Table 12)."*

GHG emissions from fuel combustion and electricity use must be determined using emission factors available in CA-GREET. If an emission factor for a particular fuel is not available in CA-

[7] This percentage changes over time and is currently capped at 4% of emissions compliance obligation for 2021-2025, increasing to 6% from 2026-2030.

GREET, applicants must refer to combustion emission factors in Tables E1-E3 in Appendix E (Table 12).

$GHG_{combustion}$= GHG emissions from fuel combustion in stationary equipment including emissions from parasitic load (MT CO_2e/year).

$EmbodiedGHG_{electricity+steam}$ = Embodied (upstream) GHG emissions from purchased electricity and steam use (MT/CO_2e year).

$EmbodiedGHG_{fuel}$ = Embodied (upstream) GHG emissions of fuel used in stationary equipment including embodied emissions associated with parasitic load (MT/CO_2e year).

Table 12. CCS Protocol stationary emission factors for petroleum fuel combustion

Table E3. Stationary Emission Factors for Petroleum Fuel Combustion[12]

Biomass-Derived Fuels (Solid)	**kg CO_2/ton**	**g CH_4/ton**	**g N_2O/ton**
Agricultural Byproducts	975	264	35
Peat	895	256	34
Solid Byproducts	1096	332	44
Wood and Wood Residuals	1640	126	63
Biomass -Derived Fuels (gaseous)	**kg CO_2/scf**	**g CH_4/scf**	**g N_2O/scf**
Landfill Gas	0.025254	0.001552	0.000306
Other Biomass Gases	0.034106	0.002096	0.000413
Biomass Fuels (liquid)	**kg CO_2/gal**	**g CH_4/gal**	**g N_2O/gal**
Biodiesel (100%)	9.45	0.14	0.01
Ethanol (100%)	5.75	0.09	0.01
Rendered Animal Fat	8.88	0.14	0.01
Vegetable Oil	9.79	0.13	0.01
Biomass Fuels (Kraft Pulping Liquor by Wood Furnish)	**kg CO_2/MMbtu**	**g CH_4/MMbtu**	**g N_2O/MMbtu**
North American Softwood	94.4	1.9	0.42
North American Hardwood	93.7	1.9	0.42
Bagasse	95.5	1.9	0.42
Bamboo	93.7	1.9	0.42
Straw	95.1	1.9	0.42

[12] U.S. EPA. Direct Emissions from Stationary Combustion Sources (EPA, 2016).

Biomass Power

The carbon intensity calculation of electricity from biomass in CA_GREET 3.0, follows a totality of emissions approach. The totality of emissions approach includes the total CO_2 being emitted from the process and also incorporates the biogenic CO_2 uptake from the atmosphere. The process of generating electricity from biomass can be divided into two major segments. First, there is the biomass farming and transportation. Second, there is the combustion of biomass in power plants to generate electricity.

Biomass farming and transportation emissions are straightforward as biogenic CO_2 is not emitted. Combustion of biomass in power plants emits biogenic CO_2 and other gases which have the biogenic carbon in them which was up taken by the biomass from the atmosphere. As mentioned above, CA-GREET 3.0 calculates and indicates the emission of total CO_2 and then subtracts the biogenic CO_2 taken by the biomass.

The biogenic CO_2 is determined by calculating the total carbon in the gaseous emissions from the power plant, occurred due to combustion of biomass. The gaseous elements presented in CA_GREET 3.0 which have carbon in them are VOC, CO, CH_4 and CO_2. The carbon content in the aforementioned gases is biogenic, and the sum gives us the total biogenic carbon in the biomass. Using this, the biogenic CO_2 uptake from the atmosphere can be calculated. CA_GREET3.0 then subtracts this CO_2 from the total CO_2 and calculates the GHG emissions. In below, the value of CO_2 in the 'Fuel' column is negative, as it has been subtracted with the biogenic CO_2. The direct GHG emissions from biomass power plants include the BUC approach. The calculation method is apparent in CA-GREET3.

In the last row of Table 13, it is clear that the biogenic C is calculated from CO_2, VOC, CO and CH_4. This shows that CA-GREET 3.0, provides a credit for the biogenic CO_2 uptake by the biomass, and that the biogenic carbon includes carbon, not only in CO_2 but also in VOC, CO, and CH_4 from the power plant.

The BUC approach is implemented in numerous energy policies as discussed in Section 3.2 In general, biotic carbon is treated based on its uptake from the atmosphere with negative emissions. The direct biotic carbon emissions from biomass combustion are treated as carbon neutral or in more detail according to the following:

$$GHG_b = VOC \times MW_{CO2}/MW_{VOC} + CO \times MW_{CO2}/MW_{CO} + CH_4 \times GWP_{CH4} + N_2O \times GWP_{N2O} + CO_2 - CO_2c \quad (1)$$

Where VOC, CO, CH_4, and N_2O and CO_2 refer to the direct emissions from combustion. The global warming potential of VOC and CO are treated as fully oxidized CO_2 due to the short lifetime of these pollutants in the atmosphere. This method is implemented in the GREET model, though some accounting schemes may not include this detail. CH_4 and N_2O emissions are multiplied by their global warming potential (GWP) and CO_2 has a GWP of 1. Finally, the uptake of CO_2 is represented in the CO_2c term, which includes all of the carbon in the biomass. This BUC approach, in effect counts the GWP weighted CH_4 and N_2O emissions. The carbon in CH_4 is often considered part of the GWP of CH_4. Therefore, CO_2c is often counted as the carbon in CO_2, VOC, and CO.

Table 13. CA-GREET3 output. The biogenic CO_2 credit is represented in the last entry

	User-Inputted Emission Factors (Default Data Here Are Emission Factors for EPA Database [g/kWh]) By Fuel-Type Plants									
	Biomass Boiler: Willow	Biomass Boiler: Poplar	Biomass Boiler: Switchgrass	Biomass Boiler: Miscanthus	Biomass Boiler: Forest Residue	Biomass IGCC Turbine: Willow	Biomass IGCC Turbine: Poplar	Biomass IGCC Turbine: Switchgrass	Biomass IGCC Turbine: Miscanthus	Biomass IGCC Turbine: Forest Residue
VOC	0.135	0.135	0.135	0.135	0.135	0.070	0.070	0.070	0.070	0.070
CO	4.755	4.755	4.755	4.755	4.755	0.071	0.071	0.071	0.071	0.071
NOx	0.927	0.927	0.927	0.927	0.927	0.078	0.078	0.078	0.078	0.078
PM10	2.814	2.814	2.814	2.814	2.814	0.024	0.024	0.024	0.024	0.024
PM2.5	1.976	1.976	1.976	1.976	1.976	0.012	0.012	0.012	0.012	0.012
SOx	0.918	0.355	2.152	1.474	0.654	0.578	0.223	1.355	0.928	0.412
BC	0.273	0.273	0.273	0.273	0.273	0.002	0.002	0.002	0.002	0.002
OC	0.644	0.644	0.644	0.644	0.644	0.004	0.004	0.004	0.004	0.004
CH4	0.493	0.493	0.493	0.493	0.493	0.033	0.033	0.033	0.033	0.033
N2O	0.066	0.066	0.066	0.066	0.066	0.094	0.094	0.094	0.094	0.094
CO2	1,630	1,621	1,662	1,599	1,499	1,031	1,025	1,052	1,011	948
CO2 (w/ C in VOC, CH4 & CO)	-1,639	-1,630	-1,672	-1,608	-1,508	-1,032	-1,026	-1,052	-1,012	-949

Woody Biomass LCFS Pathways

CARB prepared draft pathway documents for the conversion of forest residue and farmed trees to cellulosic ethanol (CARB, 2009a; CARB, 2009b). The analysis followed the CA-GREET approach which included a biogenic uptake credit for carbon in the biomass that offset the release from process emissions and fuel combustion. An example of the calculation approach from the biogenic uptake credit is shown in Table 14.

Table 14. Output from GREET pathways for cellulosic ethanol from farmed trees by fermentation

GHG Species	g/mmBtu	g CO_2e/MJ
VOC	6.0	
CO	85.2	
CH_4	11.5	
N_2O	6.85	
CO_2	112,972	
Total GHGs ($gCO_2e/mmBtu$)	115,527	**109.5**
CO_2 credit from direct use of tree burning as process fuel	(-112,751) [a]	**(-106.9)**
Total GHGs	**2,702**	**2.56**

[a] Total CO_2 exceeds biogenic CO_2 since a small amount of diesel and natural gas fuels are used in the pathway.

While biomass was treated as carbon neutral in these documents, CARB indicated that the analysis was preliminary:

> *This is a preliminary estimate of the carbon intensity for the fuel derived from the feedstock presented in this document. At this time, this document has been provided for informational purposes only. Staff is in the process of obtaining additional information to refine and/or modify the values presented in this document. The refinement is both for direct and indirect effects. When staff has completed the analysis, a final value will be presented in the future for the fuel presented in this document.*

Crop Residues

Pathways exist using GREET for lifecycle GHG emissions from crop residues to cellulosic ethanol. Following the CA-GREET approach, these pathways include a biogenic uptake credit for carbon in the biomass that offsets the release from process emissions and fuel combustion. The treatment of biogenic carbon for crop residue used as process fuel and feedstock is the same as that in Table 14.

3.2.4 Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA)

CORSIA is a global market-based mechanism established in 2016 by members of the International Civil Aviation Organization (ICAO) to calculate and address the life cycle GHG emissions of aviation fuels associated with international civil travel (Prussi, et al., 2021). CORSIA aims to mitigate aviation fuel CO_2 emissions through two mechanisms: offsetting (an action by a company or individual to compensate for their emissions by financing a reduction in emissions elsewhere), and use of lower-emission sustainable aviation fuel (SAF). Their goal is to scale up SAF and other nascent technologies such as electric and hydrogen-powered aviation, and decrease the need for offsetting.

CORSIA assumes biogenic CO_2 emissions are carbon neutral, as explained in the report detailing the methodology (Prussi, et al., 2021):

> *For biomass-derived fuels, biogenic CO_2 emissions from fuel combustion are assumed to be offset by the biomass carbon uptake happened during the biomass growth, and therefore count as zero in the LCA of SAF. Jet fuel CO_2 combustion emissions only include CO2 from fossil sources.*

3.2.5 EPA Code of Regulations

Biogenic CO_2 emissions from combustion of biomass with other fuels.

Based on the Code of Regulations the equation 1 allows to estimate biogenic CO_2 emissions for operating hour from units that combust a combination of biomass and fossil fuels (*i.e.,* either co-fired or blended fuels) (EPA, 2022a).

$$V_{Co2H} = \frac{(\%CO_2)}{100} \times Q_h \times t_h \qquad (Eq. 1)$$

Where:

V_{CO2h} = Hourly volume of CO_2 emitted (scf).

$(\%CO_2)_h$ = Hourly average CO_2 concentration, measured by the CO_2 concentration monitor, or, if applicable, calculated from the hourly average O_2 concentration ($\%CO_2$).

Q_h = Hourly average stack gas volumetric flow rate, measured by the stack gas volumetric flow rate monitor (scfh).

t_h = Source operating time (decimal fraction of the hour during which the source combusts fuel, i.e., 1.0 for a full operating hour, 0.5 for 30 minutes of operation, etc.).

100 = Conversion factor from percent to a decimal fraction.

In addition, in Table 15 is listed the biogenic CO_2 emissions from the combined combustion of biomass and fossil fuels is required for those biomass fuels; In a cases that a biomass fuel is not listed in Table 15 is combusted in a unit that has a maximum rated heat input greater than 250 mmBtu/hr, if the biomass fuel accounts for 10% or more of the annual heat input to the unit, and if the unit does not use CEMS to quantify its annual CO_2 mass emissions (EPA, 2022c).

Table 15. Default CO_2 Emission Factors and Hight Heat Values for Various Types of Biomass Fuel

Fuel type	Default high heat value	Default CO_2 emission factor
Other fuels - solid	**mmBtu/short ton**	**kg CO_2/mmBtu**
Municipal Solid Waste	9.953	90.7
Biomass fuels - solid	**mmBtu/short ton**	**kg CO_2/mmBtu**
Wood and Wood Residuals (dry basis)[a]	17.48	93.8
Agricultural Byproducts	8.25	118.17
Peat	8	111.84
Solid Byproducts	10.39	105.51

[a] Use the following formula to calculate a wet basis HHV for use in Equation C-1: $HHV_w = ((100 - M)/100) \times HHV_d$ where HHV_w = wet basis HHV, M = moisture content (percent) and HHV_d = dry basis HHV from Table C-1.

3.3 Other Analysis Schemes

The notion of carbon neutrality is a simplified version of the carbon accounting of biomass. A key aspect that is not explicitly addressed under the carbon neutral assumption is the influence of time on emissions release to the atmosphere. Annual crops such as corn and wheat exhibit relatively short cycles of growth and decay, however, woody biomass grows, decomposes and burns over varying, and sometimes longer time periods, therefore, its alternative fate is potentially more complicated than that of annual crops. Those questioning the carbon-neutral assumption point out that near-term emissions associated with use of waste residues (e.g., biomass to power or biofuel) can lead to increased climate-forcing over policy-relevant timeframes. This argument assumes that the alternative fates (decay and/or burning) of the same residues in-situ would have occurred over longer period of time.

Several modeling systems, discussed in the following sections, take into account the potential alternative fate of biomass residues, and incorporate a time-horizon for the growth and regrowth of biomass.

3.3.1 C-BREC

The California Biomass Residue Emissions Characterization Model (C-BREC) was designed as a transparent and customizable tool for calculating the life cycle impacts of residual biomass[8] for California's energy policies (Carman, et al., 2021). The framework was commissioned by the California Energy Commission to address the objective of reducing environmental and public health impacts of electricity generation and decreasing the vulnerability of California's electricity system to climate impacts, however, the model may be used to inform other biomass energy systems, including biofuel production.

The C-BREC framework authors acknowledge existing controversy regarding biogenic emissions; however, they conclude that the issue of reporting biogenic issues is straightforward when dealing with biomass residues:

> *As the biomass under consideration is residue, and the activity generating the residue is assumed not to be driven by the residue market, this question is simpler than in other biomass LCAs. There is no change in on-site C pools beyond the presence/absence of the biomass residue itself, so by tracking the full emission profile of the use case, net of the emissions from fire and decay in the reference case, we are able to account for all net emissions, biogenic and otherwise*.

The C-BREC framework addresses the assumption of carbon-neutral accounting by accounting for all emissions, including biogenic, associated with the use of biomass residues and their counterfactual (reference) fates, e.g., decay or burning – either prescribed or unplanned wildfire. C-BREC counters a common assumption that all biomass is either completely combusted through burning events or decays at a single rate, and by differentiates such parameterization across geographies and according to different in-situ spatial configuration ("disposition") of biomass residues. More specifically, emissions associated with each counterfactual fate are based on existing models and literature values, specific to species composition, size class and disposition, and climatic factors. As an example of the counterfactual fates considered under the C-BREC framework, see Table 16, and Table 17, below.

[8] Woody biomass residues are defined as those derived parts of the tree remaining after a primary silvicultural treatment that do not have a market pathway (i.e. forest slash). Agricultural biomass residues are defined as any material remaining in-field following the harvest of an annual crop, or trimmings, dead material, and plant waste from perennial crops.

Table 16. Counterfactuals for forest residues included in C-BREC framework

Definition of Reference and Use Cases for Forest Residues
F-R1. Biomass Left On-Site All residues are left on-site to decay and are subjected to annualized wildfire probability.
F-R2. Pile Burn All piles are burned in year 1 – the same year as the primary treatment. Any scattered residues are left unburned. Residues that remain are treated as scattered and subjected to decay and annualized wildfire probability.
F-R3. Broadcast Burn All scattered residues are burned in year 1 – the same year as the primary treatment. Any piles that exist are unburned. Residues that remain are subjected to decay and annualized wildfire probability.
F-R4. Pile and Broadcast Burn All piles and all scattered residues are burned in year 1 – the same year as the primary treatment. Residues that remain are treated as scattered and subjected to decay and annualized wildfire probability.
F-U1. Collect All Piles All piled residues are collected. Residues that remain are subjected to decay and annualized wildfire probability.
F-U2. Collect All Piles and/or Technically Recoverable Scattered Residues All piled residues are collected, and all technically recoverable scattered residues are collected. Residues that remain are subjected to decay and annualized wildfire probability.

Table 17. Counterfactuals for agricultural residues included in C-BREC framework

Definition of Reference and Use Cases for Agricultural Residues
A-R1. Biomass Left Scattered On-Site Residues are left scattered in-field to decay. Decomposition dynamics depend on the crop (in the case of rice, depending also on whether the field is flooded post-harvest).
A-R2. Residues Incorporated Into Soil (Straw Only) Residues are tilled into the soil in the field in which they were grown during year 1 – the same year as the primary harvest activity.. This option is limited to straw residues (corn, cotton, rice, and wheat). Decomposition dynamics depend on the crop (in the case of rice, depending also on whether the field is flooded post-harvest).
A-R3. Residues Burned On-Site All residues are control-burned during year 1 – the same year as the primary harvest activity.
A-U1. Collect Residues Biomass residues are collected. Residues that remain are subjected to above-ground decay.

Accounting for Time Dependencies

Global Warming Potential (GWP) measures the impact of a greenhouse gas on global warming over a specific time frame, typically 100 years (GWP-100). It compares the heat-trapping ability of different gases to carbon dioxide. Global Temperature Potential (GTP) measures the impact of a greenhouse gas on global mean surface temperature over a set time frame. Most regulatory frameworks, including CARB use GWP-100 for policy decisions and emissions assessments. The implications of GWP assumptions for methane are shown in Figure 3.1 below.

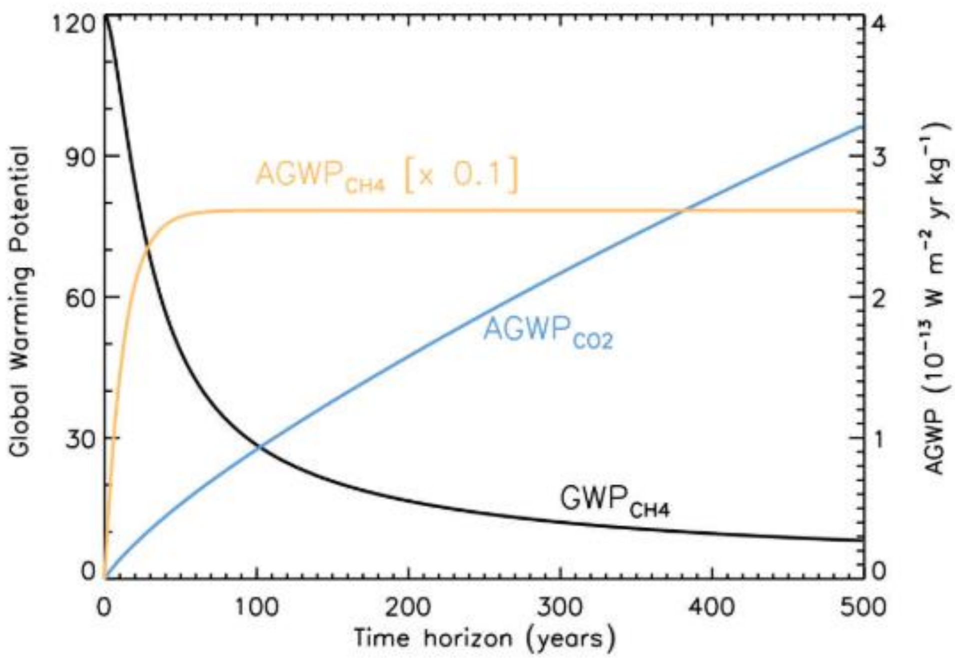


Figure 3.1. Time horizon impact on methane GWP[9].

In order to account for climate-forcing effects on policy-relevant timescales, C-BREC calculates emissions both on a GWP basis, and on a GTP basis. GTP is a measure of the heat absorbed over a given timeframe, and thus in this context, reflects the increase in temperature due to a given emissions trajectory for the equivalent GWP timeframe. C-BREC is based on burning emission factors from the Bluesky modeling framework (Larkin, et al., 2009), and decomposition emission factors based on negative exponential models of decay (Blasdel, 2020). The C-BREC model characterizes the variable emissions from different biomass supply chains as well as the counterfactual emissions from prescribed burn, wildfire, and decay avoided by residue mobilization.

Figure 3.2 illustrates the breakdown of carbon intensity outcomes (in net grams of CO_2 equivalent per kilowatt-hour) in the recent California treatments case study with carbon intensity displayed on the horizontal axis and relative prevalence of a given range of results

[9] Source: Center for Methane Research. Implications of GWP Time Horizons. https://www.gti.energy/wp-content/uploads/2019/02/CMR-Implications-Using-Different-GWP-Time-Horizons-White-Paper-2019.pdf

represented on the vertical axis. The chart also presents the CA grid average and US Grid average, the Grid values are on a life-cycle basis and are derived from Chen and Wemhoff (Fingerman, et al., 2023; Chen & Wemhoff, 2021).

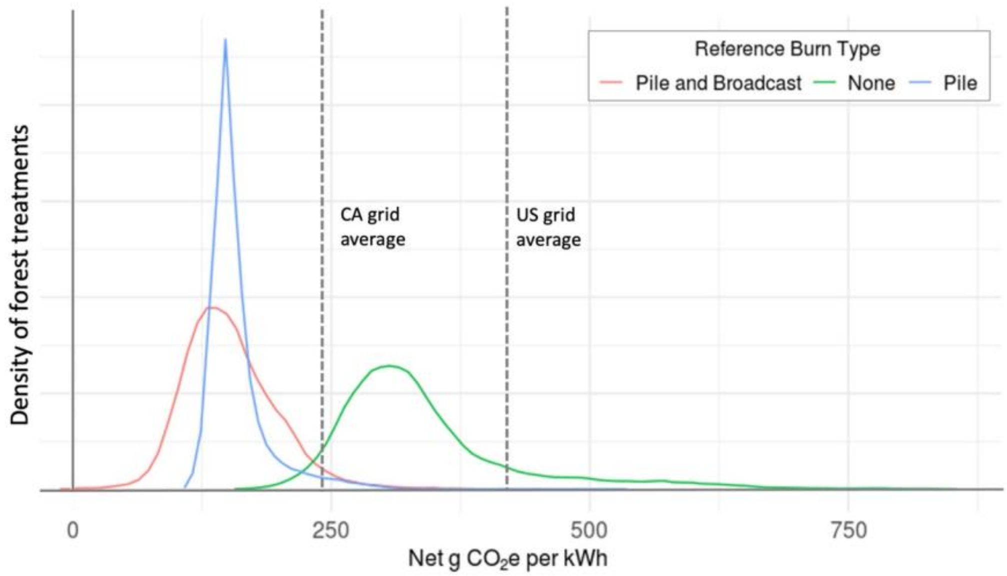


Figure 3.2. Distribution of carbon intensity results (net g CO_2e kWh−1) across the California recent treatments case study, disaggregated to illustrate the difference across reference case prescribed burn scenarios (Fingerman, et al., 2023).

CARB used the C-BREC model to characterize the amount and location of available forestry residues and affiliated criteria emissions for the five treatment scenarios they considered in the 2022 Draft Scoping Plan update (CARB, 2022c). However, C-BREC may not be a useful for accounting for lifecycle emission in the context of the California LCFS.

The California LCFS is based on the GREET model framework. GREET is available as a spreadsheet tool that can be disaggregated to reveal precisely where emission totals are coming from. C-BREC is available as a web tool. C-BREC is programmed in the programming language R. While this code had previously been publicly available on GitHub, the code is no longer available online. Thus, C-BREC is a black box that takes inputs at generates several project characteristics, such as total electricity generated, tones of total residue generated, net GHG emissions, and Net Criteria pollutants. Figure 3.3 shows one region selected for a test in North California and Figure 3.4 shows an output example using C-BREC web tool.

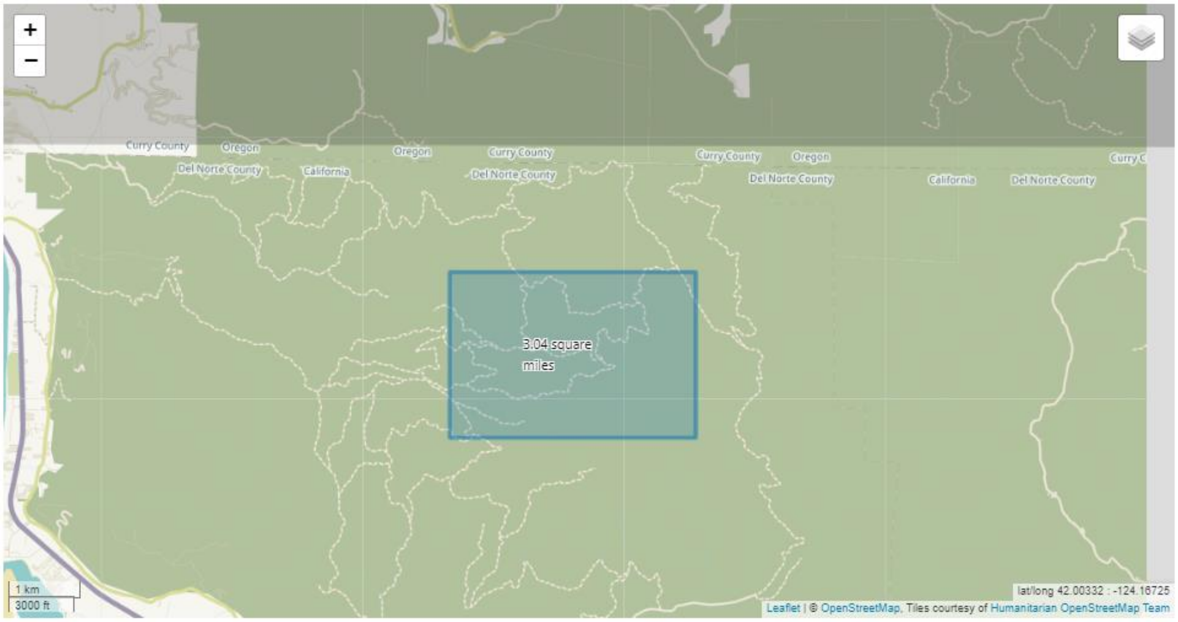


Figure 3.3. Screenshot of location selected.

Project Characteristics

Total electricity generated
2.44e+4 MWh

Tons of total residue generated
2.31e+4 metric tons

Net Greenhouse Gas Emissions

g CO_2e/kWh (100-yr GWP Normalized)	g CO_2e/kWh (100-yr GTP Normalized)	kg CO_2e (100-yr GWP Normalized)	kg CO_2e (100-yr GTP Normalized)
339.017	93.063	8.272e+6	2.271e+6

Net Criteria Pollutants

PM_{10} (g)	NO_x (g)	SO_2 (g)	CO (g)	VOCs (g)	Black Carbon (g)
-2.745e+7	2.484e+7	4.290e+6	-1.577e+8	-6.748e+7	-4.116e+6

Figure 3.4. Example C-BREC Output.

Using previously downloaded R code, allow for the development of disaggregated results; however, a complete disaggregation remains elusive. We can see that the methodology employed by C-BREC does not align with that of GREET and an external representation of sample calculations would be helpful. For example, C-BREC includes emissions that are outside the scope of the GREET system boundary. Figure 3.5 presents an example for diesel and gasoline's emission factors from EPA.

```
# emissions factors for diesel and gasoline come from the EPA:
# https://www.epa.gov/sites/production/files/2015-07/documents/emission-factors_2014.pdf
# Diesel assumed to be distillate fuel oil No. 2
CO2_diesel_grams = 10210 # LCA COMMENT - this doesn't include life cycle emissions, GREET would say 13,087
CH4_diesel_grams = 0.41
N2O_diesel_grams = 0.08

# Gasoline assumed to be motor gasoline
CO2_gas_grams = 8780
CH4_gas_grams = 0.38
```

Figure 3.5. Emission factors for Diesel and Gasoline from EPA.

The C-BREC model estimates emissions from both flaming and smoldering combustion during biomass residue burning. Flaming combustion occurs when there is sufficient oxygen available to sustain a flame and is typically associated with the initial stages of combustion while smoldering combustion occurs when there is limited oxygen and is characterized by slower, less intense burning. On the other hand, the residual emissions factor refers to the emissions that occur after the primary combustion phase, which includes both flaming and smoldering combustion. These residual emissions are typically associated with the smoldering phase of combustion, which can continue after the flames have died down. Table 18 shows those three types of emissions mentioned before.

Table 18. General emissions factors in C-BREC

Pollutant	Flaming Emission Factors (kg/kg)	Smoldering Emission Factors (kg/kg)	Residual Emission Factors (kg/kg)
CH_4	0.0038	0.0099	0.0099
CO	0.0718	0.2101	0.2101
CO_2	1.6497	1.3931	1.3931
NOx	0.0024	0.0009	0.0009
PM10	0.0086	0.0196	0.0196
PM2.5	0.0073	0.0166	0.0166
SO_2	0.001	0.001	0.001
VOC	0.0173	0.049	0.049

The C-BREC model also includes specific emission factors for open burning piles, which are commonly used for the disposal of agricultural and forestry residues. These piles can include a variety of materials, including crop residues, forest slash, and other woody debris. Table 19 present the values for those emission factors.

Table 19. Piles Emission Factors

Pollutant	Flaming Emission Factors (kg/kg)	Smoldering Emission Factors (kg/kg)	Residual Emission Factors (kg/kg)
CH_4	3.28 / 2000 = 0.0016	11.03 / 2000 = 0.0055	11.03 / 2000 = 0.0055
CO	52.66 / 2000 = 0.0263	130.37 / 2000 = 0.0652	130.37 / 2000 = 0.0652
CO_2	3429.24 / 2000 = 1.7150	3089.88 / 2000 = 1.5450	3089.88 / 2000 = 1.5450
NOx	0.00242	0.000908	0.000908
SO_2	0.00098	0.00098	0.00098
VOC	0.017342	0.0490268	0.0490268

Note that the emissions factors estimated by C-BREC are specific to the conditions and types of biomass residue burning activities that were studied in California.

C-BREC model includes some assumptions parameters for collection and processing as shown in Figure 3.6. Additionally, C-BREC includes other key input parameter as the mass loss fraction, decay mass fraction, and decay emission fraction. These analysis systems may change with updates to the model.

```
# Processing and Collection ---------------------------------------

residue_slope_cutoff <<- 80 # Slope (%) above which collection of residues is not allowed
density.threshold <<- 13 # BDT/acre. Threshold at which a project is defined as "high volume" and associated equipment is applied
ave_harvest_acres <<- 25 # acres. Associated with an average "catch basin" for in-field processing equipment. This is used to determine a multiplier for equipment hauling emissions.
harvest_tonnes_per_person_day <<- 16.04 # tonnes / person-day. From Barrett, S., Bolding, M., & Munsell, J. (2017), reported 224.62 tonne per crew per week, 2.8 people per crew, and assume 5 days per week
crew_commute_dist <<- 80.5 # km. Assumption of 50 miles
equip_commute_dist <<- 80.5 # km. Assumption of 50 miles
equip_km_per_hour <<- 58 # km/hr. Equivalent to ~36 MPH
transfer_point_distance <<- 8.04672 # kilometers, equal to 5 miles. Additional hauling distance used if project includes a transfer point
unloaded_truck_eff_improve <<- 0.15 # Assume 15% fewer emissions (15% greater efficiency) on the return trip back to the field

# Associated with set() function in year 1 calculations in run-cbrec.R

firecols <<- c('CWD_Scattered_CombustionFrac',
```

Figure 3.6. Assumptions parameters in C-BREC model.

The mass loss fraction is used to estimate the amount of biomass that is burned during a biomass residue burning activity. The mass loss factor represents the fraction of the initial biomass that is lost during the burning process due to factors such as combustion efficiency and volatilization as shown in the Figure 3.7 below.

```
# ------------------------------------------------------------------------------------------------------
# Calc power plant mass and energy inputs
# ------------------------------------------------------------------------------------------------------
# Calculate mass loss fraction after storage decay (fraction of pp_residue.delivered_tonnes)
#   Emissions from storage decay are allocated to the first year. Variable avg_storage_time_months defined in constants.R as global variable
storage_mass_lost_fraction <- round(2.1469127002*log(days_per_month * avg_storage_time_months) - 1.5039981419, 1) / 100 # From dry matter loss (DML) research
```

Figure 3.7. Mass loss fraction.

Figure 3.8 presents two more parameters used in the C-BREC model: the decay mass fraction and a CH_4 decay emissions fraction. The first one is used to estimate the amount of biomass that has decayed prior to the burning activity. This parameter is important because decaying biomass contains less carbon than fresh biomass, and therefore produces fewer emissions when burned. Additionally, the CH_4 decay emissions fraction represents the fraction of the total methane emissions that are produced due to the decay of biomass prior to the burning activity.

```
duff_decay_mass_fraction <<- 0.02 # (Mass as Duff) / (Mass Lost from Decay)
duff_k_val <<- 0.002 # Decay constant for duff for exponential decay function
CH4_decay_emissions_fraction <<- 1E-5 # (Mass Carbon as CH4) / (Mass Carbon Lost from Decay). Applied to scattered and piled woody material (forest and ag).
foliage_to_duff_trigger <<- 0.5 # (Mass Foliage Remaining) / (Original Mass Foliage) value below which all mass foliage remaining is moved to duff

# Decay of Power Plant Storage Piles ---------------------------------------------------

avg_storage_time_months <<- 6 # Average months residues are stored at power plant before combustion (must be <= 12 as emissions are allocated to first year)
CH4_decay_emissions_fraction_storage <<- CH4_decay_emissions_fraction # (Mass Carbon as CH4) / (Mass Carbon Lost from Decay)
```

Figure 3.8. Decay mass and emission fraction.

C-BREC cases

We conducted several cases using the C-BREC web tool, assessing various scenarios across a limited number of locations within California. The tool allowed us to analyze the carbon intensity outcomes of biomass treatments in diverse geographic settings, providing insights into the potential impacts of biomass utilization. By running simulations on the CBREC web tool, we could evaluate the net grams of CO_2 equivalent emitted per kilowatt-hour (gCO_2e/kWh) across these locations. Table 20 below present 6 different cases from different locations.

Table 20. Cases ran on CBREC in North, Central and South California

Location	**North CA (Shasta County)**	**North CA (Blue Mountain)**	**Central CA (Big Bar Mountain)**	**Central CA (Fox Mountain)**	**South CA (Baid Peak)**	**South CA (Hunter Peak)**
Thin part	Thin from Above	Thin from Above	Thin from Above	Thin from Above	Thin from Above	Thin from Above
% of residue in piles	70.0%	70.0%	70.0%	70.0%	70.0%	70.0%
%Basal Area removed	80.0%	80.0%	80.0%	80.0%	80.0%	80.0%
Residue Biomass collected	Piles Only	Piles Only	Piles Only	Piles Only	Piles Only	Piles Only
Type of biopower facility	**Current**	**Current**	**Current**	**Current**	**Current**	**Current**
Hauling distance	50 miles	50 miles	50 miles	50 miles	50 miles	50 miles
Type of Residue	High Residue Density: Dry, Grind	High Residue Density: Dry, Grind	High Residue Density: Dry, Grind	High Residue Density: Dry, Grind	High Residue Density: Dry, Grind	High Residue Density: Dry, Grind
Residue location	Left in Place	Left in Place	Left in Place	Left in Place	Left in Place	Left in Place
Units	Results					
kg CO	170,200,000	120,500,000	6,140,000	36,090,000	4,649	40,410
kg PM	-28,500,000	-16,670,000	-1,612,000	-13,870,000	52	451
Tonnes biomass	**10,900.0**	**9,915.3**	**472.5**	**4,272.2**	**3.7**	**32.1**
Power **(MWh)**	**10,800.0**	**9,951.5**	**474.5**	**4,101.6**	**3.7**	**31.8**
MJ Power	38,880,000	35,825,256	1,708,344	14,765,796	13,176	114,552
Efficiency	**21.0%**	**21.3%**	**21.3%**	**20.3%**	**21.0%**	**21.0%**
GJ Biomass	185,300	168,560	8,033	72,628	63	546
g/kWh	310.68	369.51	590.85	414.66	1181.54	1182.37
kg CO_2e	3.355E+06	3.677E+06	2.804E+05	1.701E+06	4.324E+03	3.762E+04
g CO_2e/kg Biomass	**307.83**	**370.86**	**593.38**	**398.10**	**1171.93**	**1171.69**
CI (g CO_2e/MJ)	16.88	20.33	32.53	21.82	64.25	64.23

The variation in carbon intensity across California location can be attributed to user error: the model allows users to choose forest locations, however not all locations are suitable for biomass power utilization. The Southern California locations chosen would not be suitable biomass power locations, and thus the resulting carbon intensity of the biomass is higher than forested location in Northern California.

3.3.2 Stand Level vs Landscape Level Forest Accounting

Comparisons of GHG depends not only on the bioenergy combustion technology and fossil fuel technology employed, but also on the biophysical and forest management characteristics of the forests from which biomass is harvested, and the starting point of the analysis. For example, 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 over an equivalent timeframe.

Stand Level

Using a stand-level approach, Walker et al. 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 (Walker, Cardellichio, Saah, & Hagan, 2013). Thereafter, forest GHG decreased incrementally in relation to fossil fuel combustion, yielding carbon dividends in the respective forest systems (Figure 3.9). They also found that replacing 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.

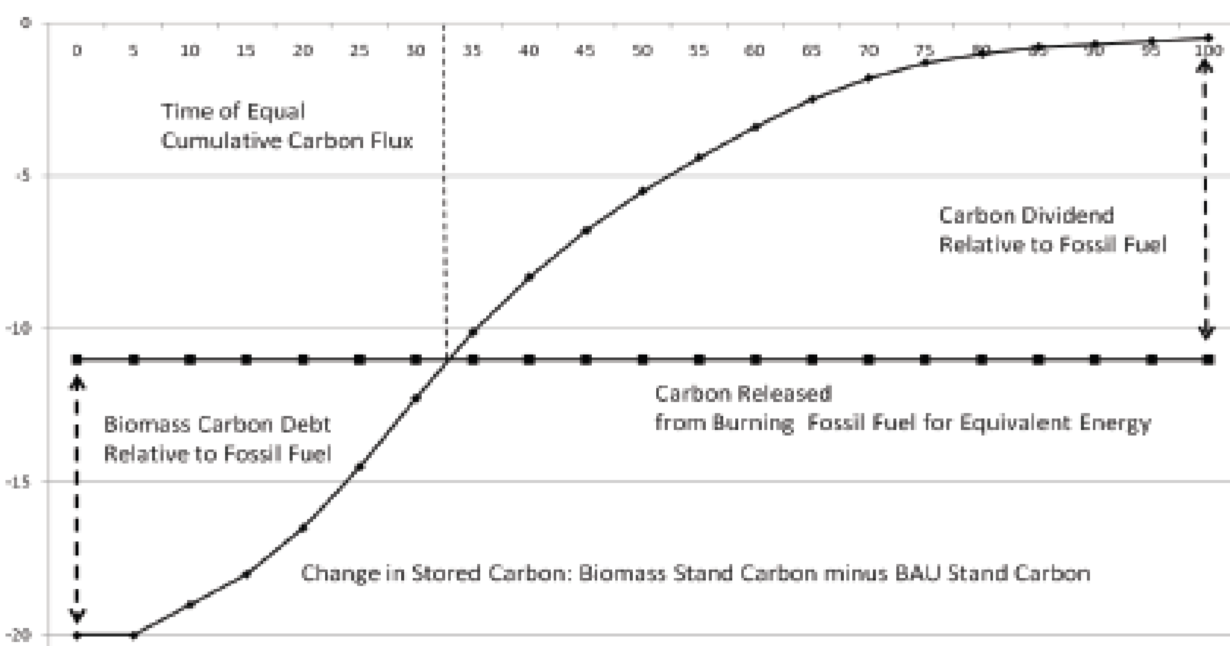


Figure 3.9. Incremental carbon storage (in tonnes) for a forest stand scenario compared to fossil fuel combustion. Source: (Walker, Cardellichio, Saah, & Hagan, 2013). Note: BAU represents a typically harvested stand.

Landscape Level

Applying a landscape-level approach to forest carbon accounting, Strauss 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 3.10) (Strauss, 2011).

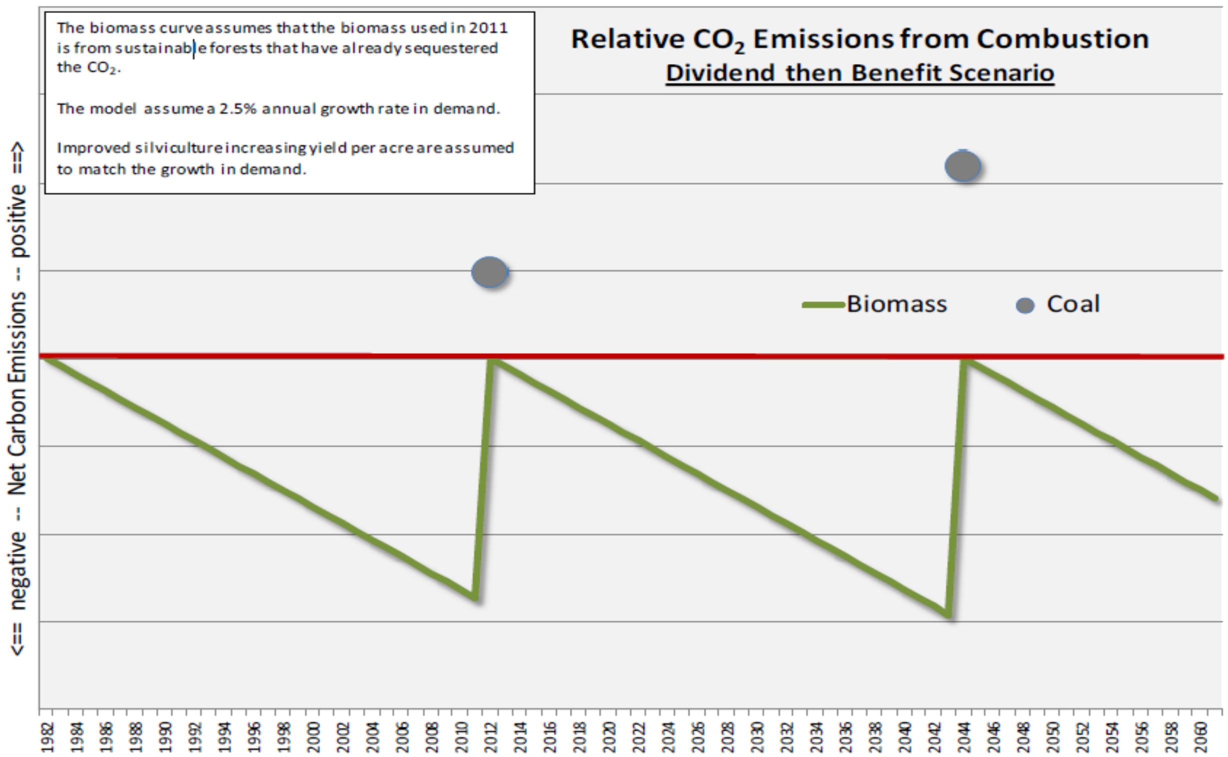


Figure 3.10. Incremental carbon storage and associated emissions in sustainably harvested forests. Source: (Strauss, 2011).

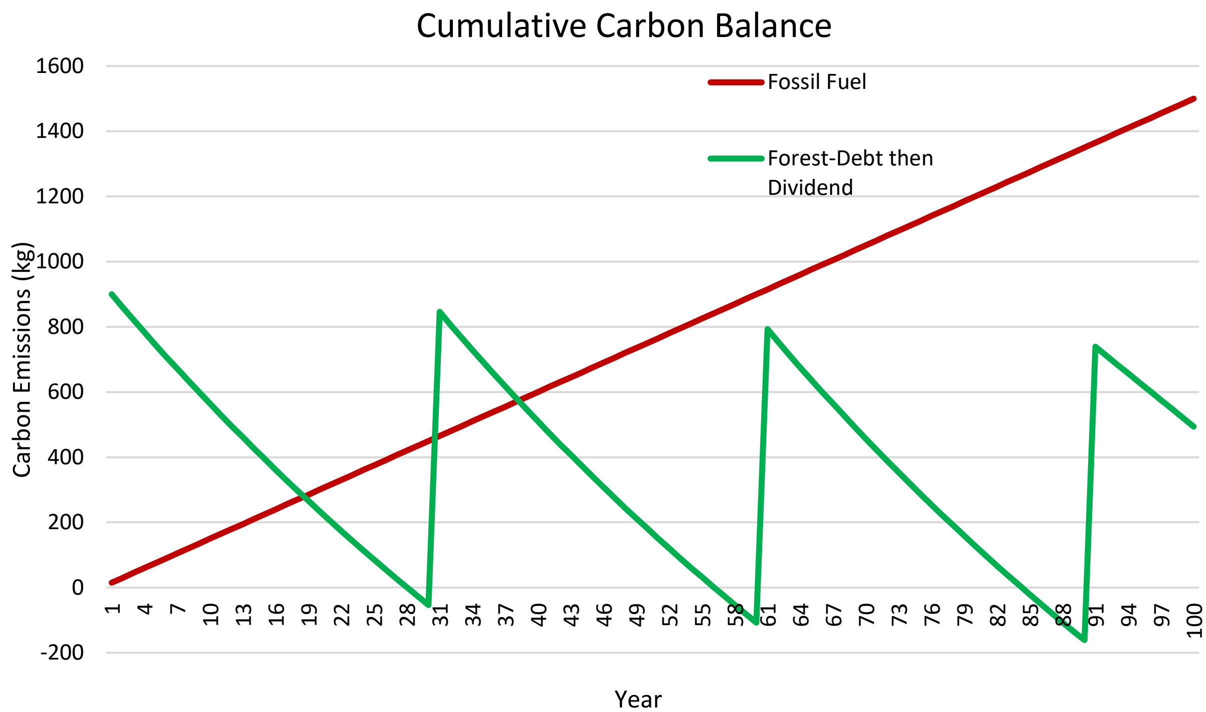


Figure 3.11. Incremental carbon storage and associated emissions.

Argonne National Laboratory and CORRIM (2018) analyzed carbon dynamics for a stand-level framework compared to a landscape-level dynamic framework (Han, et al., 2018). In their stand-level analysis two cycles were considered. In the first cycle, standing trees were harvested to produce biofuels, and then the harvest was replanted. In the second cycle, a forest harvest was planted, followed by newly grown trees being harvested for biofuel production. In both scenarios, biogenic emissions and uptake were accounted for at the point at which they occurred. In their landscape-level analysis, carbon emissions and uptake did not change over time because biomass was sustainably harvested from forests, keeping net primary productivity constant. The results of this study are summarized in Figure 3.12.

The authors 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.

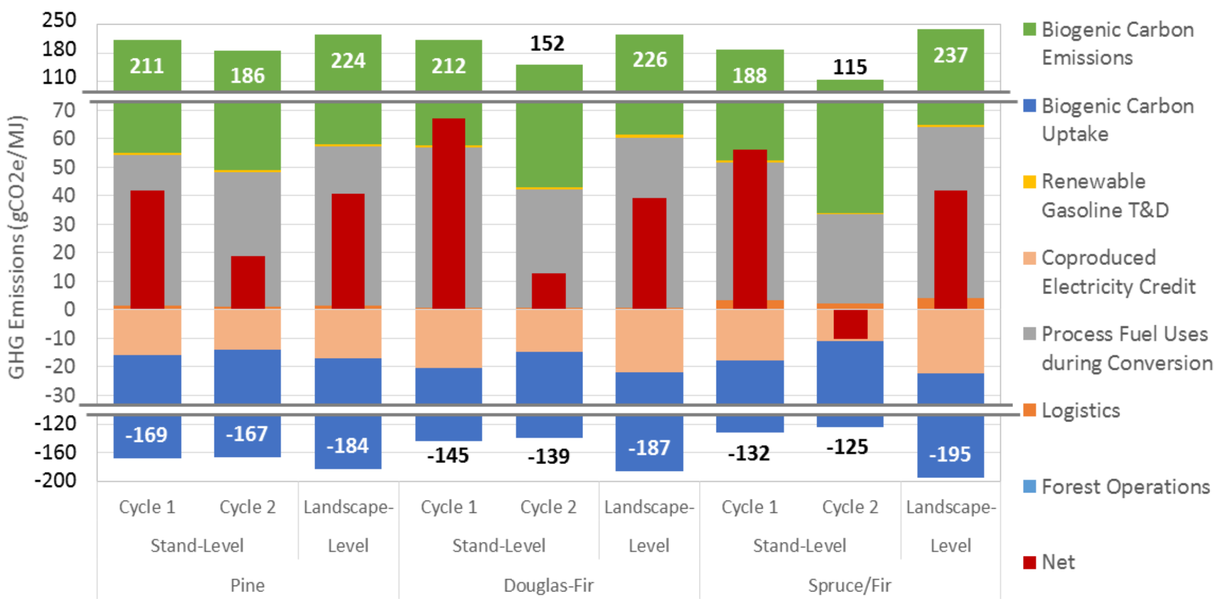


Figure 3.12. CORRIM and Argonne National Laboratory analysis of renewable gasoline from emissions Pine, Douglas-Fir, and Spruce/Fir feedstocks (Han, et al., 2018).

3.3.3 WWF Biogenic Carbon Footprint Calculator

The World Wildlife Foundation (WWF), in partnership with Quantis, Intl., developed a biogenic footprint calculator for a variety of forest-based products. The calculator takes into account the conventional carbon footprint of a bio-based product (excluding biogenic emissions), and separately accounts for biogenic emissions using dynamic methods, representing a variation of the Biogenic Uptake and Credit Approach. This dynamic accounting reflects the potential gap in carbon stocks when biomass is harvested, regrowth time, and the length of time that carbon is stored in a bio-based product (Gmunder, Zollinger, & Dettling, 2020). Figure 3.13 below demonstrates the modeled forest carbon stock after harvesting 1,000 m^3 of Spruce from a cool temperate climate to make sawlog and veneer log.

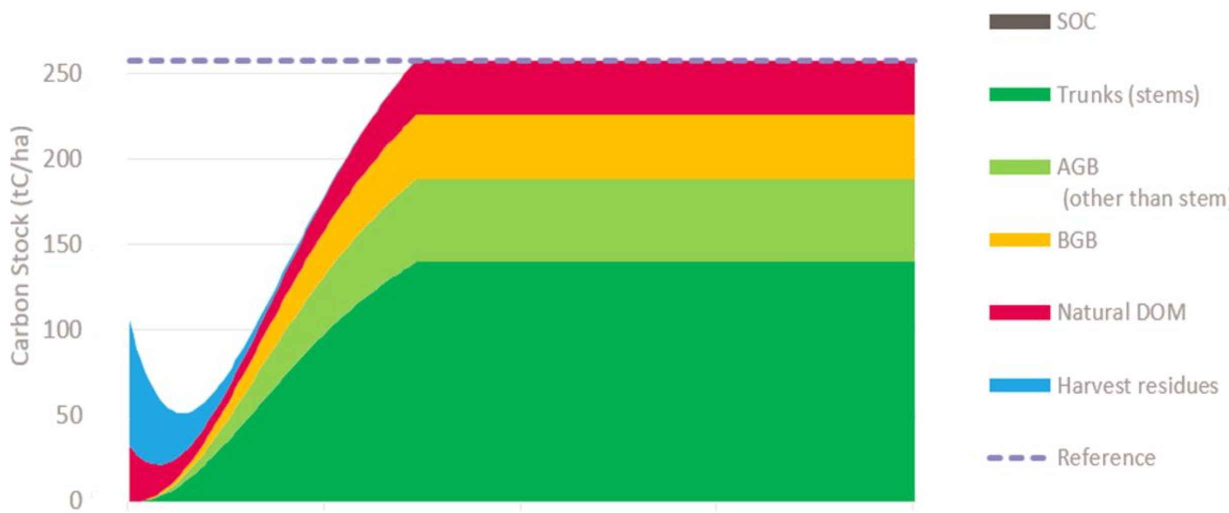


Figure 3.13. Forest carbon stock after harvesting 1,000 m^3 of cool temperate spruce starting at t_0. Carbon pool include stem wood (green), ground biomass (light green), below-ground biomass (yellow), natural dead organic matter (red), harvest residues (blue), and soil carbon (gray). The dotted purple line refers to the reference carbon stock.

3.4 Stock and Flow Accounting Framework

Stock and flow accounting seeks an alternative framework to LCA for comparing the CO_2 effects of biofuel use to that of fossil fuel use. DeCicco (2016) characterized this approach as Annual Basis Carbon (ABC) accounting and argued that the assumption of biogenic carbon neutrality embedded in LCA is inaccurate because it doesn't fully account for all emissions sources. When applied to fuels, the ABC approach accounts for all CO_2 emissions from end-use regardless of the fuel's origin. For biofuels, direct emissions to the atmosphere are reported without crediting biogenic carbon uptake. DeCicco proposed an attributional accounting protocol to report net CO_2 uptake, and credit producers when biogenic uptake exceeds biogenic emissions (DeCicco, et al., 2016).

In his 2016 study, DeCicco compared the emissions from all biofuels in the United States between 2005 and 2013 with the cumulative additional carbon uptake on cropland over the same time period. He reported that the biogenic carbon emitted from the biofuels is always greater than the additional carbon uptake on croplands over this time period, referring to this difference as the neutrality gap. Over the time period, he concluded that only a 37% of emissions are offset due to biogenic uptake, rather than the 100% offset assumed by most LCA frameworks (based on an assumption of carbon neutrality). DeCicco further concluded that a reduction in the biogenic emissions offset in LCA models would lead to drastically different carbon intensities, and in some scenarios could result in a biofuel having a greater carbon intensity than petroleum (DeCicco, et al., 2016). Figure 3.14 shows an analysis of the cumulative carbon emitted by U.S. Biofuels up to 2013.

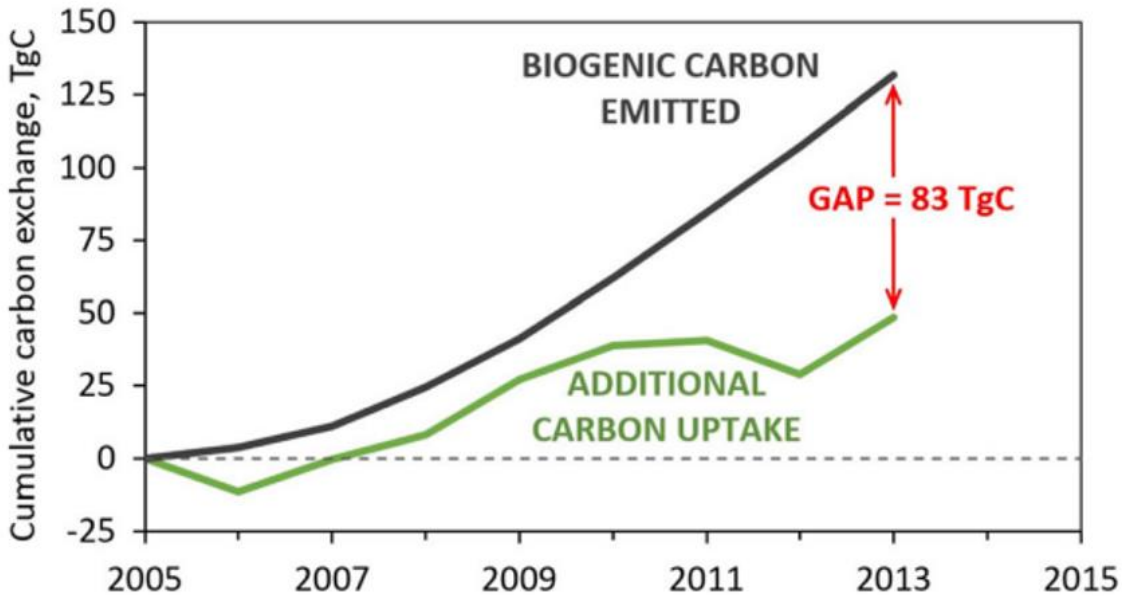


Figure 3.14. DeCicco's analysis of cumulative carbon emitted by U.S. biofuel use compared to additional carbon uptake on cropland.

Critics of DeCicco's study, including De Kleine and Mueller (De Kleine, Wallington, Anderson, & Chul, 2017; Mueller, 2016) contend that the ABC methodology has failed to establish meaningful correlations between existing biofuels policies and net carbon uptake, and that it does not include several important carbon pools in its assessment.

3.5 Summary of Carbon Balance Approaches

Each approach to accounting for biogenic carbon has strengths and weaknesses that could depend on the feedstock under consideration, process-related emissions, and the bio-product's end use. The following summarizes the biogenic carbon accounting methods discussed herein.

The simplest approach to accounting for biogenic carbon in a bio-product is to assume the biogenic carbon neutrality, and ignore emissions caused by biogenic uptake or combustion/decomposition. This approach is the simplest to model while still giving providing accurate results over a product's entire lifespan. Critics of the carbon neutral approach argue that the simplifying assumptions misrepresent the impact or timing of carbon emissions.

A variation of the carbon neutral approach, the biogenic uptake and credit approach (also called the totality of emissions approach), explicitly states the biogenic carbon flows. While this adds complexity to a model, it also allows for more detailed carbon accounting; carbon can be allocated to specific parts of a product's life cycle, or to co-products in proportion to the amount of biogenic carbon stored or released.

Several time-based approaches exist. The Debt-then-Dividend approach (Walker, Cardellichio, Saah, & Hagan, 2013) posits that a bio-product is not considered carbon neutral until enough time has passed for new biomass to accumulate the same magnitude of carbon stocks as was contained in the bioproduct. This approach may be best suited for slow growing biomass, such as trees. The approach faces critics; critics argue that Walker et al's approach incorrectly isolates carbon sources and sinks instead of modeling biomass sources and sinks as complete systems.

3.5.1 Modeling Woody Biomass at Individual and Landscape Level

CORRIM and Argonne National Laboratory's studies take a different approach to Debt-then-Dividend by modeling woody biomass at both the individual tree level and the landscape level. This approach provides valuable insights into how assumptions about biomass regrowth and temporal biogenic carbon impact the lifetime carbon emissions of a bioproduct. However, this level of detailed analysis may not be necessary for all bio-products. The study concludes that the temporal accounting of biogenic carbon emissions is most critical when feedstocks have longer growth cycles and slower-growing rates. The results from this study are especially important for policymakers, as they highlight the need for nuanced approaches to biogenic carbon accounting to accurately assess the environmental impact of bioenergy systems.

3.5.2 Annual Basis Accounting vs. LCA

DeCicco's method of Annual Basis Accounting (ABA) is the final approach to biogenic carbon accounting discussed in this review, and is separate from a life cycle assessment. Using this system-wide approach in his 2016 study, DeCicco compared cumulative biofuel emissions, including biogenic emissions, to additional cumulative crop production over a specified time period. The benefit of this approach is that it provides a high-level understanding of how the biofuel system ins performing in regards to net carbon balance. However, it may not be practical to implement for individual biofuel pathways.

3.6 Summary and Recommendations for GHG Accounting

In summary, the predominant precedent for biofuel policy is to model biogenic carbon based on a carbon neutral approach. The diversity of approaches to biogenic carbon accounting and lack of scientific consensus represents a challenge for incorporating such feedstocks into LCFS programs. The LCFS programs that do include biomass feedstocks assume carbon neutrality, either implicitly by ignoring biogenic carbon, or explicitly by accounting for offsetting biogenic carbon uptake and emissions. The carbon neutral approach, however, may not be appropriate for all biomass feedstocks, particularly those with longer growth cycles.

To date, CARB has not formally identified an approach to quantifying emissions associated with certain types of biomass residues, including those from wood and nutshells (Figure 3.15). The lack of such transparent guidance impinges the ability to plan and execute biofuel projects that can deliver alternative biomass residue fates for hard-to-decarbonize sectors such as sustainable aviation fuel. As a result, these types of biomass residues may continue to emit

GHG emissions associated with business-as-usual conventional fates, e.g., burning and decomposition, as uncertainty of their treatment in the LCFS increases perceived investor risk.

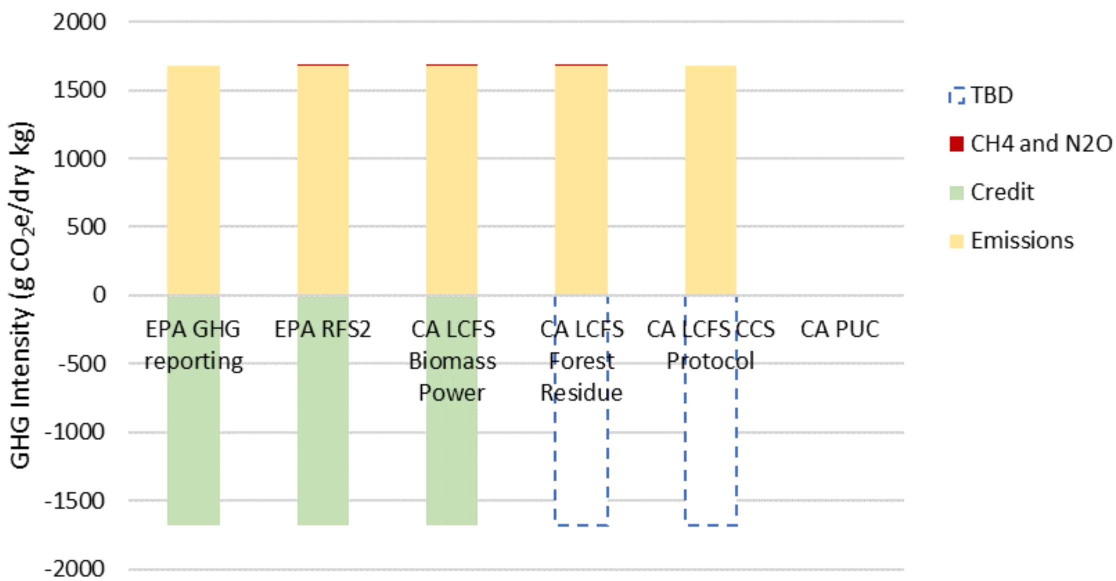


Figure 3.15. Status of federal and California biofuel policy.

In the meantime, the IPCC (IPCC, 2022)is warning, with high confidence, that global warming is likely to reach 1.5C between 2030 and 2052 if it continues to increase at the current rate, and California, and other regions of the world, are besieged by wildfires and impacted by burning and decomposition of biomass residues. In the Draft 2022 Scoping Plan, CARB acknowledges this urgency to take action to reduce reliance on fossil fuels and increase carbon sequestration. The specific issue of GHG accounting for woody biomass residues, however, has remained unaddressed since CARB published the *Detailed California-Modified GREET Pathway for Cellulosic Ethanol from Forest Waste* in 2009.

As presented in this summary of existing biofuel policies and modeling approaches, the carbon neutral approach to accounting for biogenic carbon is a simplified one. Clarification of biomass residue categories, and associated certifiable verification methods can provide information to support definition of biogenic carbon accounting methods for woody biomass and other residues not yet defined. Taking such action will provide policy certainty to support biofuel project developers, including those planning to produce sustainable aviation fuel. Therefore, we propose the following actions to advance progress on the policy treatment of biomass in the CA LCFS:

1. Establish clear categories for biomass types listed in Table 25;
2. Evaluate impacts of various alternative fates;
3. Assess feedstock verification options;
4. Develop mechanisms to assign GHG intensity for alternative fate of biomass.

Additionally, we propose a peer review of the abovementioned biomass accounting models to review the inputs, assumptions, and model implementation. Given that CARB has named the C-BREC model to characterize the amount and location of available forestry residues and affiliated criteria emissions in the 2022 Draft Scoping Plan update (CARB, 2022b), any peer review should begin with C-BREC. To further describe the treatment of biomass, CARB could consider sponsoring in depth workshops explaining model input and assumptions.

4. The Alternative Fate of Biomass

Understanding the alternative fate of biomass is essential to completing a full life cycle assessment, and a framework for determining alternative fates is essential for CARB to provide guidance. In this section, the alternative fates of biomass explored. These alternative fates include decomposition through methods such as composting, aerobic and anaerobic decomposition, combustion through controlled burning or wildfire, and transformation into marketable products such as food, packaging, and chemical products (Figure 4.1).

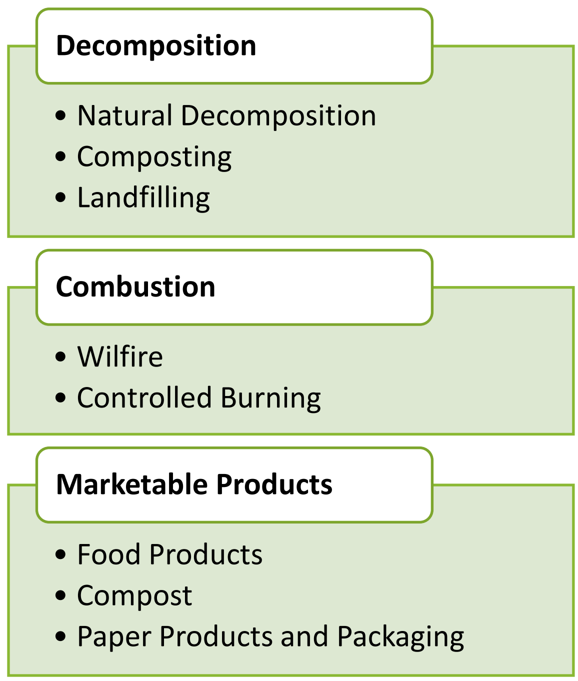


Figure 4.1. Possible alternative fates of biomass.

Each category of biomass may have different optimal fates based on its specific properties and the intended end-use. For example, food waste may be best suited for composting or anaerobic digestion, while wood waste may be better utilized through combustion or transformation into wood products. After each alternative fate of biomass is introduced, the specific alternative fates of biomass are described based on the category, location, and farming or harvesting practices surrounding the biomass feedstock.

4.1 Decomposition and Natural Processes

The process of decomposition is a fundamental part of the cycling of organic matter in the ecosystem. When dead tissues from trees and other plants are left undisturbed for an extended period of time, they begin to undergo a natural process of decomposition. The primary decomposers of these dead tissues are fungi, which break down the woody materials into simpler organic forms.

Three major factors control decomposition: climate, quality of the litter, and the soil microbial and faunal communities, as shown in Figure 4.2. Other factors can be important such as soil pH and aeration but tend themselves to be influenced by the three main factors.

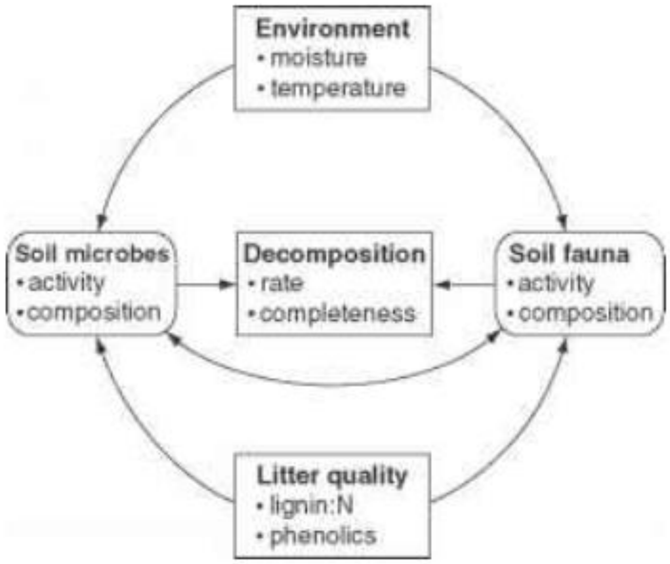


Figure 4.2. Factors that affect the decomposition time. Source: (Prescott, Maynard, & Laiho, 2000).

Decomposition of Agricultural Residues

The decomposition of agricultural biomass is influenced by various factors, including its chemical composition. A study conducted by the USDA in 2007 found that the rate of decomposition is impacted by the quality of the residue, microfaunal and soil conditions, and climate factors. Climate was found to be the best predictor of decomposition kinetics on a global scale, but within a specific climatic region, the chemistry of the biomass was determined to be the strongest predictor of decomposition kinetics. The process of decomposition plays an important role in converting biomass residues into soil organic matter, with the rate of decomposition determining the net increase in soil organic carbon (SOC) levels, which requires that inputs of carbon into the soil surpass carbon efflux (Johnson, Barbour, & Lachnicht , 2007).

Decomposition of Woody Biomass

Woody biomass undergoes a process that typically involves at least four stages of decomposition, illustrated in Figure 4.3. The first stage is a lag phase, where there is no weight loss or change in specific gravity. The length of this phase depends on the size of the substrate, with larger woody substrates generally having longer lag times. During phase 2, logs begin to weather and fragment, leading to leaching losses and microbial activity. In phase 3, there is rapid microbial mineralization and continued fragmentation. Finally, phase 4 is a stable phase that is dominated by lignin decomposition. At this point, most coniferous logs consist of a mass of crumbly brown cubical rot (Edmonds, 1991).

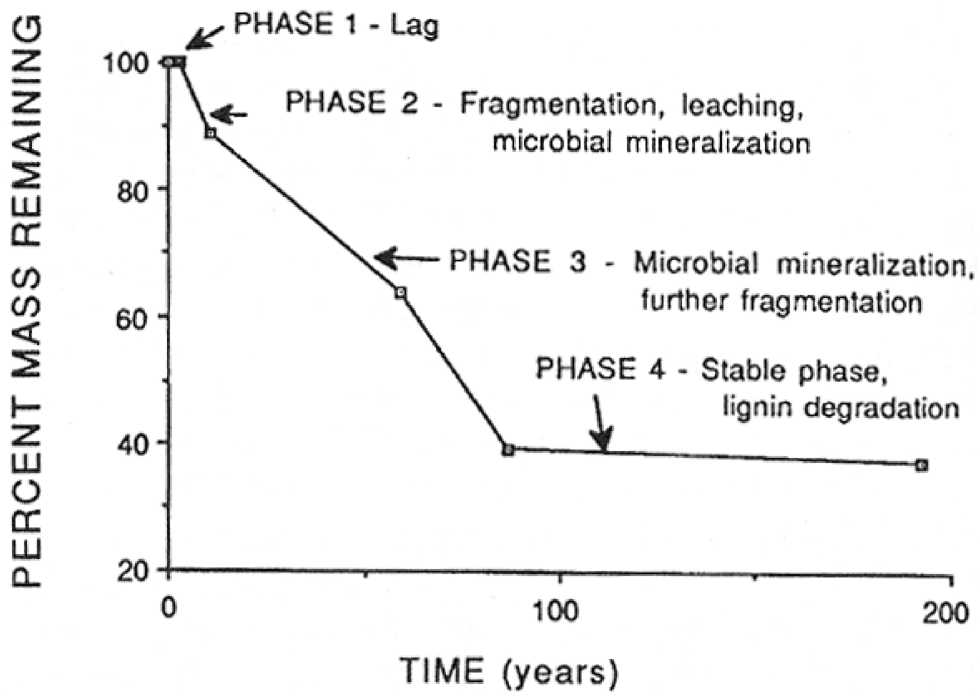


Figure 4.3. Woody biomass decomposition phases. Source: (Edmonds, 1991).

Composting

Composting is a form of decomposition that is intentionally facilitated to produce a rich soil for gardening or agriculture. During composting, microorganisms break down organic matter. Composting requires a mix of carbon-rich materials (such as dried leaves, sawdust, or shredded paper) and nitrogen-rich materials (such as food waste, grass clippings, or manure) to provide a balanced diet for the microorganisms.

Some biomass feedstocks are better suited for composting than others. For example, food waste is a candidate for composting because it is typically high in nitrogen and moisture, which provide ideal conditions for microbial activity. On the other hand, agricultural wastes such as straw or corn stalks are typically low in nitrogen and high in lignin, which are more difficult to break down and require specialized microorganisms. These types of wastes may require pre-processing or conditioning before they can be effectively composted.

Landfilling

Biomass may be disposed of in a landfill, where it may decompose. The rate of decomposition and the emissions that occur as the biomass decomposes depend on the location and management strategies at the landfill. Biomass contained in landscaping residue and construction demolition debris may be landfilled if it is not composted.

4.1.2 Factors affecting decomposition

Decomposition is affected by physical and chemical factors as shown in Figure 4.4 temperature can be considered as a prime factor in the decomposition rate, other factors are the humidity, forest type and wood source. Soil properties are another factor that affect decomposition and include: texture, the most significant factor as it stimulates nutrient and water dynamics, porosity, permeability latitude and surface area. Major chemical properties include pH, cation exchange capacity, organic matter content and nutrients, and soil microbial activity.

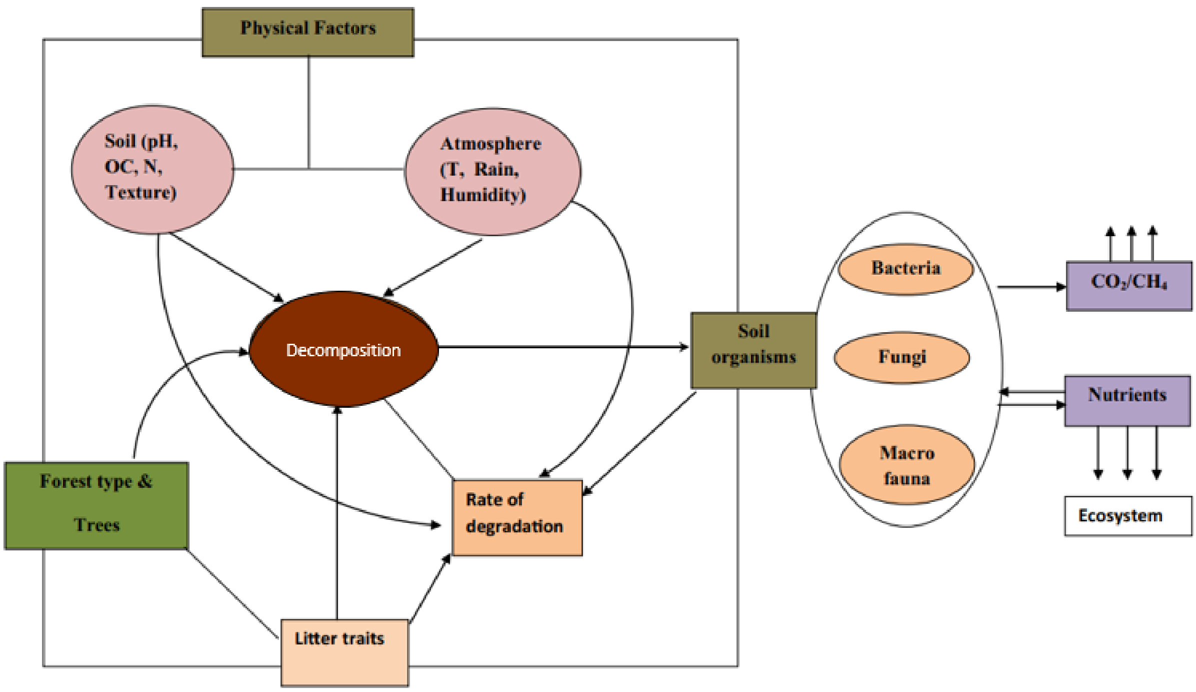


Figure 4.4. Diagrammatic representation of factors affecting biomass decomposition. Source: (Krishna & Mohan, 2017).

Other studies demonstrate that decomposition is affected by the quality of the litter and the concentration of phosphor (P), potassium (K), calcium (Ca), magnesium (Mg), carbon (C), and Nitrogen (N). Litter with high concentration of phenolics (tannin and LIGN) and low concentration of N generally decomposed slowly (Lambers, Chapin, & Pons, 1998). Litter decomposition rates increased with N, P, K, Ca and Mg but decreased with C:N, LIGN and LIGN:N (Zhang, Hui, Luo, & Zhou, 2008).

Composting and Landfilling Emission Factors

Table 21 provides emission factors for wood waste under various management scenarios, including landfilling, composting, and unmanaged composting. The table compiles data from several sources, including CARB, (Pier & Kelly, 1997; Amlinger, Florian, Peyr, & Cuhls, 2008; Pipatti, et al., 2006b). Notably, this table includes emission factors for unmanaged composting of woody biomass, which had not been previously calculated.

To estimate avoided methane emissions, we used the Tier 1 Biomethane-derived from Anaerobic Digestion of Organic Waste Calculator provided for the California Low-Carbon Fuel Standard (LCFS). The calculator estimates an overall emission factor of 277 grams CO_2e per wet kg for urban landscaping waste, based on values presented in Table 21. The emission factor range was derived from calculations from the CARB Tier 1 calculator, which considered emissions from landfilling and composting of urban landscaping waste and wood waste. However, it should be noted that the emission factors for residue piles from forest product mills are not actively managed and aerated.

Table 21. Composting and Landfilling Emission Factors for Wood Waste

Data Source	Material	Fate	Emission Factors g/AR kg			Moisture (%)
			CH_4	N_2O	CO_2e	
(CARB, 2018c)	Wood Waste[a]	Landfilling, 75% CH_4 capture	9.16	0.09	255.9	45%
(CARB, 2018c)	Wood Waste[a]	Managed Composting	0.82	0.09	47.3	45%
(CARB, 2018c)	Wood Waste[a]	64.1% Compositing, 35.9% landfilling	3.81	0.09	122.2	45%
(CARB, 2018c)	Wood Waste[a]	64.1% composting 35.9% Landfill 50% CH_4 Capture	13.2	0.09	357.1	45%
(Pier & Kelly, 1997)	Forest Products Mill Waste	Waste Piles	78	0	1,950	62.9±1.1
(Amlinger, Florian, Peyr, & Cuhls, 2008)	Green Waste[ab]	Managed Composting [cd]	0.604	0.178	68	50%
(Pipatti, et al., 2006b)	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 BDRD calculator. CO_2e 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

We utilized the midpoint of the IPCC emission factors for composting to estimate emissions and recommend their use in this design pathway. While managed composting may result in lower emissions, it may not be a feasible treatment option for all waste management scenarios. Conversely, studies have reported higher emissions from unmanaged sawdust piles (Pier & Kelly, 1997), with 7 times higher GHG emissions than assumed in this analysis.

4.2 Biomass Combustion

Biomass combustion is a process where organic materials, such as agricultural residues, woody biomass, and other forms of organic matter, are burned, resulting in the rapid release of heat energy, GHG emissions, and particulate matter (PM). This process can be intentional, such as pile burning of agricultural residues or forest thinning, or unintentional, such as wildfires caused by natural or human-induced factors.

In this section, we identify the emission factors linked to various types of biomass combustion and identify the biomass feedstock categories that are commonly associated with this alternative fate.

4.2.1 Wildfire

Forest biomass that is not utilized for bioenergy production is at risk of being burned during a wildfire, which is becoming a growing concern in many areas due to the increase in their size and frequency. The length of the wildfire season in the Western United States has increased by over 2 months, and the average annual area burned has doubled since the 1980s (Congressional Research Service (CRS), 2019). To mitigate this risk, reducing fuel loads in forests through thinning and other management practices, as well as utilizing forest waste for energy production, has been proposed.

Although wildfire is not considered in the LCFS, it is considered an alternative fate in this analysis as it displaces wood combustion. To assess the GHG emission reductions associated with biofuel production in comparison to combustion of woody biomass during wildfires, emission factors were established based on a literature review (see Table 22).

4.2.2 Controlled Burning

Controlled burning is the intentional combustion of biomass with the intent of managing agricultural or forestry systems. Here we describe two categories of controlled burning: agricultural pile burning and controlled burning for forest management and wildfire abatement.

Agricultural Pile Burning

Agricultural pile burning is a common practice used for vegetation management in various settings, including agricultural fields, orchards, rangelands, and forests. It is a useful method for removing crop residues left after harvesting grains such as hay and rice, as well as orchard and vineyard prunings and trees. Farmers also use pile burning to remove weeds, control pests, and prevent disease, particularly in crops such as rice and pears.

Despite its effectiveness, pile burning results in the rapid release of emissions and particulate matter, which can cause poor air quality in nearby communities. As a result, some California localities have implemented programs to limit agricultural burning. One such program is the "Alternatives to Burning" (ATB) program established by the San Joaquin Air Resources Board. The ATB program aims to eliminate agricultural open field burning by 2025 by reincorporating orchard removal residue back into the field through grinding, spreading, tilling, and ripping the wood residue back into the soil. Additionally, the program seeks to send the material to verified markets for beneficial reuse, including secondary uses such as landscape mulch, dust control, land spreading, Trex Decking, and soil amendments.

Forest Management and Wildfire Abatement

Prescribed burning is an intentional, valuable tool for fuel management forest and ecosystem restoration. It is a controlled application of fire to a forest to accomplish the objectives of a landowner or land manager (Grebner, Bettinger, & Siry, 2014). It could be used to assist in the development of a forest with a preferred species overstory, a midstory free of undesirable plant vegetation, and an understory composed of desirable herbaceous and woody plants (Grebner, Bettinger, & Siry, 2014).

The timing of a burn determines the plants which will be benefited and controlled, the impact on wildlife species, and safety. Most burns are conducted mid to late spring, or in the fall (Sargent & Carter, 1999). Before conducting a prescribed burn, firebreaks are created. A firebreak is an area that will contain a fire within its boundaries, for example a plowed or disced strip, reaching down to mineral soil, is the most common method of establishing a firebreak. Firebreaks can also be planted to grasses and clovers so they can provide key food and cover to wildlife; firebreaks should be at least 20 feet wide (Sargent & Carter, 1999).

Prescribed fires should be designed to meet the specified silvicultural objectives without negatively affecting off-site social values. The smoke produced by fires may not only be a nuisance for nearby communities but may also increase the risk of accidents on roads and harm poultry farms. Within the area being burned, prescribed fires can result in a short-term increase in mineral nitrogen in the soil surface and an increase in phosphorous, the level of which is a function of the duration and intensity of the fire (Galang, Morris, Markewitz, Jackson, & Carter, 2010). However, over time, prescribed burning can prevent or reduce accumulations of nutrient capital that would otherwise occur naturally (Grebner, Bettinger, & Siry, 2014).

Insect Infestation

Reducing loads of forest biomass may also prevent insect infestations in certain forests. Insect infestations (Collins, Rhoades, Battaglia, & Hubbard, 2012) and drought (Stephens, et al., 2018) have resulted in widespread tree mortality and caused concern regarding the associated increased fuel load and wildfire risk. 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.

Biomass Combustion Emission Factors

Table 22 lists emission factors used in regulatory contexts (EPA, 1995; Jenkins, 1996; Argonne National Laboratory, 2022; CARB, 2018a), and otherwise reported (Akagi, et al., 2011; Springsteen, et al., 2011). Values representing the approximate median of the reported ranges of respective emission factor values are recommended for use in this design pathway: methane emissions reported for open pile burning (3 g CH_4/dry kg - Springsteen et al., 2011); and nitrous oxide emissions reported for temperate forest wildfire ((0.16 g N_2O/dry kg - (Akagi, et al., 2011)).

Using the above methane and N_2O emission, an emission factor of 15,073 g CO_2e/MMBtu, HHV can be calculated (using 17.91 MMBtu/dry ton biomass). In an analysis for this study, a 50% burning rate was assumed as a conservative factor, reducing the emission factor used to 7,546.5 g/MMBtu. The methane, nitrous oxide and carbon dioxide emission factors listed in Table 22 include the fraction of smoldering emissions, in contrast to those produced from high temperature combustion in boilers. Emissions were estimated by converting the methane and nitrous oxide emission factors to a g/MMBtu basis, multiplying them by 100-year AR4 Global Warming Potential values (IPCC AR4, 2007), and summing those values.

Table 22. Biomass Burning Emission Factors

Data Source	System	Emission Factors g/dry kg CH_4	N_2O	CO_2	CO_2e C Neutral
(Prichard, et al., 2020)[a]	Forest	4.294 (3.387 SD)	1.304 (0.839 SD)	1595.6 (166.2 SD)	495.942
(Argonne National Laboratory, 2019)	Sugarcane Bagasse	2.7	0.07	1660	88.36
(California Air Resources Board (CARB), 2018a)[a]	Straw Burning	2.7	0.07	1830	88.36
(CARB, 2016)[b]	Rice Straw	1.17	0.02	1830	35.21
(Urbanski, 2013)[a,c]	SE Conifer PF	2.32 (1.09)	0.16 (0.21)	1703 (171)	105.68
	SW Conifer PF	3.15 (0.91)	0.16 (0.21)	1653 (34)	126.43
	NW Conifer PF	4.86 (1.37)	0.16 (0.21)	1598 (39)	169.18
	Western Shrubland PF	3.69 (1.36)	0.25 (0.18)	1674 (38)	166.75
	NW Conifer Wildfire	7.32 (0.59)	0.16 (0.21)	1600 (19)	230.68
(Springsteen, et al., 2011)[a]	Woody Biomass, Open Piles	3	NA	1833	122.68
(Akagi, et al., 2011)[a]	Temperate Forest	3.92 (2.39)	0.16 (0.21)	1637 (71)	160.58
	Crop Residue	5.82 (3.56)	NA	1585 (100)	193.18
(EPA, AP-42, 1996) (EPA, 1995)	Conifer Logging Slash, Piled	1.0 - 8.5[d]	NA	NA	115
	Pile Burn	1.0 - 4.7[e]	NA	NA	60
This Study[f]		3	0.16	Neutral	122.68

Values reported in brackets represent authors' estimates of observed parameter variation, unless otherwise specified as SD, standard deviation.

[a] Reported range reflects the following combustion categories: flaming, fire, and smoldering

[b] Based on (Jenkins, 1996); unit is % of fuel dry mass.

[c] N_2O values listed are from (Akagi, et al., 2011).

[d] Range reflects various conifer species

[e] Reported range reflects the following combustion categories: flaming, fire, and smoldering

[f] 3 g CH_4/dry kg and 0.16 g N_2O/dry kg represent the approximate median of the reported range

For the purposes of this study, the methane estimates from (Springsteen, et al., 2011), and (Akagi, et al., 2011) provided an estimate of the GHG intensity (15,073 g $C0_2e$/MMBtu, HHV) with the AR4 GWP factors.

4.3 Marketable Products

Biomass can be used in various marketable consumer products. The emissions associated with these products depend on the specific biomass, its end-use, and its disposal.

Agricultural biomass, such as corn, sugarcane, and soybeans, have a wide range of market uses, including food production such as produce, vegetable oils, and corn syrup. The emissions associated with these products vary, with some products having low emissions due to efficient production processes and others having high emissions due to energy-intensive processing or transportation.

Food waste and landscaping biomass can be composted, and the resulting compost can be sold as a marketable consumer product. Under CA State Bill SB 1383, jurisdictions are required to procure organic waste products, which can include compost for use on public property. Notably, procuring biobased compressed natural gas (CNG) for use in public vehicles is also acceptable under this regulation.

Woody biomass has traditionally been used for paper and cardboard products, with managed forests historically sending thinnings to paper mills for production. However, in recent years, markets for paper mills have not been successful, and foresters have not had a market for thinnings. This lack of market can result in higher emissions from disposing of the unused biomass, or in some cases, open burning of the material, which can have negative environmental and health impacts.

4.4 Alternative Fate by Biomass Category

Table 23 presents an overview of possible alternative fates for various types of biomass feedstock. For example, crops such as corn, sugarcane, and soybean could be utilized as agricultural products, either for direct consumption or as ingredients in food processing, if not used for biofuel production. Similarly, crop residues such as corn stover, sugarcane straw, and rice straw could be left for in-situ decay, used as animal feed, or employed for energy production if not used for biofuel production. Orchard prunings could be burned for energy production or left for in-situ decay, while lumber and farmed trees like willow and poplar could be utilized to produce commercial products like paper, pulp, and pellet fuel if not used for biofuel production.

Table 23. Biogenic carbon for commercial products feedstock categories, application, and fate

Feedstock	Possible Alternative Fate
Crops	Agricultural products
Crop residues	
Corn stover	In-situ decay; domesticated animal feed; energy production
Sugarcane straw	In-situ decay; burning; energy production
Nut shells	Animal feed, biochar; energy production
Rice Straw	In-situ decay; wildlife forage; burning
Orchard Prunings	Burning; energy production
Lumber	Commercial products
Farmed Trees	Paper, pulp, pellet fuel, energy
Energy crops	Biomass energy

Table 24 presents examples of alternative fates for different types of biomass feedstocks, along with their respective net carbon balances. For instance, forest pre-commercial thinnings and forest harvest residues can either be burned or stored, with burning leading to higher emissions and storage to lower emissions. In the case of sawmill residues, producing biofuels results in lower emissions than burning the material, while storing it has an even lower emission impact.

Table 24. Net carbon balance for waste and residue feedstock categories, application, and fate

Feedstock	Example Application and Fate	Higher Emission Alternative
Forest pre-commercial thinnings[a]	Decomposition, burning, Collateral burning	Storage
Forest harvest residues (slash)		
Sawmill residues[b]	Decomposition, burning	Storage
Municipal Sewer Waste	Landfilling, evolving composting and treatment systems.	Landfilling, evolving composting and treatment systems.
Urban landscaping		
Construction & Demolition		Particle board furnish
Tallow, UCO	Various disposal options Assumed decomposition of inedible products, various disposal options.	Boiler fuel, oleo chemical production
Landfill gas	Flaring assumed in LCFS	Power Generation

[a] Includes limbs, tree tops, and cull trees (those considered to be unsuitable for the production of lumber or other dry wood products due to either decay, form, limbiness, or splits).

[b] Include bark, shavings, chips, unfinished wood cuts, and hog fuel.

4.4.1 Forest Wastes and Residues

Standing trees exist in both managed and natural forests and on tree farms. The alternative fate is dependent on the forest type and forestry practices.

Managed Forests

Managed are an important source of timber products, providing a renewable resource for construction, paper, and other wood-based industries. These forests are carefully planned and maintained to ensure sustainable and responsible use of the resource.

Managed forests operate on rotation periods. This is the length of time between harvesting trees in a given area. The specific length of the rotation period depends on factors such as tree species, local climate, and market demand for timber products. For example, a rotation period for a fast-growing species like pine might be 25 years, while a slower-growing species like oak might have a rotation period of 50 years or more. During this time, the forest is allowed to regenerate, with new trees growing to replace those that have been harvested.

During the harvesting process, there is often leftover material such as branches and tops of trees, which is called slash. Slash can be left on the ground to decompose naturally, which can help to improve soil health and promote new tree growth. Alternatively, it can be chipped or ground into small pieces and used as biomass for energy production. This can help to reduce reliance on fossil fuels and promote the use of renewable energy sources.

Thinnings are another important aspect of managed forests. As trees grow, they compete with each other for resources such as sunlight, water, and nutrients. Thinning involves selectively removing some trees from a forest to reduce competition and promote the growth of the remaining trees. Thinnings can be used for a variety of purposes, including pulpwood for paper production or sawlogs for lumber. In addition to promoting healthy forest growth, thinnings can also provide a source of revenue for forest owners.

Natural Forests

Natural forests can be managed to mitigate risks such as wildfire and insect infestations through the harvest of biomass. The practice involves removing excess vegetation, such as small trees and brush, from the forest floor. This reduces the amount of fuel available for wildfires and also helps to prevent insect infestations by reducing the amount of available habitat for insects.

The biomass harvested from natural forests can be used for a variety of purposes, including the production of wood chips, pellets, and biofuels.

Farmed trees

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 alternative fate to paper products is associated with the impact of indirectly effecting the conversion of land to tree farms.

Sawmill Residue

Lumber mills produce saw dust and residues remaining from milling trees for lumber products. Sawmill residues include bark, stems, shavings, chips, unfinished wood cuts, and sawdust that are produced from a commercial mill, and hog fuel that are byproducts of milling saw logs. These woody waste products generally do not meet EISA RFS requirements as feedstocks for renewable fuel production as their source cannot be traced back to the initial harvesting site and therefore cannot be proven to be from forest land meeting EISA 2007 requirements. Typically sawmill waste is not sent to landfills due to the increasing cost associated with tipping fees, as well as states like California[10], with mandates limiting the percent of organic material allowed in landfills. The material decomposes through several mechanisms, including by application as wood chips for landscaping, as landfill cover, while stored in feedstock piles at power plants, and when integrated into compost.

4.5 Southeastern U.S. Forest Biomass

Understanding Managed Forestry in South

The importance of forestry in the Southeastern U.S. cannot be overstated, and the success of forestry in The Southeastern U.S. today was not inevitable. In the early days of logging, forests were exploited, leaving the state with millions of acres of barren lands. Today, Southeastern U.S. forests are diverse and plentiful. Exploitation is no longer a viable option for a sustainable timber business, and instead the timber industry has become a major factor in replenishing and increasing forest yield throughout Louisiana.

Threats to South Eastern U.S. Forests

Maintaining and growing forests in the Southwest does not come without challenges. In 2020, the state of Louisiana published a Forest action plan to assess the current state of forestry and identify key threats. In the report, three primary threats are identified (Greene & Brasher, 2020):

- Lack of active management on private lands,
- Challenges to forest health, and
- Challenges facing wildland fire management.

[10] CA Senate Bill 1383, effective January 1, 2022

Active management of private lands, is inextricably linked with the other challenges faced. For example, lack of appropriate forest management has led to a buildup of fuels that can increase the risk of wildfires. Additionally, poor forest management can result in the spread of many forest insects and diseases (Greene & Brasher, 2020).

Figure 4.5. An older pine tree splitting and breaking due to fungal infection. Photo courtesy of David J. Moorhead, University of Georgia, Bugwood.org.

The Role of Thinning in Maintaining Healthy Forests

Selectively cutting trees, or "thinning," is integral to maintaining the health of managed forests. Wildlife biologist have long recognized that thinning pine timber stands can increase forest heath. When a forest is thinned, space between the trees allows sunlight to reach the ground, stimulating plant growth and allowing for rich biodiversity on the forest floor. Additionally, thinning can remove diseased or damaged trees that are competing with healthy trees, allowing the healthy trees to thrive. In an ideally managed forest, stands would be thinned to allow for 60 percent of the ground to be in direct sunlight at noon (Georgia Department of Natural Resources). Failure to thin trees results in the following:

- ***Tree death***. Because the trees are competing for sunlight, water, and nutrients, failure to thin them will ultimately result in self-thinning. Trees stressed due to lack of resources are more susceptible to disease and insect infestation. Many or all the trees within a timber stand may die. None of the trees will grow to a height or diameter sufficient for economic removal for lumber production.

- ***Increased risk of insect infestation***. Insufficient resources for the trees make them more susceptible to insect infestation, especially Southern Pine Beetles (SPB). Thinning stands is an established best practice to reduce risk of beetle infestations (Hahne, 2021).

- ***Increased risk of disease***. Thinning not only removes rows of trees, but selectively removes diseased trees, reducing the risk of spreading disease to other trees (Dickens & Moorhead, 2015).

- ***Increased risk of wildfire***. Thinning provides increased separation of trees and reduces the risk of trees catching fire.

- ***Decreased wildlife***. Under forest growth positive for wildlife. "Wildlife biologists have recognized the value of thinning pine timber stands for wildlife management for a long time. The benefits to wildlife are derived from opening a closed tree canopy to allow sunlight to reach the ground. The sunlight stimulates plant growth and produces an abundance of various food and cover plants valuable to wildlife (Georgia Department of Natural Resources).

Alternative Fate of Managed Forest Waste in the Southeastern U.S.

The fate of managed forest waste sourced in the Southeastern U.S. depends on if the waste comes from slash or thinnings.

Pulpwood Markets & the Health of Managed Forests

Foresters and wildlife biologists agree that thinning managed forests results in healthier trees, more biodiversity, and a more productive forest.

When paper mills were active in the Southeastern U.S. region, foresters sold trees cut during thinnings as pulpwood for paper production. However, in the past several decades paper production has halted in the region, and there is no longer a market for pulpwood.

Without a market for the pulpwood, many foresters choose not to thin. The consequences of this are directly tied to the threats to forests outlined in Louisiana's forest action plan.

Slash is the residue, including treetops, branches, and bark, left on the ground after logging or accumulating as a result of a storm, fire, delimbing, or other similar disturbance. These materials are produced during both thinning operations, and in the final harvest prior to replanting. The amount of slash as a percentage of the total harvest for plantation pine forest is estimated to be 20%. When there is not a market for slash, it is distributed across the forest floors, or used in the logging trails to improve traction in wet weather. Typically, the forest residues are fully decayed within 1-2 years.

Figure 4.6. Thinning piles near Columbia, LA

Thinnings, as described in the previous section, are reductions in the number of trees within a timber stand that done to enhance the growth of the remaining trees within the stand (Figure 4.6). Due to lack of demand for pulpwood within the project region, substantial amounts of thinnings are stacked at the edge of the timber stand and allowed to decay. Foresters estimate that about 10% to 20% of the thinnings in the region are left to rot.

In either scenario, the biomass piled or left on the forest floor will release biogenic carbon dioxide, methane and nitrous oxide into the atmosphere. For biomass that left on the forest floor, the rate of decomposition affects how quickly emissions occur. This rate of decomposition will be dependent on a number of factors, including temperature, precipitation, altitude, latitude, and different biological and mechanical degradation processes. With increasing temperature, precipitation, and biological vectors, decomposition will increase (Dai, 2021). Given these factors, slash on forest floors would decompose faster than slash in a typical California forest. In typical forest, slash left on the forest floor will decompose within one to two years. In this scenario, a managed forest will be a net source of GHG emissions (Clark, Gholz, & Castro, 2004). Therefore, converting slash from managed forests into fuel can offset fossil fuel use, and be a net positive for short-term climate goals (McKechnie, Colombo, Chen, Mabee, & McLean, 2011).

Both models and observations show that proper forest management can increase carbon sequestration and improve tree health. However, without markets for forest wastes and residues, private landowners cannot afford to adequately manage their forests. The results are (a) dense forests that stunt tree growth and promote disease spread, or (b) the accumulation of forest wastes that will rot, emitting CO_2, CH_4, and N_2O.

Slash

- Scattered throughout forest floor to rot

Thinnings

- Mismanaged or stacked and left to rot

For the purposes of complying with statewide low carbon fuel regulations, the net GHG balance of using forests wastes and residues as a transportation fuel compared to conventional fuel must be quantified. Given that (1) land management activities, such as thinning, result in increased carbon sequestration, and (2) wastes and residues produced during thinning would be left to emit all of their biogenic GHG back into the atmosphere, it could be argued that some forests wastes and residues are carbon negative.

While quantifying the precise amount of additional carbon sequestered due to active forest management remains a challenge, assuming carbon neutrality is a conservative approach. Many life cycle assessment programs, models, and studies treat biogenic carbon in biomass from various sources as carbon-neutral.

Through photosynthesis, trees fix carbon from the atmosphere as they grow. When trees are harvested or die, the woody biomass decays or combusts, and an equivalent amount of carbon is released to the atmosphere. Thus, over an entire life cycle, such biomass can be considered carbon-neutral.

This is fitting with current approaches to corn accounting in LCFS programs. While corn is grown and harvest on shorter time scales than forest residues, the resulting carbon balance is better for managed forestry than for corn farming. As shown in Figure 4.7, harvesting biomass initially decreases the amount of carbon stored in the forest biomass, but when the forest regrows, it will sequester more carbon than without thinning. The slash left behind from thinning operation would otherwise decompose on the forest floor, and thus emissions would occur regardless of if they are used for transportation fuel or not. Both are consistent with carbon neutral carbon accounting.

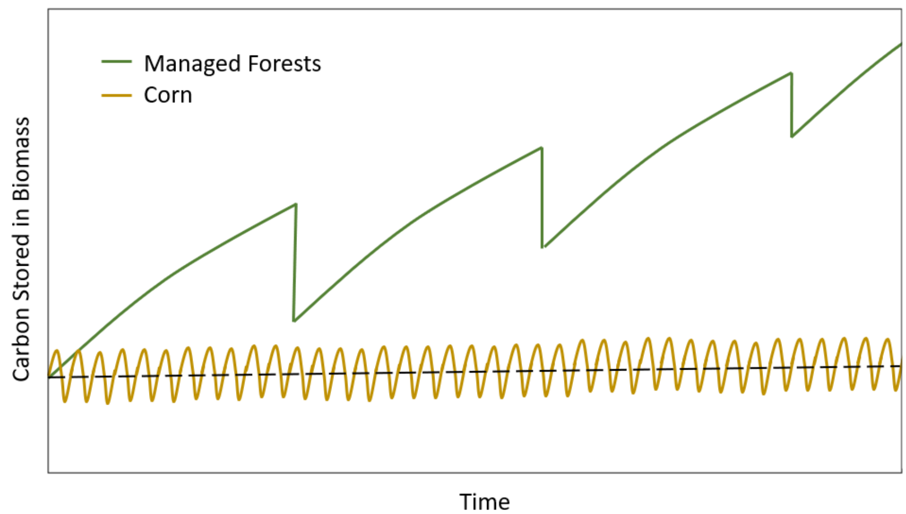


Figure 4.7. Fluxes in carbon stored in biomass for managed forests and corn grown for energy use.

4.6 Orchard Prunings

Fate of Agricultural Waste in the San Joaquin Valley

The San Joaquin Valley in California has developed a program called Alternatives to Burning (ATB) to reduce agricultural emissions. The program aims to eliminate open-field burning by 2025 and has two goals. The first is to incorporate orchard removal residue back into the field by grinding, spreading, tilling, and ripping the wood residue back into the soil. The second is to send the material to verified markets for secondary use, such as landscape mulch, dust control, Trex Decking, and soil amendments. The program financially subsidizes the growers or landowners to comply with the program, but uses of agricultural residue involving combustion or gasification of biomass resulting in emissions are non-compliant and are not incentivized.

Agricultural wastes in the valley often end up in residue piles. There are no designations or GPS mapping of existing residue piles, and they are not tracked. However, the Almond Board and agricultural agencies track removals annually to document the number of acres planted, removed, and in production. The current biomass residue has no economic value in the field or at processing/recycling yards based on existing market conditions, and its value depends on its production to the consuming markets' specifications and designated transport.

The outlook for selling residues in the present California biomass residue market is mixed. The existing biomass power producer biomass market is still the highest volume market, but the ability to sell at a monetized value has diminished due to the closures of biomass power-producing facilities and downward price pressure. The biomass market desperately needs a regulatory strategy and long-term consuming markets to support the abundant supply of residue.

Fate of Woody Biomass in California Forests

Excess biomass in California's forests can lead to an increased risk of forest fires due to the accumulation of dead and dry plant material. The buildup of this fuel source can create a highly combustible environment that is more susceptible to ignition from natural causes like lightning strikes, as well as human activities like campfires and fireworks. In addition, the excess biomass can provide a continuous source of fuel for fires, making them more difficult to control and extinguish. Figure 4.8 shows a forest incinerating near Midpines.

Figure 4.8. A forestburns near Midpines, northeast of Mariposa. Photograph: David McNew/AFP/Getty Images.

One way to mitigate the risk of forest fires caused by excess biomass is through active forest management practices, such as fuel reduction treatments. These treatments involve removing excess biomass through prescribed burning, mechanical thinning, and other techniques. By reducing the amount of dead and dry plant material in the forest, the risk of ignition and the severity of potential fires can be significantly reduced. In addition, fuel reduction treatments can also help promote forest health by increasing the availability of nutrients and reducing competition among trees.

Currently, there are limited markets for biomass removed from forests, which hinders the ability to effectively mitigate wildfire risk.

5. EMISSIONS FROM BIOMASS COLLECTION AND USE

The life cycle inventory (LCI) data in the GREET model provides valuable insights into the energy and emissions involved in the biomass life cycle, including crop growth, transportation, land use changes, fertilizer production, and combustion. The LCI data is organized as arrays of energy use and emissions values, which can represent either a single process fuel or feedstock or aggregated fuel cycle results.

By combining process-specific input parameters and downstream loss factors with the LCI data, organizations can use the information to model new fuel pathways and estimate emissions associated with different biomass feedstocks. This allows for effective comparisons of emissions from different fuels or feedstocks.

The LCI data in GREET is kept up-to-date with the latest scientific knowledge and advancements in biomass production and use, making it a reliable source of information on the emissions associated with biomass transportation and harvest.

However, it is important to also consider the alternative fate of biomass, which refers to the scenario in which it is not used for energy generation. This factor plays a critical role in determining the overall emissions associated with biomass use and, despite its significance, is poorly understood.

To get a complete picture of emissions from biomass utilization, it is crucial to take both the LCI data and the alternative fate of biomass into account. A comprehensive cradle-to-gate life cycle assessment can provide a more comprehensive evaluation of emissions from biomass by considering both of these factors. This paper seeks to provide a better understanding of the alternative fates of the several categories of biomass described in Section 2.

The emissions of CO_2 are found in every step of biomass process (From farm to gate); however, each type of biomass include different levels of emissions. In the following table you can find a summary between energy crops and residues emissions and the section where you can read more details about it in the report.

Processing Stage	Residues	Energy Crops	Report Section
Farm to Gate			
Felling	x	x	Section 5 and 5.3
Chipping	x	x	Section 5.3
Fertilizer		x	Section 5.2
Fertilizer N_2O		x	Section 5.2
Transport	x	x	Section 5.2
Avoided Emissions			
Burning	x		Section 4.6
Decomposition	x		Section 4.5
Collateral burning/effects	x	x	Section 4.6
Indirect Land Use		x	Section 2.2

5.1 Biomass Collection

Biomass collection and transportation play a crucial role in determining the carbon emissions associated with biomass energy production. The manner in which biomass is collected and transported can significantly impact the energy inputs and emissions generated during the process. The collection of biomass can take several forms, including harvesting crops and residues, collecting forest residues and thinnings, or gathering waste streams. The type of biomass and the method of collection play a role in the carbon footprint of the final energy product.

Transportation of biomass from the collection site to the processing plant is also a significant contributor to the carbon footprint of the energy production process. Long-distance transportation, particularly by truck or train, can result in significant emissions due to the energy consumption of the vehicles. Additionally, the energy used to dry the biomass for transportation can also result in emissions.

The collection method it would depend of the final use of the product or residue. However, the common factor in all the methods is the use piles to collect any waste initially before any other action. Table 25 presents a summary for collection methods in various types of biomass from different sources as farming residues, forest products and residues and urban landscaping.

Table 25. Biomass Types and Collection Methods

Biomass Types	Biomass Collection Methods
Farming Residues	
Crop Residues	The conventional baling system produces rectangular bales that measure approximately 14 in. x 18 in. x 50 in. and weigh 35 to 100lb (Dauve & Flalm, 1979).
Corn Stover	One-pass stover harvest is performed now for silage, so collecting the grain and stover when the grain dries to 24% or lower and the stover is still high in moisture is feasible (Atchison & Hettenhaus, 2004).
Sugarcane Straw	The straw left on the ground is collected and shredded by a self-propelled forage harvester, loaded onto trucks and transported to the mill separately from the cane (Carvalho, Veiga, & Bizzo, 2017).
Nut Shells	Usually, the nut shells are pelletized or torrefied, that is, they are collected in piles and transported to the final use (Noszczyk, Dyjakon, & Koziel, 2021).
Rice Straw	Could be collected by the use of conventional baling equipment to make two or three-wire rectangular bales. Buck rakes to make large piles of residue. Field cubing equipment. Field chopping equipment (Kadam, Forrest, & Jacobson, 2000).
Forest Products and Residues	
Energy Crops	The biomass is felled by a feller/buncher before the conventional harvest to get it into piles to be transported to the final facility.
Lumbermill waste	Collected in bins or containers stations organize by different sizes and shapes (Woodweb, 2022).
Forest Thinnings	Piles disposal for thinnings mostly small diameter thinning (Page-Dumroese, Busse, Archuleta, McAvoy, & Roussel, 2017).
Forest Slash	Slash piles are currently used as the preferred method for residue disposal. The piles can be burned at various times of the year, offer a larger margin of safety (Page-Dumroese, Busse, Archuleta, McAvoy, & Roussel, 2017).
Urban Landscaping Residues	Some cities utilize a "Master Composter" where the municipalities provide low-cost compost bins. The schools have a red bin to these residues (Schoolmaster, S., & Hudak, 2000).
Construction & Demolition waste	Usually, these residues are collected in trucks to be transported to their final destination.

Life cycle inventory (LCI) data can provide valuable information on the energy inputs and emissions associated with the collection and transportation of biomass. The LCI data in the GREET model (Greenhouse Gases, Regulated Emissions, and Energy use in Transportation) provides information on the energy and emissions associated with various stages of the biomass life cycle. The LCI data can be used to model new fuel pathways and compare the emissions of different biomass types. The LCI data in GREET is based on the latest scientific knowledge and is updated regularly to reflect the latest advancements in biomass production and use.

5.2 Material Flow

Material flow refers to the movement of materials, such as biomass, through different stages of the production and consumption process. In the context of biomass collection and use, material flow encompasses the physical and logistical aspects of obtaining, transporting, and converting biomass into useful energy and products. Understanding material flow is critical in evaluating the carbon emissions associated with biomass utilization, as the emissions generated at each stage of the flow will affect the overall emissions of the entire life cycle.

In terms of biomass collection, material flow begins with the harvesting of the feedstock, whether it be forest residue, agricultural waste, or purpose-grown energy crops. The type of harvesting equipment used will impact the energy required and emissions generated, as well as the quality of the biomass produced. For example, the use of commercial scale logging equipment may increase productivity and safety, but also increase the potential for residual damage to the environment. On the other hand, traditional chainsaw methods may cause less damage, but may not be as efficient.

Once the biomass is harvested, it is typically chipped on-site to reduce the size and make it easier to transport. The biomass is then transported to the processing facility or energy plant. The mode of transportation can have a significant impact on the emissions generated, as the distance and type of vehicle used will affect fuel consumption and emissions.

At the processing facility, the biomass is converted into energy or further processed into other products, such as biofuels or pulp and paper. The energy requirements and emissions generated at this stage will depend on the type of conversion technology used, as well as the quality and composition of the feedstock. For example, using advanced technologies such as gasification or pyrolysis can reduce emissions compared to traditional combustion technologies.

GHG emissions for woody biomass and agricultural residues

As mentioned before, the emissions from biomass will depend on its management method, the technology used, transportation, and its final use.

Figure 5.1 compares GHG emissions for four different woody biomass sources and an agricultural source, in Ethanol production.

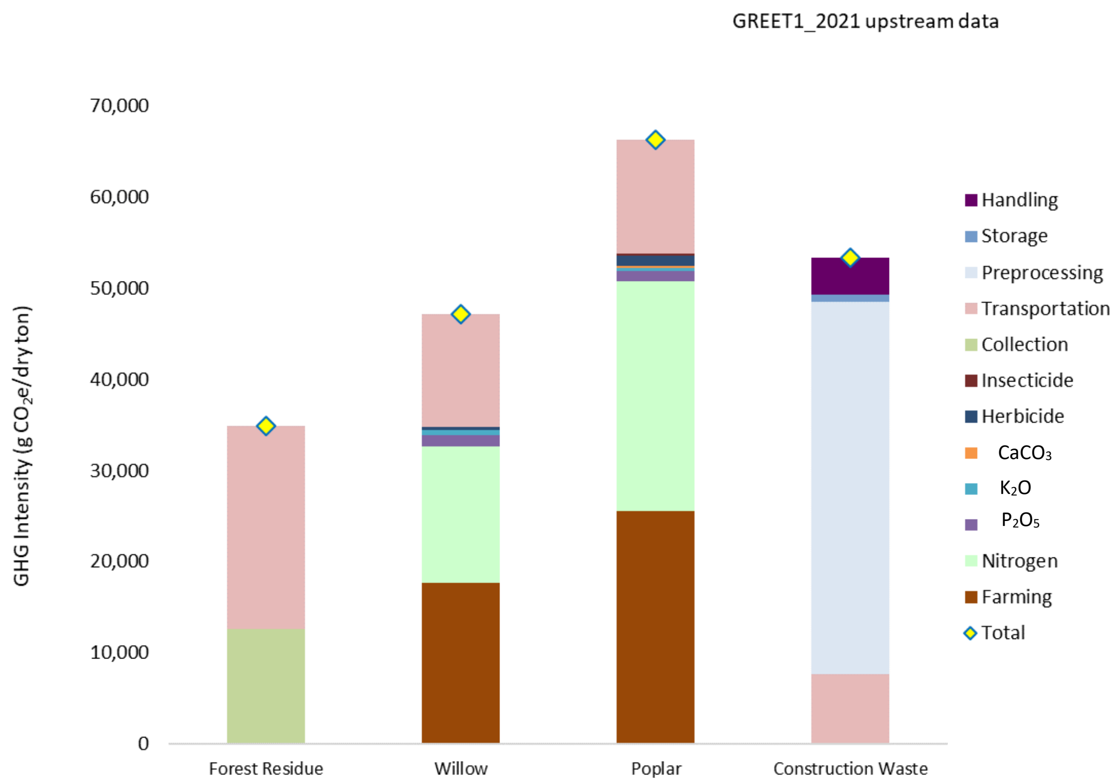


Figure 5.1. GHG Intensity for biomass depending on energy inputs and transportation logistics. GHG emissions correspond to 40% to 51% carbon in biomass.

As is noticed in Figure 5.1 the GHG emissions evaluated include collection, transportation, farming, fertilizer, herbicide, insecticide, handling, pre-processing, and storage when it is applicable using the GREET 2021 upstream data.

As it is shown in Figure 5.1 the emissions for woody biomass are between 35,000 gCO_2/dry ton (Forest Residues) and 66,000 gCO_2/ton (Poplar), in the case of construction waste are around 53,000 gCO_2/ton. Zhang et al. showed that the emissions for woody biomass in their study are between 23,000 gCO_2/ton and 56,000 gCO_2/ton (Zhang , Johnson, & Wang, 2015; Sonne, 2006); another study presented the emissions from woody biomass is 40,000 gCO_2/ton, however this study was focus on Michigan, that could means the distances in that study can be shorter than in California generating less emissions in transportation (Handler, Shonnard, Lautala, Abbas, & Srivastava, 2014).

Transportation is one of the factors that released an important quantity of emissions, at least for construction waste, willow, and poplar which represent between 14% to 26% of the emissions. These results are congruent with the percentage of transportation emissions presented in Xu et al. study where transportation represent between 12.1% to 34.4% of the emissions for forest (Xu, Latta, Lee, Lewandrowski, & Wang, 2021). However, for forest residue the percentage of emissions for transport is around 64%, in this case the emissions from transport are higher because for woody biomass the transportation is usually done in trucks which could increase a little the emissions; Sonne's study for woody biomass, transportation represented 69% of the emissions, which is not very far from the result from greet (Sonne, 2006). It is important to highlight that transportation emissions depend of the method on transportation and the distance between the farm or land to the facility and all the studies mentioned before have different locations.

The collection for forest residues represents around 36% of the emissions. Zhang's study in Michigan found that the emissions for harvesting of forest biomass supply were 17.4 kgCO_2/ton; and for forest residues, in Figure 5.1 the collection is around 12.50 kgCO_2/ton, representing a better scenario (Zhang , Johnson, & Wang, 2015). As it was expected, collection is less GHG-emission intensive for forest residue than for the farm-based feedstocks because we assume forest residue is a waste product. The allocation method and type of timber harvesting operation assumed could both have significant implications for the overall life cycle impacts derived from forest residues (Hsu, et al., 2010).

Particularly for willow and poplar, nitrogen and farming are notorious sources of the emissions. This result is congruent because they are feedstocks which actually include the farming into the boundaries of study. Carbon is found in all living organisms and is the major building block for life on Earth. Carbon exists in many forms, predominately as plant biomass, soil organic matter, and as the gas carbon dioxide (CO_2) in the atmosphere and dissolved in seawater. Carbon can remain stored for a long time, or be quickly released into the atmosphere (Schlesinger, 1999). In the cases of willow and poplar, all the carbon that is in the plant is released in the atmosphere during the harvesting, representing between 37% - 39% of the GHG emissions which is between the range of emissions presented for others studies, for example, Handler et al. showed that the farming emissions factor represented between 32% and 44% of the emissions, however in those cases they included the harvest and timber as part of the farming, which may slightly increase emissions (Handler, Shonnard, Lautala, Abbas, & Srivastava, 2014; Sonne, 2006).

Moreover, nitrogen represent between 31% and 38% of the emissions for willow and poplar, which represent a logical result because nitrogen is one of the most common fertilizers used for plants since it can move around the plant supporting plant growth (Phoslab, 2013). The rest of fertilization and herbicides contribute around 0.2% - 2% in the emissions.

Last but not least, around 1% of the emissions for constructions waste is the storage. Generally, the residues from construction get stock for a period of time in piles before to be transported to their last use, and this produce an important generation of emissions.

5.3 Woody Biomass feedstock

Wood pellets are a renewable energy source derived from compressed sawdust or other forms of wood waste. They are commonly used for heating and energy generation purposes, and their popularity is growing as a result of the increased focus on renewable energy sources. The production of wood pellets requires a significant amount of energy inputs, including the energy used in harvesting and processing the raw materials, transportation of the materials, and energy required to produce the final product.

Logging and Feedstock Collection

The wood harvesting process typically involves felling trees using chainsaws or mechanical felling machines and moving the logs to a central location (skidding). The equipment used for these activities typically runs on diesel fuel. The choice between using chainsaws versus commercial scale logging equipment depends on the evaluation of factors such as productivity, safety, and potential for residual damage, particularly in heavily forested regions.

The portion of the tree that is converted to biomass feedstock is chipped on-site and then transported for further processing for biomass energy or pulp/paper operations. The handling and chipping of the remaining portions of the log that are not converted to lumber also requires energy input, with a preliminary estimate being the same as that for forest residue. The alternative fate of lumber mill residues, such as storage in debris piles, may also require energy and should be considered in the evaluation of biomass utilization emissions.

For this study, several sources were consulted to estimate energy inputs for collection of woody feedstocks. Table 26 lists values from the GREET model and those derived for this Study. Considerations for the latter category include the following: since feedstock to lumbermills is already transported for that purpose, the emissions associated with feedstock transportation are zero.

Table 26. Diesel Consumption for Collection of Woody Feedstocks

Biomass Type	Btu/BD[a] ton	gal/AR[c] ton	MC[b]	gal/BD 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
Logging Residues	188,829	1.37	50%	
Forest thinnings	292,706		50%	
Construction & Demolition Waste	408,068	3.18	15%	3.74
Source: Derived in Study				
Lumber Mill Waste	0	0	40%	0

[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 sourced from Unnasch and Buchan, 2021.
[c]As-received
[d] Compare to 1.37 gal/AR ton in (Zhang , Johnson, & Wang, 2015).

The energy inputs for wood pellet production are a crucial aspect of the life cycle analysis of this energy source. The energy requirements specified by Kingsley for processing forest residue are approximately double the values estimated by GREET for forest residue (Kingsley, 2008). However, Kingsley's estimates for forest product mill waste are consistent with those in the GREET database for clean pine and willow. The main energy inputs for the life cycle analysis are diesel fuel for the harvesting, collection and transportation of feedstock. In modern pellet mills, electric-powered motors are used to operate the mechanical equipment, while yard equipment is powered by diesel. The drying process during the pelletizing process requires energy and is typically provided by natural gas or biomass. The energy inputs for pelletizing operations are therefore a combination of diesel fuel as shown in Table 27, electricity, and biomass or natural gas.

Table 27. Diesel Inputs for Forestry Harvesting and Estimates for Lumber 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 moisture content of the biomass feedstock is a significant factor in determining the energy inputs for wood pelletization, Figure 5.2. The production process requires energy to dry the feedstock to the acceptable level for pelletization. The feedstock is stored on-site before pelletization and tends to lose some moisture during this storage period. Additionally, drying energy is applied to further dry the feedstock to the level required for the pelletization process. It is estimated that 1,800 Btu (HHV) per pound of water removed is required for this process. The pellet production process is assumed to be the same regardless of the type of feedstock used.

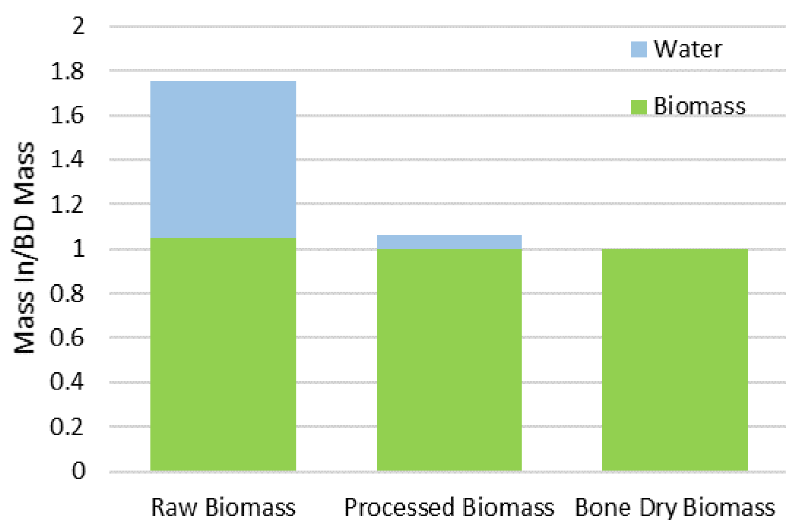


Figure 5.2. Relative moisture content of different states of woody biomass.

6. Well to Wheel Life Cycle Analysis of biomass

The GREET model considers several biomass feedstocks including forest residue and farmed trees. The analysis described below is for the disaggregated well-to-wheels life cycle emissions of several biomass types to renewable diesel or hydrogen compared to conventional fuels.

Lumbermill residue would result in lower energy inputs for collection than forest residue. Farmed trees are not an expected feedstock. Waste biomass is also a potential feedstock. The collection and chipping energy for waste biomass is generally higher than that of energy crops. For the analysis here, energy inputs for forest residue in GREET were assumed.

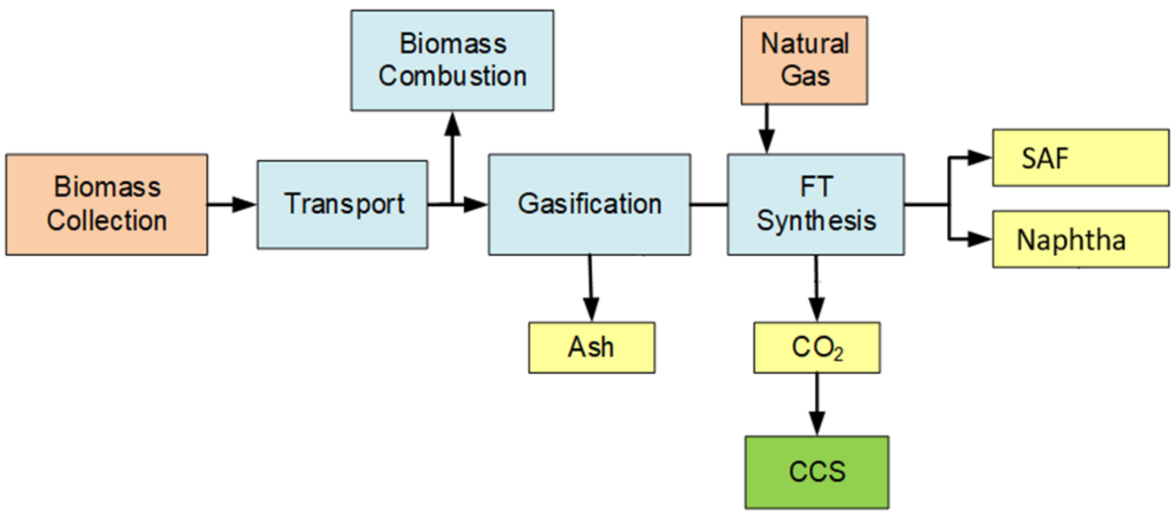


Figure 6.1. System Boundary Diagram for Biomass to Fuel. (Jiqing , et al., 2010)

6.1 Biomass Cultivation and Harvesting

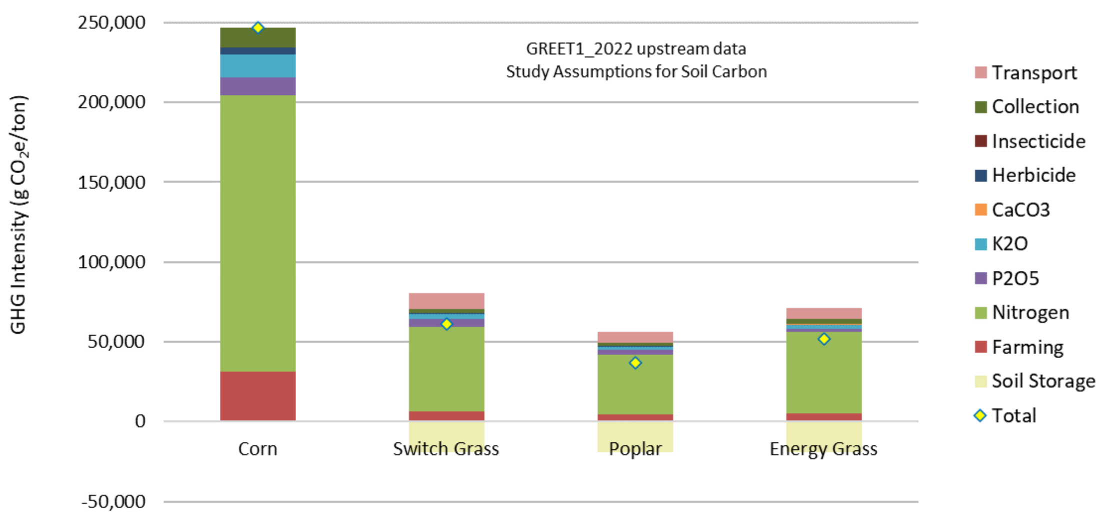
The complete greenhouse gas (GHG) assessment of a biomass to biofuel pathway involves considering the life cycle emissions from biomass cultivation and harvesting. These emissions are influenced by factors such as the type of biomass, location, and specific cultivation and harvesting techniques. Studies have examined these emissions for different feedstocks, including short rotation forestry (SRF) willow, SRF poplar, hardwood residue from existing forestry operations, and waste wood available at pyrolysis oil production sites (citation here).

Researchers conducted separate life cycle assessments for willow and poplar energy crop cultivation. For willow, the assessment included inputs such as nursery stock production, fuel for farming equipment, fertilization, pest control, and equipment manufacture. In the case of poplar, operational inputs for a 16-year rotation were considered.

Analyzing woody logging residue as a feedstock involved accounting for fuel consumption during forwarding and biomass grinding, as well as equipment production.

Regarding waste wood, as it is assumed to be on-site at pyrolysis plants, there were no additional materials or energy inputs, resulting in minimal environmental impact during the biomass cultivation stage.

The summarized results of this assessment are provided below.



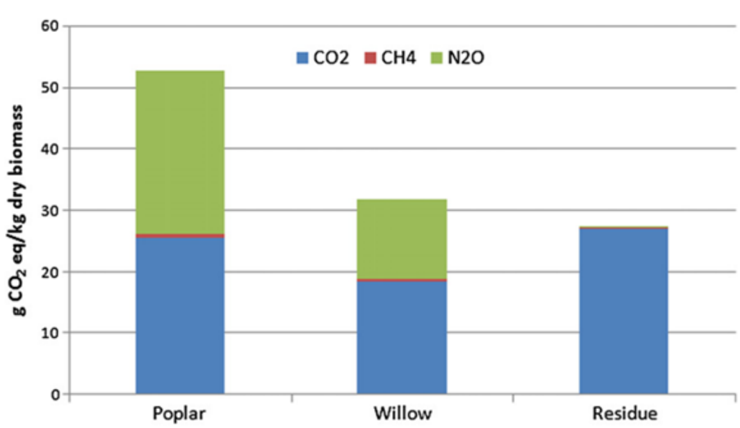


Figure 6.2. GHG Emissions of biomass harvesting (excluding transportation). GHG emissions released to produce 1 kg dry biomass feedstock[11].

[11] Source: J. Fan et al. / Renewable Energy 36 (2011) 632e641

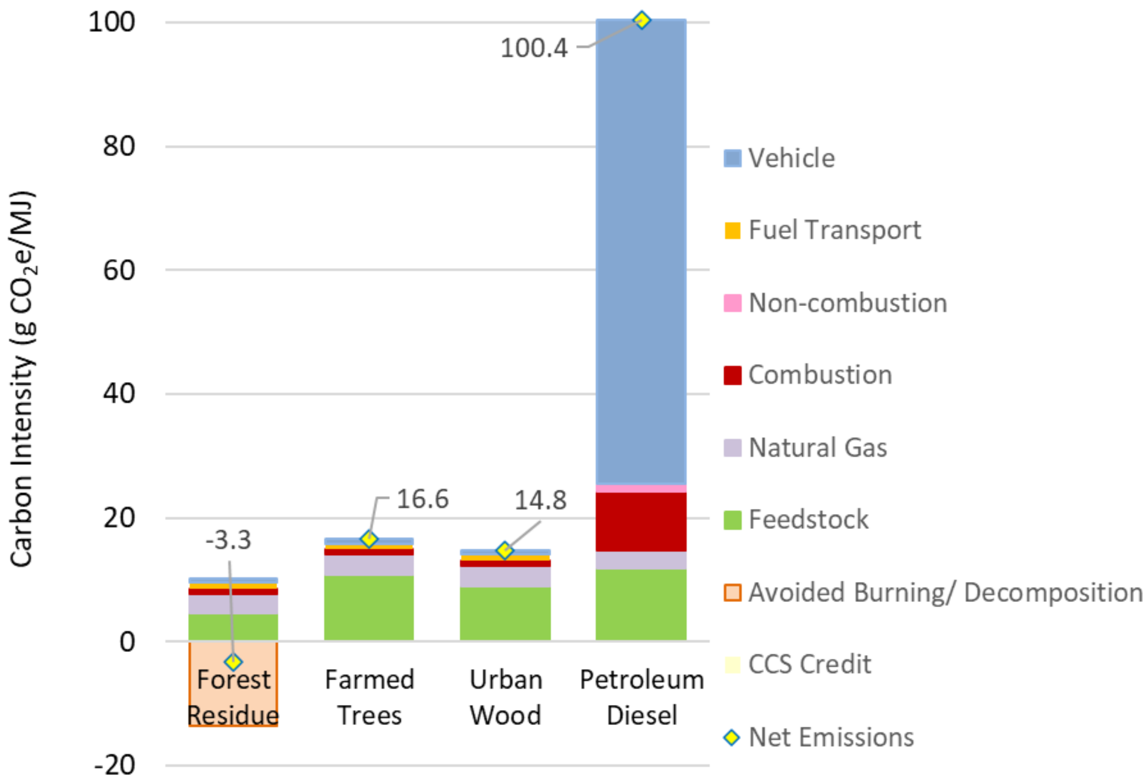


Figure 6.3. GHG Emission using Fischer-Tropsch Diesel

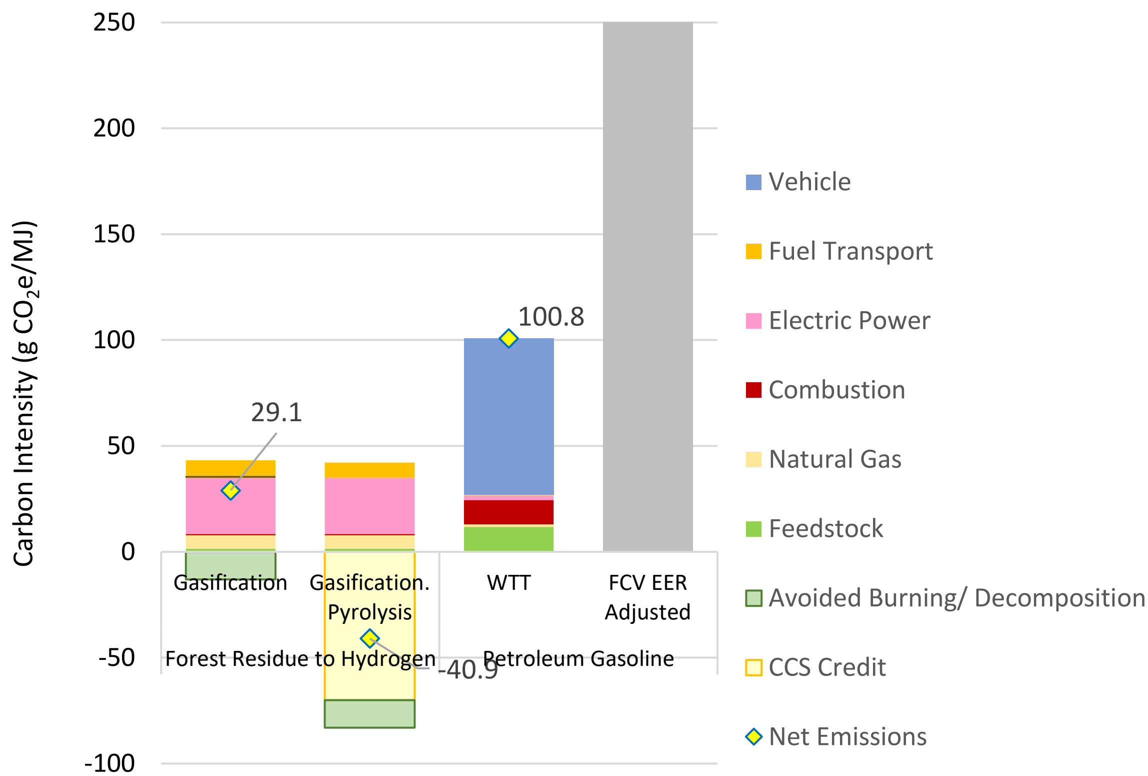
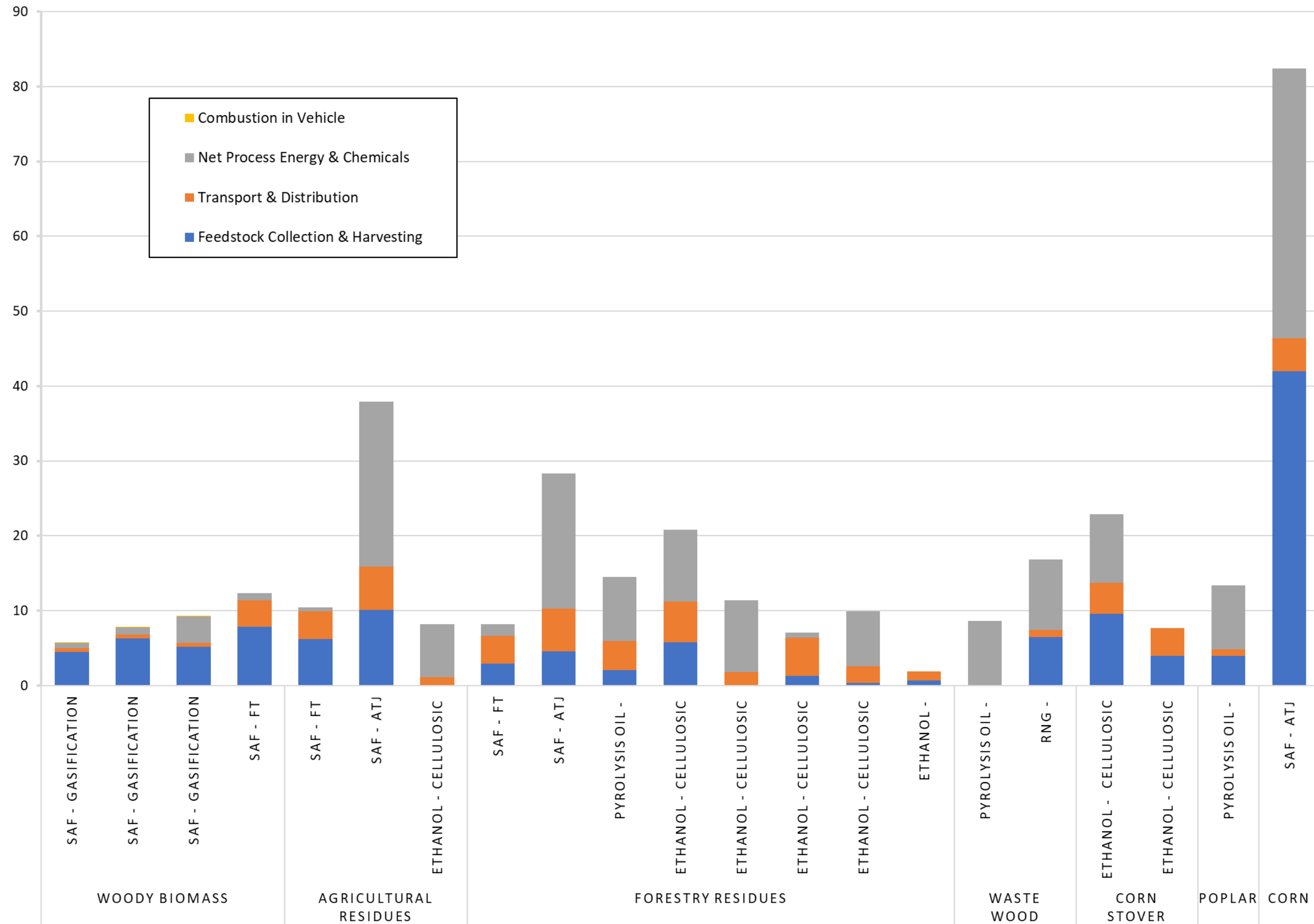


Figure 6.4. GHG emissions for hydrogen

6.2 Literature Review

As part of this analysis, a literature review was conducted on well-to-wheel life cycle assessments of biomass-to-biofuel pathways. Various studies and reports are examined that evaluate the GHG emissions of different biomass conversion technologies for the production of sustainable aviation fuel (SAF), ethanol, and renewable natural gas (RNG). The review includes research from sources such as the National Renewable Energy Laboratory, Argonne National Laboratory, and the University of Groningen. It covers a range of biomass feedstocks and conversion processes, including gasification, Fischer-Tropsch synthesis, and pyrolysis. The assessments consider factors such as carbon emissions, energy consumption, and transportation emissions to provide a comprehensive understanding of these biofuel pathways.

A chart demonstrating the results of this literature review is displayed on the next page. Notably, all biomass to biofuel pathways in the studies examined had lower well to wheel GHG emissions than fossil alternatives.



90
80
70
60
50
40
30
20
10
0
Combustion in Vehicle
Net Process Energy & Chemicals
Transport & Distribution
Feedstock Collection & Harvesting
SAF - GASIFICATION
SAF - GASIFICATION
SAF - GASIFICATION
SAF - FT
SAF - FT
SAF - ATJ
ETHANOL - CELLULOSIC
SAF - FT
SAF - ATJ
PYROLYSIS OIL -
ETHANOL - CELLULOSIC
ETHANOL - CELLULOSIC
ETHANOL - CELLULOSIC
ETHANOL - CELLULOSIC
ETHANOL -
PYROLYSIS OIL -
RNG -
ETHANOL - CELLULOSIC
ETHANOL - CELLULOSIC
PYROLYSIS OIL -
SAF - ATJ
WOODY BIOMASS
AGRICULTURAL RESIDUES
FORESTRY RESIDUES
WASTE WOOD
CORN STOVER
POPLAR
CORN

7. Verification Options

Undoubtedly, verification of the harvesting and management of biomass will be required under California LCFS. This verification is crucial for the integrity of the program, particularly in ensuring that waste feedstocks are genuine byproducts of operations, that biomass harvested from forests is done sustainably and with the goal of improving forest health, and that biomass harvested from natural forests is used to reduce the risk of wildfires.

Investors in next-generation fuels need a clear understanding of how biomass verification will operate under the LCFS to advance their plans. To establish robust verification metrics, CARB must define measurement criteria, assessment frequency, data types, validation requirements, and record-keeping practices. Measurement criteria could include factors such as carbon emissions produced during feedstock production and transportation, feedstock energy content, and land-use change associated with feedstock production. Assessment frequency will vary depending on feedstock type and origin, and data may be collected through on-site measurements, laboratory analyses, or remote sensing. To ensure data accuracy and reliability, validation requirements such as quality control procedures and independent verification may be implemented. Comprehensive record-keeping will also be crucial to promote transparency and allow for auditability if needed.

By setting up robust verification metrics for biomass feedstocks, CARB can equip developers with the appropriate tools to verify feedstocks as part of their development plans. Figure 7.1 illustrates the areas where discussion and resolution are needed in order to advance biomass to biofuel pathways. The first step is to define biomass activity, followed by aligning these activities with their alternative carbon fate. CARB must then determine how fuel pathways involving waste biomass will be verified. Finally, approved fuel pathways will be established.

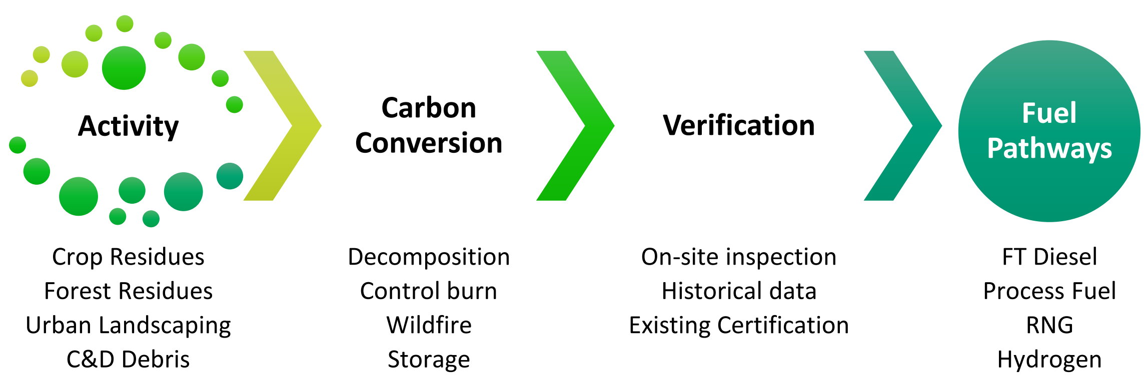


Figure 7.1. Steps to advancing biomass based on waste products into an approved fuel pathway.

7.1.1 Options for Verifying Forest Management Practices

Several options are available for verifying forest management practices. CARB may require on-site measurement, and laboratory analysis, as well as quality control procedures, independent verification, and comprehensive record-keeping to ensure data accuracy and reliability.

There are already forest certification schemes in use that may help inform verification under the LCFS. The United Nations Food and Agriculture Organization (FAO) and many countries, including Federal, State, and private forested areas, establish forest management guidelines. Here are some options for verifying forest management practices:

- Sustainable Forest Management Practices: Forests used to produce fuels that meet Renewable Fuel Standard (RFS) requirements must have been actively managed before December 19, 2007. Sustainable management practices are designed to ensure constant net primary productivity (NPP).

- Forest Certification Programs: Forest certification is a voluntary market-based approach that recognizes sustainable forest management by labeling forest and wood products from those forests as being managed under certified standards. Various certification programs exist, such as 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).

    - Sustainable Forestry Initiative (SFI) standards are commonly used in the United States and Canada, and they include measures to protect water quality, biodiversity, wildlife habitat, species at risk, and forests with exceptional conservation value. The standard applies to any organization that owns or manages forests in the United States or Canada.

    - FSC principles and criteria provide a foundation for forest management standards globally, including 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, as principles and criteria from FSC and RSB standards are aligned. In most cases, FSC-certified forests are considered to be in compliance with RSB-F's principles and criteria. In a comparison of forest certification programs, FSC is found to be more detailed and prescriptive in almost all aspects considered for forest certification (Garzon, et al., 2020).

    - The Roundtable on Sustainable Biomaterials (RSB) is a certification program that verifies the sustainability of biomass feedstocks and their supply chains. The RSB certification focuses on environmental, social, and economic aspects of sustainability, and is recognized by several sustainability initiatives

Existing sustainable forestry certification schemes are explored in the following subsections.

7.2 Verification Protocols

Table 26 provides a summary of four sustainability standards and certifications: Roundtable on Sustainable Biomaterials (RSB), Sustainable Forestry Initiative (SFI), Forest Stewardship Council (FSC), and International Sustainability and Carbon Certification (ISCC).

The four sustainability standards and certifications discussed in Table 26 share some commonalities. For instance, all of them prioritize the conservation of high biodiversity land, protect soil, water, and air quality, and promote climate change mitigation efforts. Additionally, they require responsible management practices for feedstocks or forests that avoid causing any harmful environmental impacts. Moreover, they aim to support rural and social development, while respecting the rights of Indigenous Peoples.

One key difference between these certifications is their feedstock coverage. RSB covers multiple agricultural feedstocks and forests, while SFI covers biomass used to produce renewable energy derived from trees, plants, and other biological organic matter. FSC, on the other hand, covers forest feedstocks and operations that provide environmental, social, and economic benefits. ISCC covers multiple agricultural feedstocks, such as sugarcane, cotton, corn, and wheat, and ensures that all processes are carried out without generating environmental consequences.

RSB, SFI, and FSC have similar processes that involve application, preparation for audit, and audit, with certification validity ranging from 2 to 5 years. ISCC has a one-year certification validity and requires a traceability/mass balance system in place and a list of all wood suppliers.

Table 28. Summary of sustainability standards and certifications

Certification	RSB	SFI	FSC	ISCC
Basic Information				
Feedstock coverage	Multiple agricultural feedstocks: material of biological origin produced through agricultural process and forest. Annual crops, woody biomass, crop residues[a].	Biomass used to produce renewable energy, this includes any organic products and byproducts derived from trees, plants, and other biological organic matter, (limbs, bark and other cellulosic material, organic byproducts from wood pulping, and other biologically derived materials).[i]	Forest feedstocks (timber, all wood, slash, thinning, paper and other wood-based material) and operations this is refer to any responsibly managed forests that provide environmental, social and economic benefits.	Multiple agricultural feedstocks (sugar cane, carton, cotton, corn, wheat) and operations refers that all processes are carried out without generating environmental consequences.
Geographical coverage	Global	United States and Canada	Global	Global

Certification	RSB	SFI	FSC	ISCC
No. of companies certified	86 certificates have been issued of which 49 certificates are still valid[b].	245 certificate holders meeting the SFI program's fiber sourcing or responsible procurement requirements.[j]	400 million acres of forest are FSC certified[c].	40,549 certificates have been issued of which 7,619 certificates are still valid[d].
Goals				
Environmental	○ Preservation of high biodiversity land and high carbon stock land ○ Soil, water and air protection ○ Waste management. ○ Mitigate climate change[a].	○ Preservation of high biodiversity land. ○ Soil, water and air protection ○ Promotes reforestation.[k]	○ Preservation of high biodiversity land. ○ Soil, water and air protection ○ Waste management ○ Reduction of deforestation[e].	○ Preservation of high biodiversity land, high carbon stock land, and peatlands. ○ Soil, water and air protection. ○ Good agricultural and environmental condition (GAEC) standards.
Social	○ Contribution to rural and social development. [a] ○ Stakeholder involvement according to Free Prior and Informed Consent (FPIC) in land acquisition.	○ Improved community structures and external relations. ○ Recognize and respect Indigenous People Rights.[k] ○ Provides education to the landowners through the organizations SFI certified.[k]	○ Contribution to rural and social development. ○ Improved community structures and external relations. ○ Legal and customary rights	○ Labor rights and working conditions. ○ Land use rights.
Economical	○ Business plan of the economic operator must reflect a commitment to long-term economic viability[a].	○ The SFI label reflect the excellent forestry operations and non-genetically modified product. Which means an increment of price in the final product or feedstock.	○ The FSC label reflect a long-term commitment to responsible forest management, allowing you to get support from public and private organizations during many years. ○ The FSC label reflect the efficiency and effectiveness on financial standing for forestry operations. Which means an increment of price in the final product or feedstock.	○ Not applicable.

Certification	RSB	SFI	FSC	ISCC
Certification process				
How does it work?	○ Application ○ Preparation for audit ○ Audit[a].	○ Select the Standard that applies to your organization ○ Complete and submit the application form ○ Audit	○ Choose certification body ○ Assessment (preparation for audit) ○ Certification report[f].	○ Registration ○ Preparation for audit ○ Audit[h].
Application	https://rsb.org/get-certified/	https://www.surveymonkey.com/r/PLLNSJM	https://us.fsc.org/en-us/certification/certifying-bodies-in-the-us	https://www.iscc-system.org/process/registration-for-certification/
Auditing				
Requirements	○ Biofuel Producer: Self Risk Assessment, Screening exercise, GHG calculations, Environmental and Social Management Plan, Chain of Custody Procedure and Claims Procedure. ○ Biofuel Blender: GHG calculation, Chain of Custody Procedure and Claims Procedure. [a]	○ Small lands group certification: wood and fiber supply area plan (review of non-timber activities, determination of long-term sustainable harvest, map of the area and plan of protection). Forest management plan (practices prescribed to control pests, prescribed burns, species on the property, practices to promote the forest health.	○ Forest Management Certification: use of the forests, environmental impact (conserve biological diversity and its associated values, water resources, soils), management plant (condition of forest, yields of forest products, chain of custody, management activities) and the plantation plan to restoration and conservation of natural forests[g].	○ Traceability/mass balance system in place ○ List of all wood suppliers ○ Sustainability requirements (ISCC Principles 1-6) for all Forest Managements Units ○ GHG calculation (for wood-based biofuels processed from wood) [h]
Certificate validity	○ 2 years (dependent on risk class) ○ 3 months (risk class 6)	5 years with annually audits	1 year	1 year

[a] (A Guide to RSB Certification, 2020)
[b] (RSB Certificates, 2022)
[c] (Forest Stewardship Council (FSC), 2022)
[d] (International Sustaibility Et Carbon Certification (ISCC), 2022)
[e] (FSC user-friendly guide to FSC certification for smallholders, 2009)
[f] (Forest Stewardship Council (FSC), 2022c)
[g] Missions and vision (Forest Stewardship Council (FSC), 2022b).
[h] (How to become certified, 2022)
[i] SFI Definitions. (Sustainable Foresr Initiative (SFI), 2022).
[j] SFI certification program. (Sustainable Foresr Initiative (SFI), 2022c)
[k] Comparing SFI and FSC Certification Standards. (Sustainable Forestry Inicitive (SFI), 2020)

7.2.1 SFI

United States and Canada, and it focuses on four pillars: standards, conservation, community, and education. The SFI forest management standard is designed to promote sustainable forestry practices, based on 13 Principles, 17 Objectives, 41 Performance Measures, and 141 Indicators. These requirements include measures to protect water quality, biodiversity, wildlife habitat, species at risk, and forests with exceptional conservation value. The SFI 2022 Forest Management Standard applies to any organization in the United States or Canada that owns or manages forestlands.

All SFI Standards require third-party independent certification audits by competent and accredited certification bodies, and all certification bodies must be accredited by a member of the International Accreditation Forum, including the ANSI-ASQ National Accreditation Board (ANAB) or the Standards Council of Canada (SCC). To get certified by SFI, organizations need to follow six principal steps, which include determining which SFI Standard(s) applies to their organization, completing and submitting the AFI PARTICIPATION APPLICATION FORM to SFI, preparing for the audit, getting audited, signing a SFI Trademark License Agreement, and using SFI Trademarks.

The SFI Standards include:

SFI FOREST MANAGEMENT: This is the largest single forest management certification standard in the world, and it requires measures to protect water quality, biodiversity, wildlife habitat, species at risk, and forests with exceptional conservation value. This certification is for organizations that own or have management authority for forestlands in the USA and/or Canada. This includes industrial and family forest owners, universities, conservation groups, public agencies, timber investment management organizations, and real estate investment trusts.

SFI FIBER SOURCING: This Standard is for manufacturers that source from a variety of ownerships or that don't own forestland. The SFI Small Lands Group Certification Module is designed for any organization certified to the SFI Fiber Sourcing Standard. This module applies to organizations that source roundwood or field-manufactured or primary-mill residual chips to support a forest products facility in the USA and/or Canada.

SFI CHAIN OF CUSTODY: The SFI Chain-of-Custody Standard is an accounting system that tracks forest fiber content through production and manufacturing to the end product. This standard also has measures to avoid controversial sources in the supply chain. This certification is for organizations that source, process, manufacture, handle, trade, convert, or print forest-based products globally.

SFI CERTIFIED SOURCING: This Standard contains the requirements for SFI-certified organizations to use the SFI-certified sourcing claim and label. It is the right option for organizations that source, process, manufacture, handle, trade, convert, or print forest-based products globally.

Overall, the SFI Standards aim to promote responsible forestry practices, support rural and social development, and recognize the rights of Indigenous People. By following the certification process, organizations can demonstrate their commitment to sustainability and contribute to the protection of our natural resources.

7.2.2 FSC

The Forest Stewardship Council (FSC) is a globally recognized non-governmental organization that aims to promote sustainable forest management practices worldwide. Its inception can be traced back to the Earth Summit held in Rio in 1992, where deforestation was a pressing issue that needed immediate attention. To address this concern, a group of environmentalists, businesses, and community leaders joined forces to create the FSC.

After the first FSC General Assembly in 1993, the organization began developing a market-based approach that would improve forest practices on a global scale. The FSC's secretariat was initially established in Oaxaca, Mexico, but later moved to Bonn, Germany, in 2003. The FSC now operates in over 80 countries worldwide.

One of the FSC's primary objectives is to promote responsible forest management practices that are environmentally sound, socially beneficial, and economically prosperous. The organization has developed ten principles and 57 criteria that apply to FSC-certified forests worldwide. These principles cover a range of issues, including compliance with laws and FSC principles, tenure and use rights and responsibilities, indigenous peoples' rights, community relations and worker's rights, benefits from the forest, environmental impact, management plans, monitoring and assessment, maintenance of high conservation value forests, and plantation management.

The FSC certification program ensures that products originating from responsibly managed forests provide environmental, social, and economic benefits. The FSC has two types of certifications: Forest Management and Chain of Custody. Both types of certifications involve independent FSC-accredited Certification Bodies that verify that all FSC-certified forests conform to the requirements contained within an FSC forest management standard.

7.2.3 RSB

The Roundtable on Sustainable Biomaterials (RSB) is an independent, multi-stakeholder organization that strives to advance the development of sustainable solutions in the bioeconomy. Initiated by the Swiss Federal Institute of Technology Lausanne (EPFL), the RSB has been an autonomous organization based in Geneva since January 2013. The RSB is guided by a multi-stakeholder steering board, with each member representing one of the seven RSB "cabinets" consisting of all biofuel sectors and stakeholders, including farmers, biofuel producers, the transportation industry, environmental and social NGOs, research institutes, governments, and investors.

The RSB is known for being a comprehensive voluntary system in promoting sustainability, demanding compliance with sustainability criteria, and promoting rural development and food security. The RSB Principles & Criteria are considered best-in-class and recognized for their comprehensive approach to addressing key sustainability issues. The 12 Principles and associated Criteria provide guidance on producing biomass, energy, and material products from bio-based and recycled carbon and renewable energy, while ensuring environmental, social, and economic responsibility.

The RSB offers various sustainability certifications for a wide range of products, approaches, and issues to verify the sustainability of their production and use. These certifications are voluntary and evaluated by an independent third party to ensure credibility. RSB certification applies to the production, processing, conversion, trade, and use of biomass and biofuels, material products from bio-based and recycled carbon, including fossil waste, as well as biofuel blenders.

For alternative fuel producers, RSB offers RSB EU RED and RSB Global Certifications. RSB EU RED certification is recommended for producers in the EU or those outside the EU selling into the European Union region, while RSB Global certification is suggested for producers who operate and sell in other regions. For non-fuel biomaterials producers, RSB offers the RSB Bioproducts Standard. Additionally, RSB offers a low Indirect Land Use Change (iLUC) certification to demonstrate low iLUC risk.

Currently, the RSB has approximately 45 active operators across America, Europe, and Asia, with most being certificated with the RSB Global certification.

RSB Certification Requirements for Woody Biomass

In the most recent proposal for the LCFS regulation, posted in December 2023, CARB included language on requirements for woody biomass to be certified by a third party (California Air Resources Board (CARB), 2024). RSB published sustainability requirements for woody biomass in December 2021 that are expected to meet the CARB criteria in the new LCFS regulation (RSB, 2021). Three primary goals of the woody biomass framework are the effective management of forests to conserve biodiversity and ecosystem services, the effective accounting of carbon extracted from the forests, and that harvesting and processing residues are true residues.

The framework is verified by examining forest management practices rather than limited to sourcing polices. General requirements for all feedstocks are shown in Table 29. Complete details related to each category as well as alien invasive species information can be found in the full RSB text.

Table 29. RSB Certification Requirements for Woody Biomass

RSB Requirements	Woody Biomass Details
End-of-life forestry materials	
Specifications	○ Woody material from park and garden maintenance ○ Recycling wood ○ Woody material from orchards, construction sites, or tree hedges
Feedstock specific sustainability requirements	○ Orchards require evidence for point of origin, tree species, and began operating prior to January 1, 2008. ○ Construction material cannot originate from land forested after January 1, 2008.
GHG calculation	○ The GHG calculation starts from the collection at the point of origin where GHG intensity is 0 kg CO_2e/kg.
Forestry harvesting residues	
Specifications	○ Slash left after logging or accumulated from a storm or fire ○ Salvage logging wood in forest management units – damaged, dying or dead trees. ○ Early/non-commercial thinnings – performed for silvicultural or ecological reasons with diameter at breast height less than 10 inches. ○ Stumps are not considered forestry harvesting residues nor is low quality roundwood.
Sustainability requirements	○ Forest management must comply with RSB 12 Principles & Criteria[12] or other equivalent certification standards. ○ Soil organic carbon loss must be minimized through sufficient biomass left on the ground to maintain or improve soil health and biodiversity. ○ Requirements on areas identified as "no-go areas" that cannot be used to source biomass and include protected areas, wetlands, biosphere reserves, and ancient and endangered forests. ○ Feedstock identified as low risk for unaccounted emissions from forest carbon pool changes are eligible for certification.
GHG calculation	○ The GHG calculation starts from the collection at the point of origin where GHG intensity is 0 kg CO_2e/kg.
Forestry industry processing residues	
Specifications	○ Sawmill residues – slabs, chunks, bark, shavings, sawdust ○ Tall oil, brown liquor, and black liquor ○ Other residues that meet RSB Standard for Advanced Fuels requirements

[12] https://rsb.org/framework/principles-and-criteria/

RSB Requirements	Woody Biomass Details
Sustainability requirements	○ Point of origin requires a chain of custody certification system in place.
GHG calculation	○ The GHG calculation starts from the collection at the point of origin where GHG intensity is 0 kg CO_2e/kg. ○ The materials have to meet the eligibility requirements for the RSB Standard for Advanced Fuels[13], otherwise the GHG calculation includes forest management.
Short rotation woody crops	
Specifications	○ Perennial cropping systems that produce biomass or fibers with a lifetime less than 20 years and harvest every 1-5 years. ○ Species may include poplars, willows, maples, black locust, Acacia, Gmelina, Eucalyptus, among others
Sustainability requirements	○ No conversion of high carbon stocks and forest land with a cut-off date of January 2008. ○ The operator must implement practices preventing invasive species from invading areas outside of the operation. ○ The plantation must not deplete surface or groundwater resources beyond replenishment capacities.
GHG calculation	○ The GHG calculation starts from the cultivation of the crop, including applicable land use change. ○ The methodology should follow RSB GHG Calculation Methodology[14], or RSB EU RED GHG Calculation Methodology[15], or RED as incorporated in the UK Solid or Gaseous Biomass Carbon Calculator (Ofgem)[16].

7.2.4 ISCC

The International Sustainability & Carbon Certification System (ISCC) is a globally recognized certification system that focuses on sustainability and carbon reduction across various industries, including agriculture, forestry, and waste management. The initiative was established as a multi-stakeholder effort in 2006 by Meo Carbon Solutions, a consultancy company, and received support from the German Federal Ministry of Food, Agriculture, and Consumer Protection (BMELV) through the Agency for Renewable Resources (FNR), as well as the German Ministry of Environment (BMU).

[13] https://rsb.org/wp-content/uploads/2024/03/RSB-STD-01-010-RSB-Standard-for-advanced-fuels_v2.6-1.pdf
[14] https://rsb.org/wp-content/uploads/2020/06/RSB-STD-01-003-01-RSB-GHG-Calculation-Methodology-v2.3.pdf
[15] https://rsb.org/wp-content/uploads/2020/06/RSB-STD-11-001-01-010-v.2.1-RSB-EU-RED-Standard-Adv-Fuels.pdf
[16] https://www.ofgem.gov.uk/sites/default/files/docs/2016/08/renewables_obligation_-_uk_user_guide_for_the_solid_and_gaseous_biomass_carbon_calculator.pdf

ISCC aims to promote sustainable practices and reduce carbon emissions in different industries by providing a framework for assessing and certifying sustainability and carbon reduction. The certification system includes requirements related to traceability, environmental and social impacts, greenhouse gas emissions, and waste management, among others.

ISCC operates two versions of the certification system: ISCC EU and ISCC DE. ISCC EU was formally recognized as a voluntary scheme by the European Commission on July 19, 2011, while ISCC DE was recognized by the German government before the EU version. Both versions of the scheme operate in parallel, with ISCC DE being used mainly in the German market and recognized as a voluntary scheme in Austria.

One of the key differences between the two versions of the scheme is the percentage of farms that need to be audited, which is higher in ISCC EU. ISCC DE includes specific requirements for the traceability of waste and residues, which were mandated by the German government. Other EU Member States are free to recognize ISCC DE, but most simply recognize the EC recognized version of the scheme.

7.2.5 RFS and BioMat

Current regulatory frameworks may also inform options for verifying biomass feedstocks. Table 28 provides an overview of two regulatory programs that incorporate biomass feedstocks for the purpose of energy production: the Renewable Fuel Standard (RFS) and the BioMat program.

The RFS is a federal program that requires transportation fuel sold in the United States to contain a minimum volume of renewable fuels. The program requires feedstocks, process, and fuel to meet an approved pathway. Participants need to register their company and facility in the RFS program and submit an engineering review and materials to the Environmental Protection Agency (EPA). The EPA has worked with companies to verify woody biomass feedstocks under the RFS.

In contrast, BioMat is a renewable energy feed-in tariff (FIT) established by the California Public Utilities Commission (CPUC) that covers biogas or biomass from a facility on other agricultural premises. BioMat participants need to use at least 100% of fuel from BioMAT biogas/biomass with 80% from the applicable bioenergy category. The program requires forest biomass to be “sustainable” as defined by the CPUC, which includes a specific checklist that assures the waste comes from projects associated with current forest practice act and other federal and state rules. The table suggests that BioMat has a more detailed verification process for feedstocks, particularly for forest biomass, compared to the RFS program.

Table 30. Renewable Fuel Standard and BioMat program.

Program	RFS	BioMat
Basic Information of the outline		
What is it?	Renewable Fuel Standard is a federal program that requires transportation fuel sold in the United States to contain a minimum volume of renewable fuels.	Bioenergy Market Adjusting Tariff (BioMat) is a renewable energy feed-in tariff (FIT) established by California Public Utilities Commission (CPUC).
Feedstock coverage	Biomass (Slash, pre-commercial Thinnings, tree residue, natural forest, plantation forest, logging)[f]	Biogas or biomass from facility on other agricultural premises
Geographical coverage	National	California
Principal goal	50% GHG reduction in 2022[a].	47MW from biomass projects[c].
Eligibility		
Requirements	○ The fuel must be a renewable fuel. ○ The feedstock must be renewable biomass. This section is broken out in two primary feedstocks types: - Slash: Silvicultural prescription, management, or timber harvest plan. Truck weight records for each load; if slash is removed from the forest, include mass balance of slash/roundwood extracted[f]. - Pre-commercial Thinnings: Silvicultural prescription, management, or timber harvest plan. Certifications, like SFI or FSC; For plantations: consult 40 CFR 80.1454	○ Project must be located in PG&E's service territory and be connected on the distribution or transmission system[c]. ○ Must use at least 100% of fuel from BioMAT biogas/biomass with 80% from the applicable bioenergy Category[e]. ○ Project may be sized 5 MW or smaller, provided that no more than 3 MW is delivered to the grid at any time. ○ The operations must start after June 1, 2013. ○ The project needs to have passed the interconnection Fast Track screens, passed Supplemental Review, completed a System Impact Study in the Independent Study Process, completed a Distribution Group Study Phase 1 Interconnection Study in the Distribution Group Study Process, or completed a Phase 1 Study in the Cluster Study Process[c].

Program	RFS	BioMat
	(d)(2); Documentation to verify ownership of the land to be thinned [f]. ○ Feedstocks, process and fuel meet an approved pathway[d]. ○ Should produce at least 32 billion gallons of renewable fuel in 2022[a].	○ Forest biomass must be "sustainable" as defined by the CPUC specifically for this program, as waster derived from fire threat reduction activities, fire threat clearance activities; Infrastructure clearance projects or "other" waste wood that must be analyzed through a check list that generally assures it comes from projects associated with current forest practice act and other federal and state rules.
Online application	https://www.epa.gov/fuels-registration-reporting-and-compliance-help/tutorial-creating-cdx-account	https://pgebiomat.accionpower.com/_pgebiomat/disclaimers.asp
Process to participate		
How does it work?	○ Register Online ○ Assemble all documents required in §80.1450(b)(1). ○ Obtain an engineering review conducted by a third-party independent professional engineer. ○ Create a New Company Request in CDX OTAQReg to register your company and facility in the RFS program under Part 80[d]. ○ Submit the engineering review and materials required under §80.1450(b)(1) to EPA[d].	○ Apply online (website above) creating a Program Participation Request (PPR) ○ Once the PPR is approve BioMAT Queue Number will be assigned[f].

[a] Overview for Renewable Fuel Standard. (Environmental Protection Agency (EPA), 2023a).
[b] Frequently Asked Questions PG&E BioMAT Feed-in Tariff Program. (PG&E, 2014).
[c] Bioenergy Market Adjusting Tariff, Overview. (PG&E, 2022)
[d] How to register a New Renewable Fuel Producer for the Renewable Fuel Standard (RFS). (Environmental Protection Agency (EPA), 2023b).
[e] Bioenergy Market Adjusting Tariff (BioMat) Public Webinar. (PG&E, 2015).
[f] Practical Guide to Forestry Feedstock under the Renewable Fuel Standard. (SBF, 2024).

7.2.6 USDA Project for RFS Biomass Verification

The Renewable Fuel Standard (RFS) and RFS2 were established to increase the use of renewable fuels in the United States, with the goal of reducing air pollution and greenhouse gas emissions. RFS2 specifically requires that biofuels be derived from renewable biomass, and the EPA has strict criteria for determining what qualifies as such. To ensure that forests and other ecologically sensitive areas are not being harmed in the process, certain types of land are excluded from the definition of renewable biomass.

To comply with these regulations, Strategic Biofuels has launched a project to create a user-friendly, fraud-resistant tracking system for forestry feedstocks. This system aims to accurately and conveniently collect and transmit data from key sectors such as landowners, loggers, sawmills, and forest products manufacturers. The first phase of this project involves identifying the source and type of qualifying material harvested, developing compliance documentation requirements for each source stand of timber, establishing the point of origin and chain of custody for each load of compliant wood, and creating auditable reports for audit purposes. The second phase of the project is the development of a mobile device system that meets EPA audit requirements while being user-friendly for loggers, forestry managers, and regulators. This cloud-based system will allow for the accurate and efficient tracking of costs and information throughout the supply chain, ensuring compliance with RFS2 and other renewable fuel credit systems.

8. Conclusions

The California Air Resources Board (CARB) has the opportunity to bolster the effectiveness of its climate policies by aligning the goals of its scoping plan with existing policies, namely the California Low Carbon Fuel Standard (LCFS), and by providing clear guidance to developers on policy implementation. The LCFS is a powerful tool for reducing greenhouse gas (GHG) emissions in California's transportation sector. Alternative fuels producers receive credits under the LCFS based on the GHG reductions they achieve, as determined by a life cycle assessment (LCA) and verified by third-party reviewers.

Developers seeking to invest in infrastructure and technology for producing low-carbon next generation biomass-derived fuels face several significant challenges. These include a lack of guidance on how the net carbon balance of biomass will be assessed under California's LCFS regulation, the need to educate CARB staff on the specific alternative fate of their particular biomass feedstock, and the uncertainty around what CARB will require for verification of biomass-derived feedstocks.

This paper has addressed each of these challenges by:

1) Providing insights into the net carbon balance of different types of biomass
2) Describing the alternative fates of biomass based on category, location, and collection practices

3) Reviewing current verification schemes and options for each biomass category and location.
4) Recommending actions that would provide an immediate path forward for developers seeking to invest in low-carbon next-generation biomass derived fuels.

Investors in next-generation fuels need a clear understanding of how biomass verification will operate under the LCFS to advance their plans. To establish robust verification metrics, CARB must define measurement criteria, assessment frequency, data types, validation requirements, and record-keeping practices. Measurement criteria could include factors such as carbon emissions produced during feedstock production and transportation, feedstock energy content, and land-use change associated with feedstock production. Assessment frequency will vary depending on feedstock type and origin, and data may be collected through on-site measurements, laboratory analyses, or remote sensing. To ensure data accuracy and reliability, validation requirements such as quality control procedures and independent verification may be implemented. Comprehensive record-keeping will also be crucial to promote transparency and allow for auditability if needed.

To date, CARB has not formally identified an approach to quantifying emissions associated with certain types of biomass residues, including those from wood and nutshells. The lack of such transparent guidance impinges the ability to plan and execute biofuel projects that can deliver alternative biomass residue fates for hard-to-decarbonize sectors such as sustainable aviation fuel. As a result, these types of biomass residues may continue to emit GHG emissions associated with business-as-usual conventional fates, e.g., burning and decomposition, as uncertainty of their treatment in the LCFS increases perceived investor risk.

8.1 Recommendations

The challenges related to biomass-derived fuels are multifaceted and have been a topic of ongoing discussion among scientific and policy experts. While these challenges are complex, it is crucial to address them in order to support the development of alternative fuels and to help California achieve its environmental goals. In addition to reducing greenhouse gas emissions, the promotion of alternative fuels can also help mitigate the risks of wildfires and prevent natural resource loss.

There are several steps CARB can take immediately to advance biomass-derived fuels under the LCFS. They are outlined here:

Action:

- Develop a near-term solution for biogenic carbon that enables future development by treating biomass from forest residues, crop residues, forest slash, and thinnings using the GREET modeling carbon-neutral framework.
- Create a Tier 1 calculator framework for the conversion of biomass to synthetic fuels, ethanol, hydrogen, and CNG.
- Establish a temporary fuel pathway code that has a safety margin for carbon neutrality.

• Create a temporary fuel pathway code for biomass fuels and fuel production with CCS.
• Provide an initial 10-year implementation period based on carbon-neutral biomass.

Workshop:

• Organize annual woody biomass to energy/LCFS workshop to enhance understanding of biogenic carbon neutrality issues that builds upon the California 2024 biomass utilization workshop.

Research:

• Participate in an interagency working group to develop a Tier 1 LCFS pathway for woody biomass to fuels and power.
• Support ongoing research on forestry biomass by arranging field trips to view a range of forest management activities and slash piles.
• Establish a working group of experts to investigate the biogenic treatment of forest material.

Verification:

• Define categories of biomass feedstocks, including thinnings and slash, agricultural residue, energy crops, and urban waste.
• Review verification protocols and ensure alignment with LCFS program requirements, including RFS protocols for thinning and slash and existing forestry certification schemes such as the Sustainable Forestry Initiative (SFI) and the Forest Stewardship Council (FSC).

9. Appendix A

Table 31. Default CO_2 Emission Factors and Hight Heat Values for Various Types of Biomass Fuel.

Fuel type	Default high heat value	Default CO_2 emission factor
Coal and coke	**mmBtu/short ton**	**kg CO_2/mmBtu**
Anthracite	25.09	103.69
Bituminous	24.93	93.28
Subbituminous	17.25	97.17
Lignite	14.21	97.72
Coal Coke	24.80	113.67
Mixed (Commercial sector)	21.39	94.27
Mixed (Industrial coking)	26.28	93.90
Mixed (Industrial sector)	22.35	94.67
Mixed (Electric Power sector)	19.73	95.52
Natural gas	mmBtu/scf	kg CO_2/mmBtu
(Weighted U.S. Average)	1.026×10^{-3}	53.06
Petroleum products - liquid	mmBtu/gallon	kg CO_2/mmBtu
Distillate Fuel Oil No. 1	0.139	73.25
Distillate Fuel Oil No. 2	0.138	73.96
Distillate Fuel Oil No. 4	0.146	75.04
Residual Fuel Oil No. 5	0.140	72.93
Residual Fuel Oil No. 6	0.150	75.10
Used Oil	0.138	74.00
Kerosene	0.135	75.20
Liquefied petroleum gases (LPG)[1]	0.092	61.71
Propane[1]	0.091	62.87
Propylene[2]	0.091	67.77
Ethane[1]	0.068	59.60
Ethanol	0.084	68.44
Ethylene[2]	0.058	65.96
Isobutane[1]	0.099	64.94
Isobutylene[1]	0.103	68.86
Butane[1]	0.103	64.77
Butylene[1]	0.105	68.72

Fuel type	Default high heat value	Default CO_2 emission factor
Naphtha (<401 deg F)	0.125	68.02
Natural Gasoline	0.110	66.88
Other Oil (>401 deg F)	0.139	76.22
Pentanes Plus	0.110	70.02
Petrochemical Feedstocks	0.125	71.02
Special Naphtha	0.125	72.34
Unfinished Oils	0.139	74.54
Heavy Gas Oils	0.148	74.92
Lubricants	0.144	74.27
Motor Gasoline	0.125	70.22
Kerosene-Type Jet Fuel	0.135	72.22
Asphalt and Road Oil	0.158	75.36
Crude Oil	0.138	74.54
Petroleum products - solid	mmBtu/short ton	kg CO_2/mmBtu.
Petroleum Coke	30.00	102.41.
Petroleum products - gaseous	mmBtu/scf	kg CO_2/mmBtu.
Propane Gas	2.516×10^{-3}	61.46.
Other fuels - solid	mmBtu/short ton	kg CO_2/mmBtu
Municipal Solid Waste	9.95[3]	90.7
Tires	28.00	85.97
Plastics	38.00	75.00
Other fuels - gaseous	mmBtu/scf	kg CO_2/mmBtu
Blast Furnace Gas	0.092×10^{-3}	274.32
Coke Oven Gas	0.599×10^{-3}	46.85
Fuel Gas[4]	1.388×10^{-3}	59.00
Biomass fuels - solid	mmBtu/short ton	kg CO_2/mmBtu
Wood and Wood Residuals (dry basis)[5]	17.48	93.80
Agricultural Byproducts	8.25	118.17
Peat	8.00	111.84
Solid Byproducts	10.39	105.51
Biomass fuels - gaseous	mmBtu/scf	kg CO_2/mmBtu
Landfill Gas	0.485×10^{-3}	52.07
Other Biomass Gases	0.655×10^{-3}	52.07
Biomass Fuels - Liquid	mmBtu/gallon	kg CO_2/mmBtu

Fuel type	Default high heat value	Default CO_2 emission factor
Ethanol	0.084	68.44
Biodiesel (100%)	0.128	73.84
Rendered Animal Fat	0.125	71.06
Vegetable Oil	0.120	81.55

[1] The HHV for components of LPG determined at 60 °F and saturation pressure with the exception of ethylene.

[2] Ethylene HHV determined at 41 °F (5 °C) and saturation pressure.

[3] Use of this default HHV is allowed only for: (a) Units that combust MSW, do not generate steam, and are allowed to use Tier 1; (b) units that derive no more than 10 percent of their annual heat input from MSW and/or tires; and (c) small batch incinerators that combust no more than 1,000 tons of MSW per year.

[4] Reporters subject to subpart X of this part that are complying with § 98.243(d) or subpart Y of this part may only use the default HHV and the default CO_2 emission factor for fuel gas combustion under the conditions prescribed in § 98.243(d)(2)(i) and (d)(2)(ii) and § 98.252(a)(1) and (a)(2), respectively. Otherwise, reporters subject to subpart X or subpart Y shall use either Tier 3 (Equation C-5) or Tier 4.

[5] Use the following formula to calculate a wet basis HHV for use in Equation C-1: $HHV_w = ((100 - M)/100)*HHV_d$ where HHV_w = wet basis HHV, M = moisture content (percent) and HHV_d = dry basis HHV from Table C-1.

10. APPENDIX B – C- MODEL

Table 3: Description of Forest Silvicultural Treatments

Treatment	Label	Description
Remove 100%	RM100	Clear-cut 100% of standing trees
Snags	Snags	Remove 100% standing dead wood
Thin from Below by 20%	TFB20	Remove 20% of basal area starting with smallest DBH trees
Thin from Below by 40%	TFB40	Remove 40% of basal area starting with smallest DBH trees
Thin from Below by 60%	TFB60	Remove 60% of basal area starting with smallest DBH trees
Thin from Below by 80%	TFB80	Remove 80% of basal area starting with smallest DBH trees
Thin from Above by 20%	TFA20	Remove 20% of basal area starting with largest DBH trees
Thin from Above by 40%	TFA40	Remove 40% of basal area starting with largest DBH trees
Thin from Above by 60%	TFA60	Remove 60% of basal area starting with largest DBH trees
Thin from Above by 80%	TFA80	Remove 80% of basal area starting with largest DBH trees
Proportional Thin by 20%	TP20	Remove 20% of basal area proportionally across all tree sizes
Proportional Thin by 40%	TP40	Remove 40% of basal area proportionally across all tree sizes
Proportional Thin by 60%	TP60	Remove 60% of basal area proportionally across all tree sizes
Proportional Thin by 80%	TP80	Remove 80% of basal area proportionally across all tree sizes

Figure 4: Forest Biomass Resource Size Classes

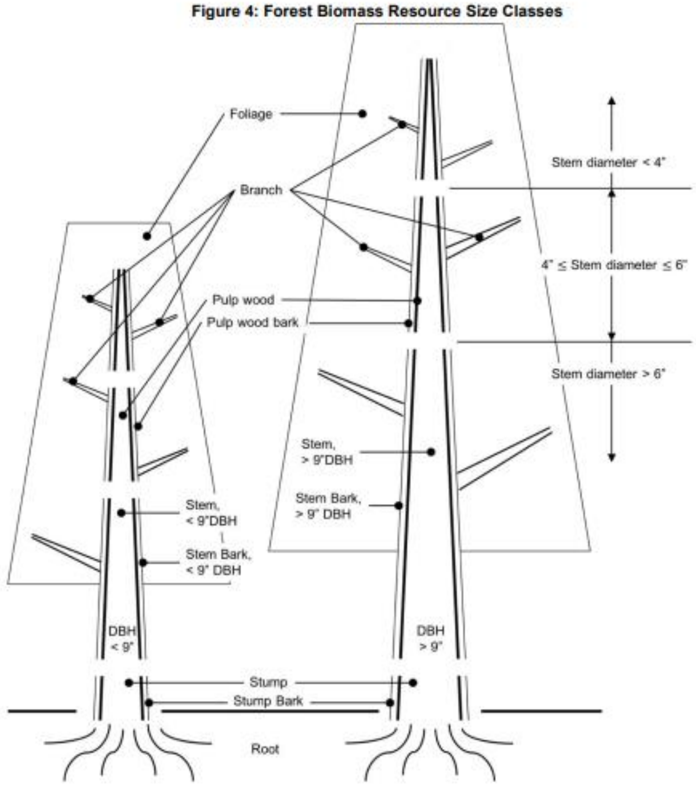
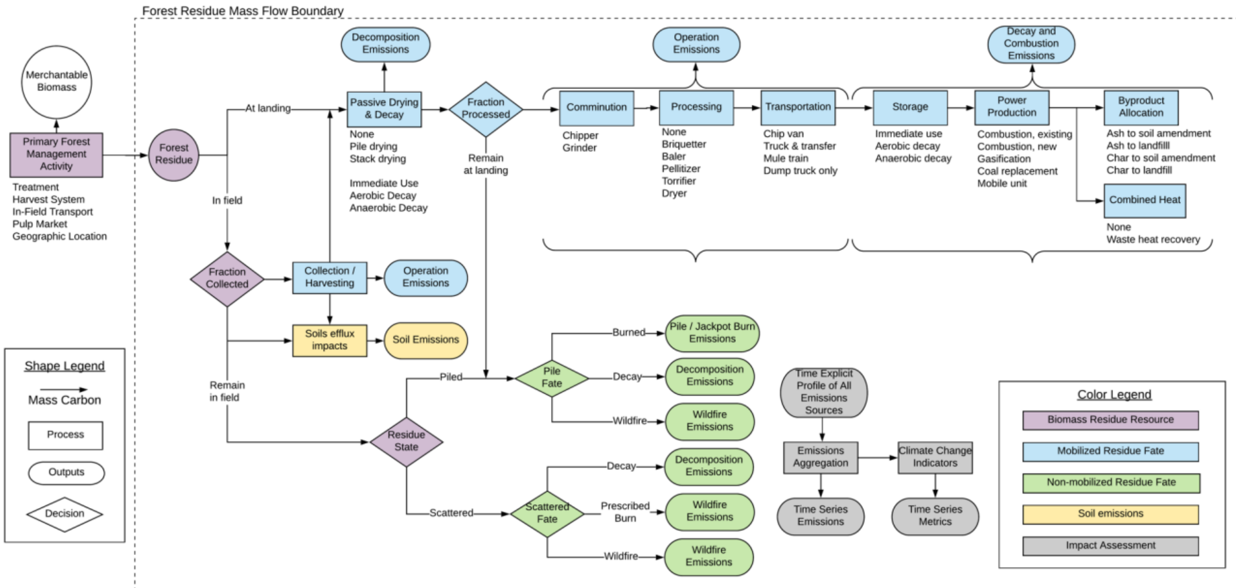


Figure 2: Forest Residue Mass Flow Boundary



11. LCA REPORT - BIOMASS

The following Report was published in Biomass Magazine in February 2024:

Pathways for Negative Carbon Intensity Biomass Fuels

Prepared by Anna Redmond and Stefan Unnasch | Life Cycle Associates

Overview

California generates millions of tons of wood waste from its farms and forests annually, but less than 20% is repurposed for commercial use[17]*. The majority is left to decay in place or burned, contributing to greenhouse gas (GHG) emissions and air pollution. California's wildfire prevention efforts, which aim to reduce biomass fuel loads on one million acres of land each year, will exacerbate the state's wood waste problem.*

Converting wood waste into biofuels can reduce overall emissions to the atmosphere as shown in Figure 1. Utilization of biomass residues *would not only avoid the negative impacts of current disposal practices, but also drive rural economic development, technological innovation, and further emissions reductions by replacing fossil fuels.*

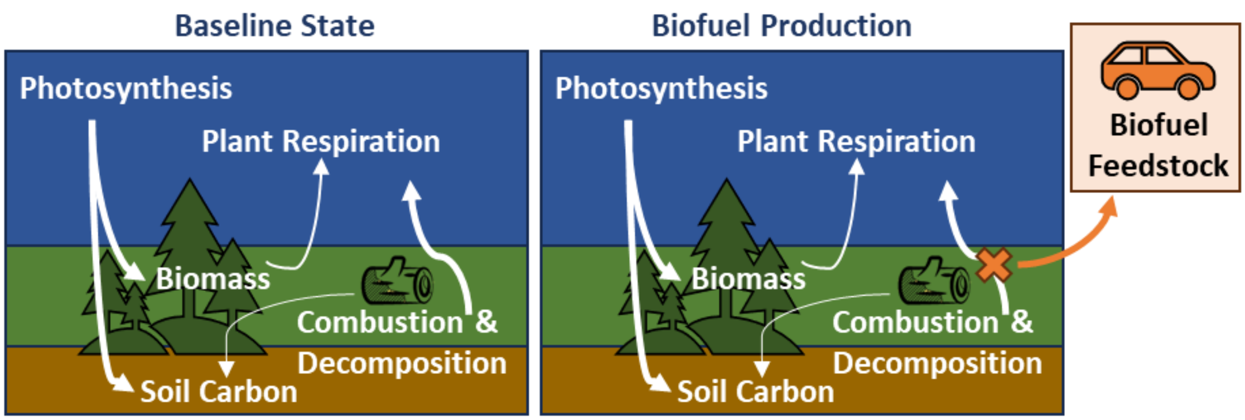


Figure 11.1. The Biogenic Carbon Cycle. Arrows are not drawn to scale.

Renewable fuels such as hydrogen, biomethane, ethanol, and sustainable aviation fuel are promising options for replacing conventional transportation fuels and reducing CO_2 emissions. Adding carbon capture and storage (CCS) to these fuel production facilities can provide even greater carbon dioxide removal, a key goal of Gov. Newsom and the California Air Resources Board. Co-producing biochar, a carbon-rich material that can be sequestered in the soil, can further reduce the emissions impact of a biofuel system. Another approach involves the utilization of lignin for the production of biomaterials or use as a petroleum bitumen substitute[18]*.*

Previous studies have explored the life cycle carbon intensity (CI) of various biomass-to-biofuel pathways, encompassing diverse feedstocks, technologies, and end products, such as including wood waste to RNG

[17] California Department of Resources Recycling and Recovery. https://calrecycle.ca.gov/condemo/wood/

[18] https://www.biofuelsdigest.com/bdigest/2021/06/06/lignin-leads-the-way-worlds-first-lignin-bio-asphalt-road-lignins-array-of-applications-and-more.

via anaerobic digestion[19]*, biomass to electricity via pyrolysis*[20] *, and woody biomass to sustainable aviation fuel via gasification and Fisher-Tropsch synthesis.*[21]

11.1 *System Boundaries*

Quantifying the carbon intensity (CI), or the amount of CO_2e emissions per MJ of fuel, of a biofuel involves a comprehensive approach known as Life Cycle Assessment (LCA). LCA evaluates the environmental impact of a product or process across its entire life cycle, from the extraction of raw materials to its eventual disposal.

To gauge the CI biofuels, an LCA begins by establishing baseline data and cataloging the energy and materials consumption of all involved processes, including carbon capture, transportation, storage, and monitoring. Subsequently, they calculate the corresponding GHG emissions released into the environment. Finally, they assess the cumulative environmental effects within predefined system boundaries stemming from the biofuel system.

In the case of a waste and residual biomass to biofuel system, system boundaries include:

- *Biomass production and collection, including direct and indirect land use change*
- *Transportation of biomass to the facility*
- *Biomass preparation, including biomass chipping or grinding*
- *Biofuel production*
- *CCS at biofuel production site*
- *Co-products, such a biochar*
- *Fuel Combustion in vehicle*

In some cases, if the biomass were to be transported to an alternate disposal site in the baseline, the net difference for the transportation to the facility may be compared to the baseline and accounted for.

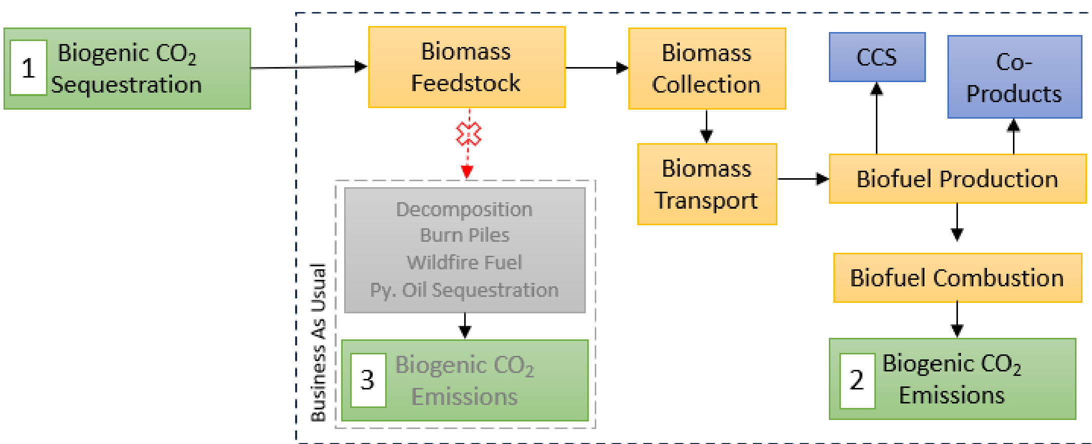


***Figure 11.2**. Example system boundary diagram for waste biomass to biofuel system.* In this accounting scheme biogenic CO_2 sequestration (1) occurs outside of the system boundary. The sequestration occurs with or without the biofuel system's existence. The biofuel will be credited for the biogenic CO_2

[19] https://www.gti.energy/wp-content/uploads/2019/02/Low-Carbon-Renewable-Natural-Gas-RNG-from-Wood-Wastes-Final-Report-Feb2019.pdf

[20] Fan, J., Kalnes, T. N., Alward, M., Klinger, J., Sadehvandi, A., & Shonnard, D. R."Life cycle assessment of electricity generation using fast pyrolysis bio-oil.

[21] https://www.nrel.gov/docs/fy22osti/82703.pdf

emissions that would have occurred in the absence of the biofuel systems (3). This can be represented by subtracting box (2) from box (3).

11.2 *Carbon Intensity Calculations*

To calculate the net CO_2e emissions from a biomass to biofuel system, we first need to establish an LCA baseline. This baseline is a comparison of the greenhouse gas emissions from the biofuel project to the emissions from the way that the biomass fate in the absence of the project. For example, if the biomass would be left to decompose in the field, the baseline scenario would include the emissions from methane production.

We also need to consider the timing of emissions in the LCA. For example, if the biomass would decompose over time, we should consider the cumulative emissions from the biomass over its lifetime. However, if the biomass would decompose quickly or combust, we can safely ignore the timing of emissions.

For this pathway example we will consider only feedstocks that would have otherwise combusted, such as wildfire abatement residues or agricultural residues that would have been disposed of in burn piles.

Combustion of biomass can occur for various reasons, including:

Agricultural burning: Farmers burn crop residues left in fields after harvest, as well as prunings from orchards and vineyards, to clear land, dispose of waste, and control weeds, diseases, and pests. In some cases, such as rice and pear cultivation, burning is the most efficient and effective method for disease control.

Forest residue burning: The U.S. Forest Service conducts controlled burns of piles of woody debris, commonly referred to as slash, to reduce hazardous fuels in forested areas. These piles are formed from the leftover woody materials following tree thinning or cutting activities.

When biomass is burned, all of the carbon that was sequestered in the biomass is released into the atmosphere over a short period of time. This can be modeled as a single time pulse. The biogenic carbon released during burning is equal to the biogenic carbon that would be released from the biofuel during vehicle combustion. Therefore, the emissions from avoided burning and vehicle combustion cancel each other out, and the feedstock can be considered biogenic carbon neutral.

11.2.1 GHG Analysis

The GREET model considers various woody biomass feedstocks, such as forest residue and farmed trees. The life cycle GHG emissions for forest residue to FT diesel are shown in Figure 3 with two different accounting systems. First all of the carbon flows are shown including the net biogenic uptake and CO_2 released from the process. In the pathway without CCS, process emissions plus fuel combustion equal the biogenic carbon into the process. GREET treats the net biogenic carbon flow as neutral assuming that removal and additional growth balance. The RFS also requires that forest thinnings used for biofuel production result in increased growth of surrounding trees. When CO2 from processing emissions is stored the net emissions are reduced. The biogenic process emissions are no longer emitted and the net uptake results in a credit. The identical results are achieved with a biogenic carbon neutral accounting system. The biogenic uptake credit is omitted and stored CO_2 is treated as a credit. The latter accounting system is represented for the well to tank emissions in the GREET model. CCS represents a significant fraction of the CI reduction and results in a very low CI. The extent of CCS is variable with the proposed process. For example, a lower level of CO_2 storage could be achieved if only concentrated CO_2 sources are captured. This approach would simplify the CO_2 recovery efforts. Also, grid power could be used to operate equipment. Both of these process changes would affect system complexity, cost, and GHG emissions.

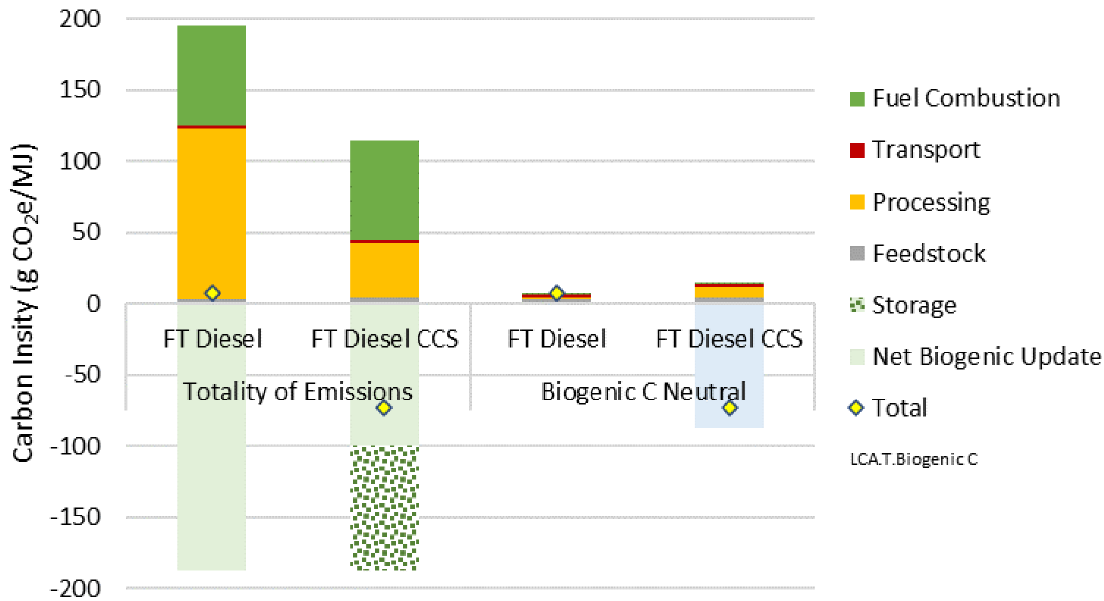


Figure 11.3. *Life Cycle GHG emissions for forest residue to FT diesel with totality of emissions and biogenic carbon neutral accounting system. FT diesel with CCS achieves a negative CI.*

The model is configured with a range of fuel pathways including gasification, pyrolysis, and fermentation technologies. The model examines numerous fuel pathways including hydrogen, FT diesel and jet, pyrolysis fuels, renewable natural gas, and ethanol. GREET explicitly models CCS for several fuel pathways and treats the storage of organic residue from pyrolysis and anaerobic digestion as a storage credit. All of the CO_2 storage options provide a route for a carbon negative pathway whether CO_2 is stored as a gas or as a soil additive or other product. The factors influencing life cycle GHG emissions encompass energy inputs, yields, and carbon storage strategies for biomass-to-fuel conversion technologies.

Table 32 presents a range of carbon-negative technologies, offering a basis for evaluating the impact of biomass conversion to fuels. Each technology includes parameters such as biomass-to-fuel yield, power consumption, natural gas consumption, carbon storage technology, and carbon capture efficiency. The default approach in the GREET model accounts for Fischer-Tropsch conversion without any carbon storage. Other cases examined include gasification, pyrolysis, and fermentation technologies. These methods produce a spectrum of fuels with varying strategies for carbon storage.

The information presented in this table draws from an array of sources to provide comprehensive background details. These sources include the GREET model, ongoing project announcements, and scientific literature.

Table 32. Fuel Options with a Pathway to Negative Carbon Intensity

Feedstock	Conversion Technology	Fuel	Carbon Storage	CI (gCO_2e/MJ)
Forest Residue	Gasification + FT	Diesel	none	5 to 25
Forest Residue	Gasification + FT	SAF	CCS	< -50
Forest Residue	Gasification + PSA	Hydrogen	CCS	< -50
Forest Residue	Pyrolysis	Diesel	BioChar	< -50
Ag. Residue	Gasification + FT, H2 Boost	SAF	CCS	< -50
Ag. Residue	Fermentation	Ethanol	Lignin Product	< -50

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