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FINAL PROJECT REPORT

California Biopower Impacts Project

Climate and Air Pollution Impacts of Generating Biopower from Forest Residues in California

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation and bring ideas from the lab to the marketplace. The CEC and the state's three largest investor-owned utilities—Pacific Gas and Electric Company, San Diego Gas & Electric Company and Southern California Edison Company—were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The CEC is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

California Biopower Impacts Project is the final report for the California Biopower Impacts Project (Contract Number: EPC-16-047) conducted by the Schatz Energy Research Center in partnership with Humboldt State University, the Natural Resource Spatial Informatics Group, the Consortium for Research on Renewable Industrial Materials, the Sierra Institute for Community and Environment, the Watershed Research and Training Center, and California State University, Chico. The information from this project contributes to the Energy Research and Development Division's EPIC Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the CEC at ERDD@energy.ca.gov.

ABSTRACT

California faces crisis conditions on its forested landscapes. A century of aggressive logging and fire suppression in combination with conditions exacerbated by climate change have created an ongoing ecological, economic, and public health emergency. Between ongoing commercial harvest on California's working forestlands and the increasing number of acres the state treats each year for fire risk reduction and carbon sequestration, California forests generate millions of tons of woody residues annually that are typically left or burned in the field, impacting air quality.

State policymakers have turned to bioelectricity generation as a key market for woody biomass in the hope that it can support sustainable forest management activities while also providing low-carbon renewable electricity. However, open questions surrounding the climate and air pollution performance of electricity generation from woody biomass have made it difficult to determine how best to manage the risks and opportunities posed by forest residues.

The California Biomass Residue Emissions Characterization (C-BREC) model offers a spatially-explicit Life Cycle Assessment framework to rigorously and transparently establish the climate and air pollution impacts of bioelectricity from forest residues in California. C-BREC has shown that the life cycle "carbon footprint" of biopower from residues of a majority of forest management activities ranges between that of solar photovoltaics and natural gas power. This variation stems largely from the heterogeneity in the fire and decay conditions these residues would encounter if left in the field. This report documents the methods and findings of the C-BREC model across recent forest treatments in California. C-BREC can be used to identify the locations and treatment types in which utilization of forestry residues offers climate and air pollution benefit and could be useful to state policymakers in shaping California's energy and forest management policies going forward.

For more information about the C-BREC model, see schatzcenter.org/cbrec/.

Keywords: Life cycle assessment, waste-to-energy, bioelectricity, criteria pollutant emission, greenhouse gas emission, wildfire risk mitigation, forest management, forest residue

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TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

Background

About one-third of California – 33 million acres – is forest land that provides enormous benefits to society, including clean water and air, habitat, recreation, natural resources, and jobs for many Californians. It also stores a vast amount of carbon acting as a critical buffer against climate change. Decades of aggressive fire suppression and intensive logging practices have caused much of the forest to become too dense and unhealthy. This, in conjunction with drought and hotter, drier, windier weather conditions brought on by climate change, has created increasingly severe wildfire conditions, leading to an ongoing ecological, climate, economic, and public health crisis on California's forested landscapes.

The state estimates that 15 million acres of forest need treatment, of which 2/3 is federal land and 1/3 private and other public land. In light of these conditions, California and the federal government have agreed to a target of treating one million acres of forest per year, with treatments such as thinning, reforestation, prescribed fire, and sustainable timber management. Such a massive effort will be required to restore forest health and resilience, reduce the threat of wildfire, and maintain the role of forests in mitigating and adapting to climate change.

This forest management activity, combined with the ongoing commercial harvest on California's working forestlands, generates millions of tons of wood waste, or "biomass residues" every year. The term "biomass" refers generally to organic material, and specifically here to woody material that can be burned or otherwise converted to create electricity. Forest biomass residue typically includes the small-diameter treetops and branches that are not part of the merchantable portion of the whole tree. These residues are typically left or burned in place, which impacts air quality, creates wildfire hazard, and leads to further ecosystem disruption. State policymakers have promoted the idea of using these woody residues to generate electricity (known as bioelectricity or biopower) in the hope that this could financially support sustainable forest management activities while also providing low-carbon, renewable power. However, there are legitimate concerns surrounding climate, air quality, and ecosystem health effects of many biopower options, making it difficult to determine how best to manage the risks and opportunities posed by forest residues.

Project Purpose

The California Biopower Impacts Project investigated many of the environmental, economic, and policy aspects of using forest-derived woody biomass residue for electricity and process heat generation. A key element of this research effort was the development of the California Biomass Residue Emissions Characterization (C-BREC) model, to transparently calculate the climate and air quality emissions of biopower from woody residues across the varying conditions and supply chains in California. In particular, the model can identify the geographic locations and forest treatment types in which use of woody biomass residuals offers the greatest climate and air pollution benefit to structure incentives accordingly.

Project Approach

The C-BREC model is a life cycle analysis tool, enabling transparent accounting for the greenhouse gas (GHG) and criteria air pollutant emissions associated with biopower generation from forest residues in the state. To run the model, a user must provide the following information about the system being used:

- Location of residue generation and use.
- Type of forest treatment being conducted (such as clearcutting or various types of thinning).
- The fate of biomass residues if not removed from the field after forest treatments were conducted (piled, scattered, or burned).
- Key supply chain characteristics such as any post-harvest treatment and energy generation technology.

The C-BREC model quantifies the emissions associated directly with a "use" case in which biomass residues are removed from the field for use in biopower generation and a "reference" case in which they are left in the forest. The use case includes emissions from collecting, processing, and transporting woody residues to the biopower facility, and converting them to electricity. The avoided emissions in the reference case represent three processes:

- Prescribed burning of residues at the completion of forest management activity.
- Decay extending for 100 years of material piled or scattered on the forest floor.
- Ongoing exposure to wildfire over a 100-year period.

For a given project profile, C-BREC reports net emission values for GHGs and criteria air pollutants. Pollutant species tracked include the following: carbon dioxide, carbon monoxide, methane, nitrous oxide, volatile organic compounds, oxides of nitrogen, sulfur dioxide, particulate matter, and black carbon.

Project Results

Modeling with C-BREC indicates significant variation in the climate and air quality performance of biomass electricity derived from residues of forest management in California. For material sourced from most forest management activities across the state, life cycle "carbon footprint" of this biopower ranges from comparable with that of solar photovoltaics on the lower end to comparable with that of electricity from natural gas on the upper end. Carbon intensity differs based on system variables such as forest treatment type, residue disposition (piled vs scattered), transport distance, and power plant technology as well as geographic characteristics such as tree species, decay rate, and wildfire probability.

The study found the following key climate impact results:

- There are almost no circumstances examined in which biopower from woody residues has a zero or net negative carbon intensity, with the possible exception of facilities employing efficient combined heat and power to offset natural gas heating alongside electricity generation.
- The carbon footprint of biopower is lower when the residues would have otherwise been burned in the field rather than left to decay.

- There is significant spatial variation in the carbon intensity of power generated from woody residues sourced from across the state's forestlands, driven primarily by geographic factors such as the tree species and size of the pieces of residue as well as the climatic drivers of both decay and wildfire emissions.

For criteria air pollutants, the research team found that removing residue from the forest generally reduces emissions over a 10-year period. This reduction is greatest where biomass would otherwise have been burned in the field. For residues that would otherwise have been left in the forest, the net effect of removal for biopower is mixed. For most of the air pollutants tracked by C-BREC, the emissions from the biopower case are less than those from wildfire over a 10-year period, leading to a slightly negative net emissions for biopower generation. The exceptions are oxides of nitrogen and sulfur dioxide, which are only present in the case removal and transportation of biomass to biopower facilities.

It is worth noting that while use of this woody biomass may reduce the total mass of criteria pollutants emitted per ton of residue, it also concentrates these emissions at the biopower facility, which may be closer to human populations. This report does not evaluate the human exposure to these pollutants, nor the equity of distribution of that health burden across populations. This is an important area for future research that will be enabled by the modeling tools and datasets developed by this project.

Knowledge Transfer

The C-BREC model offers the most rigorous and transparent accounting of the life cycle GHG and criteria pollutant impacts of forest residue-to-electricity systems to date. As discussed briefly above, C-BREC results reveal significant variation across energy supply chains, residue types, and geographies in California. Given this variation, the C-BREC model can be useful in shaping the biomass energy system and other uses for woody residues that maximize net benefits. The research team developed a simplified form of C-BREC online (see schatzcenter.org/cbrec) with a user-friendly interface requiring no specialized analytical skills to operate. The goal of this adaptation is to enable foresters, biopower facility operators, policymakers, and other stakeholders to calculate the impact of proposed actions and to evaluate the sensitivity of those impacts to different systems characteristics and model parameters.

The authors have engaged with policymakers and stakeholders in the forest products and energy sectors. They made dozens of presentations (such as to relevant state agencies, legislative staff, and research colleagues at national labs and universities) to explain the C-BREC model, describe its many possible applications, and summarize the results of the case study. They also disseminated findings through their participation in the California Biomass Working Group, the California Public Utilities Commission's Bioenergy Market Adjusting Tariff Technical Working Group, and the Joint Institute for Wood Products Innovation Forest Biofuel Working Group. The project was guided by interaction with a Technical Advisory Committee, consisting of expert representatives from government, utilities, industry, environmental non-profits, and scientific research institutions.

Benefits to California Ratepayers

The California Biopower Impacts Project has generated critical knowledge necessary to ensure that the biomass residue-to-energy economy in California develops in an environmentally sustainable fashion. This should help California achieve its interrelated goals for forest management, wildfire risk abatement, renewable energy, air quality, and climate. Using C-BREC to assess the life cycle emissions from forest residue biopower will help define an appropriate use for fuel from high-hazard zones, promoting a responsible wildfire prevention plan. Furthermore, establishing the true GHG impact of bioelectricity generation from forest residue will guide the extent to which California should depend on biomass to provide renewable power.

The C-BREC model offers the most rigorous and transparent accounting of the life cycle GHG and criteria pollutant impact of forest residue-to-electricity systems to date. It could be useful in shaping the biomass energy system and other uses for woody residues, enabling fuel treatment activities to be targeted to where they offer the greatest advantage. This would benefit Californians not only through climate and air pollution mitigation, but also by enabling policymakers to promote biopower systems specifically where they can offer enhanced forest management, fire risk reduction, rural economic development, and power grid resilience. For example, the model could be expanded to evaluate other use cases for woody residues. This would aid in shaping residue mobilization and conversion supply chains to minimize emissions by identifying what improvements will offer the greatest life cycle emissions reduction potential. In addition, it could be applied as a screening tool for programs that seek to manage forestlands for carbon sequestration and fire risk reduction, such as the California Department of Forestry and Fire Protection's Forest Health Grant program or programs seeking to provide low-carbon energy such as the Public Utilities Commission's Bioenergy Market Adjusting Tariff program and the Air Resources Board's Low Carbon Fuel Standard.

CHAPTER 1: Introduction

California faces a forest management crisis. Drought, pest infestation, and wildfire — all exacerbated by climate change — have led to increasingly challenging conditions on the state's forested landscapes. These risks are heightened by the overstocking of biomass on the landscape brought about by a history of intensive logging and aggressive fire suppression (Collins et al., 2014). *California's Forest Carbon Plan* (Forest Climate Action Team, 2018) identifies insufficient forest management activity rates, limited biomass processing and utilization infrastructure, and unprecedented deterioration of forest health as critical barriers to managing forests for resilience and net carbon sequestration.

Recognizing the significant ecological, economic, and health risks associated with this crisis as well as the potential of sustainable forest management to deliver climate change mitigation and adaptation through a single action, the state has prioritized funding for forest treatment. The California Department of Forestry and Fire Protection (CAL FIRE) has spent nearly $1 billion since 2014 through its California Climate Investments (CCI) program on sustainable forestry and wildfire management projects, (California Air Resources Board, 2021). This spending is expected to continue growing, as the state pursues its goal of treating 1 million acres of forestland annually.

This management activity, as well as the commercial harvests carried out annually on California forestlands, creates a new problem in the form of significant residual woody biomass that must be managed on-site. Woody residues from forest harvest and restoration activities in California are typically left or burned in the field. This residue disposal can impact air quality, create wildfire hazard, and lead to further ecosystem disruption. Despite the difference in impact between residues being burned vs left to decay, there is no systematic recordkeeping in California to determine the relative prevalence of these two outcomes. A related challenge faces the disposal of woody residues from agricultural production in the state. From 2005-2012, open burning of agricultural residue in the San Joaquin Valley had been reduced by more than 80 percent, but drought and the shutdown of six biopower facilities in the region led to a significant increase in open burning, bringing open burning back above 2005 levels. Most of this increase stems from disposal of biomass from pruning and removal of orchard trees. Under business-as-usual projections, open burning of agricultural residues—and the resultant emissions of health harming air pollutants—are expected to increase (Jessica Olsen, 2017).

Residues generated by forest thinning and fuels treatment as well as commercial forestry have the potential to be transformed from a waste stream into a renewable energy resource, broadly described as bioenergy. Biopower (or bioelectricity) is the generation of electricity from biomass. If managed properly, biopower can support sustainable forest management activities while also advancing California's Renewable Portfolio Standard goals. However, there are legitimate concerns surrounding climate, air quality, and ecosystem health implications of many biopower systems.

The California Biopower Impacts (CBI) Project has sought to rigorously and transparently establish the environmental performance of biopower from forest residues as well as investigate many economic and policy dimensions. Key project goals were to:

1. Assess and map technically recoverable forest biomass residue in California that could be used for electricity and heat generation.
2. Conduct a landscape-level assessment of the fire emission implications of forest residue removal.
3. Develop and implement the California Biomass Residue Emissions Characterization (C-BREC) Model to conduct life cycle assessment of the use of woody residues for biopower generation.
4. Characterize and report on key positive and negative environmental impacts of residual biomass removal such as changes to soil nutrient balance and carbon stock, and air quality effects from altered black carbon and criteria air pollutant emission profiles.
5. Assess the potential to offset residue mobilization costs for forest management activities through value added supply chains, post-harvest processing, payments for ecosystem services and similar structures.
6. Consolidate project results into actionable policy recommendations, and disseminate these recommendations to California stakeholder groups.

Detail on the approaches and findings for each of the above research goals across the CBI Project can be found in reports available at schatzcenter.org/cbrec/. This report focuses on the climate and air quality impacts of forest residue-to-electricity systems, as that is an area of great uncertainty and policy implication in California today. The climate performance of electricity generation from woody biomass residues can be quite variable, and there has been a great deal of debate in the academic literature as well as among state policy makers as to how to best account for these emissions. The core of the CBI Project effort has been development and implementation of the California Biomass Residue Emissions Characterization (C-BREC) Model, a life cycle assessment (LCA) framework specific to the use of California forest residues for electricity generation. This model, and the simplified web tool version that can be found at schatzcenter.org/cbrec/, enables robust and transparent accounting of the greenhouse gas (GHG) and air pollutant emissions associated with residual woody biomass energy systems in California.

CHAPTER 2: California Biopower Emissions Characterization Model

This chapter describes the methods used in the C-BREC model and its application to the case study evaluated. More detail on every facet of the model, including its structure, assumptions, and underlying data, can be found in the C-BREC model framework, which can be accessed at schatzcenter.org/cbrec/.

To evaluate the impact of a forest residue-to-electricity system, a C-BREC user specifies the following key system characteristics:

- Location of residue generation.
- Type of forest treatment activity being conducted and baseline residue disposition.
- Location of residue utilization.
- Reference fate of unremoved biomass (prescribed burn, left in place).
- Key supply chain characteristics such as biomass removal level, location of biopower generation, any post-harvest treatment, and end-use energy conversion technology.

For a given project profile, the C-BREC model generates an emissions time-series and reports net CO_2-equivalent (CO_2e) emission values for two different time-explicit climate metrics. It quantifies the emissions associated directly with a "use" case in which biomass residuals are mobilized from the field for use in a biomass energy supply chain, and a "reference" case in which they are not mobilized. The net emissions of the biopower system is the difference between these two fates for the same material. The use case includes emissions from collection, processing, mobilization, transportation, storage, and end-use. The reference case is made up of three distinct processes:

- Pile or broadcast burning of residuals in year-1.
- Decay extending for 100 years of material piled/scattered on the forest floor.
- Ongoing exposure to wildfire over 100 years.

Because there is no coordinated record-keeping of the prevalence and location of prescribed burning in California, the researchers modeled the carbon footprint of biopower for residues that would have otherwise been burned and those that would have been left in place. Where residues are left on site, they are decayed over time and exposed to wildfire. C-BREC models wildfire emissions in a probabilistic fashion for any given ton of biomass.

Other air pollutants, particularly those regulated under the Clean Air Act — commonly referred to as "criteria air pollutants" — have important human health and environmental impacts and can also be emitted, or mitigated, by the systems under consideration. Therefore, C-BREC also tracks the following gross and net air pollutant species:

- Volatile organic compounds (VOCs): for sources that report nonmethane hydrocarbons (NMHC) or nonmethane volatile organic compounds (NMVOC), these are aggregated under VOC.

- NO_X: nitrogen oxides.
- SO_X: sulfur oxides (as SO_2).
- PM_{10}: particulate matter less than 10 microns in diameter.
- $PM_{2.5}$: particulate matter less than 2.5 microns in diameter.
- BC: black carbon as a fraction of $PM_{2.5.}$

Most early LCAs of woody biopower made the simplifying assumption that CO_2 emissions from combustion of biomass (that is "biogenic" emissions) do not contribute to climate change because they represent a closed loop between biomass growth and fuel consumption. Using this assumption, these studies typically found significant net reductions in GHG emissions when biopower replaces fossil energy. One meta-analysis of 94 LCA studies of bioelectricity systems found only one case study which accounted for the climate change impact of biogenic CO_2 emission (Cherubini & Strømman, 2011). Other recent literature has called this assumption into question by pointing out that near-term emissions lead to increased climate forcing over policy-relevant time frames even if it is assumed that the CO_2 emitted is eventually re-sequestered in forest regrowth or as in the case of residues would have been emitted later by decay or wildfire (Brack, 2017; Buchholz et al., 2016, 2016; Cornwall, 2017; Sterman et al., 2018).

Emerging from this literature is the consensus that the comprehensive approach to LCA for biopower from woody residues is to quantify emissions—including biogenic emissions—from the use of residues and their counterfactual, or "reference," fate. However, while many recent studies have done so, these typically assume that all residues not removed for biopower will decay in place (Giuntoli et al., 2016; Gustavsson et al., 2015; Jäppinen et al., 2014; Madsen & Bentsen, 2018; McKechnie et al., 2011) and that this decay will occur at a single rate regardless of residue type or location (Giuntoli et al., 2016; Gustavsson et al., 2015; Madsen & Bentsen, 2018). This ignores the possibility of these residues being burned in place, either through a prescribed burn aimed at waste management or by subsequent wildfire (Buchholz et al., 2016; Ter-Mikaelian et al., 2015). In the few studies that have incorporated a burn counterfactual, it is typical to assume that biomass is completely consumed through prescribed burn, leading to instantaneous emission of all carbon present, plus additional forcing from a fixed amount of methane and nitrous oxide emitted by the fire (Liu & Rajagopal, 2019; Miner et al., 2014; Springsteen et al., 2011). This fails to account for the unconsumed fraction of biomass or the formation of recalcitrant char materials as well as the spatial and material-type variation in the dynamics of combustion (Ter-Mikaelian et al., 2015).

The C-BREC model improves on the existing LCA approaches by capturing the significant spatial and supply-chain variability in life cycle emissions where many prior analyses have evaluated a single case and assumed it to be broadly representative. It also assesses emissions transparently, providing a model that can be used to evaluate the sensitivity of results to various key input parameters and assumptions. Finally it is becoming increasingly clear that the timing of emissions must be considered in life cycle GHG accounting (Buchholz et al., 2016; Helin et al., 2013; Reid et al., 2020). Where many prior assessments of bioelectricity climate impact fail to do so, C-BREC applies time-explicit climate metrics and reports them per guidance by the United Nations Environment Programme / Society for Environmental Toxicology and Chemistry (UNEP/SETAC) Global Guidance for Life Cycle Impact Assessment Indicators (Levasseur et al., 2016).

There are several other models and tools in use today for which C-BREC provides complementary insights and with which this model could be productively integrated. One clear example is the Greenhouse Gas Regulated Emissions and Energy use in Technologies (GREET) model.[1] Developed by Argonne National Laboratory, the GREET model is a widely-used tool for LCA of bioenergy pathways. GREET's treatment of woody residues from forest management, however, is relatively simple and coarse, and the project team has been working with the GREET team to identify an opportunity to conduct model integration activities to enable GREET to draw on the detailed residue base and counterfactual fate modeling in C-BREC. In a similar vein, the Feedstock Production Emissions to Air Model (FPEAM),[2] developed by the National Renewable Energy Laboratory, provides detailed assessment of criteria pollutant emissions across bioenergy supply chains. Like GREET, it does not assess the counterfactual emissions from forest residues in detail, making intercomparison and integration with C-BREC a promising possibility.

The State of California also recently supported the development of a related model, CALAND (Di Vittorio et al., 2021). CALAND estimates the effects on the landscape carbon budget in natural and working lands from a suite of land management practices designed to reduce GHG emissions or increase carbon storage. While CALAND does include a biopower pathway, it does so in a simplified, uniform fashion, whereas C-BREC provides detailed analysis of the impact of residue mobilization and use. The two models could be linked to provide a more complete analysis of the carbon effects of forest/land management strategies and the biopower pathway.

Biomass Residue Base

The residual biomass resource base of interest is from forestry activity in California. C-BREC categorizes forest treatments into thirteen different types, covering most common forestry activities as defined by California Forest Practice Rules (California Department of Forestry and Fire Protection, Resource Management, Forest Practice Program, 2017). The harvest activities modeled are:

- Clearcut.
- Thin from below (selecting for small-diameter trees) removing 20, 40, 60, and 80 percent of total tree basal area. A sample of this residue base is shown in Figure 1.
- Thin from above (selecting for large-diameter trees) removing 20, 40, 60, and 80 percent of total tree basal area.
- Proportional thin (select equally across small and large diameter trees) removing 20, 40, 60, and 80 percent of total tree basal area.

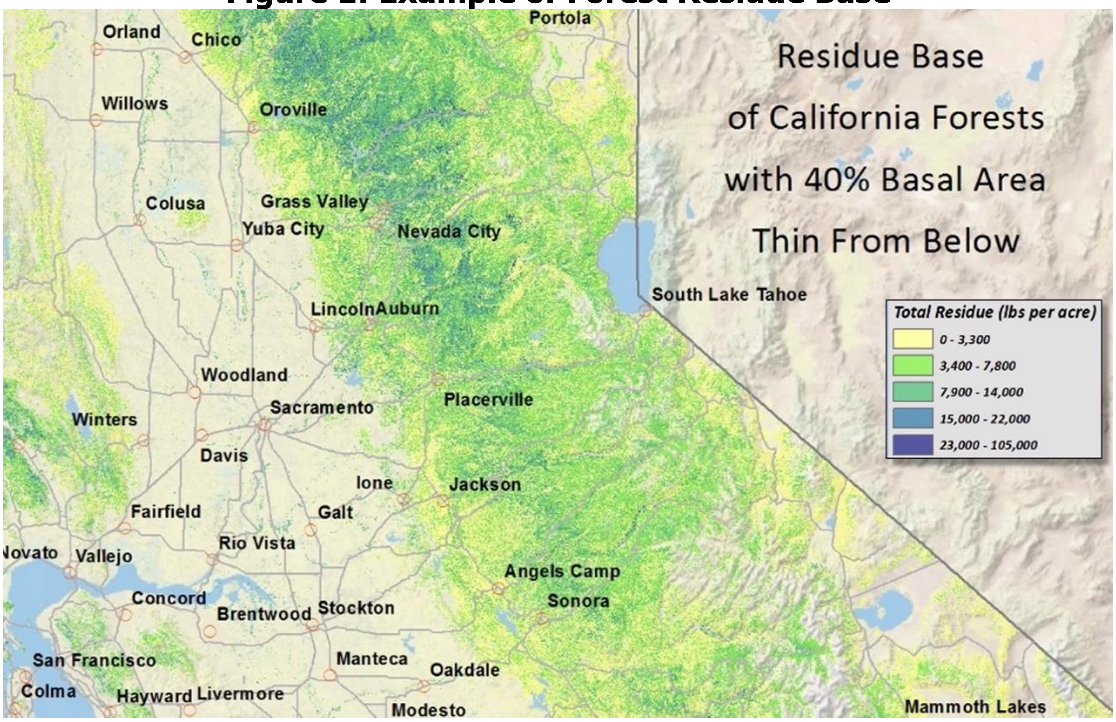
For each of the above forest harvest activity types, total recoverable biomass residue resource base was modeled at 30-meter grid resolution, divided by residue type and size class. Forest parcels were characterized based on tree list inventory (GNN) data produced by the Landscape

[1] https://greet.es.anl.gov/

[2] https://www.nrel.gov/analysis/biofuels-emissions.html

Ecology, Modeling, Mapping and Analysis (LEMMA) group at Oregon State University.[3] These data were updated in California with timber harvest, fire, tree mortality events, and growth, occurring between 2012 and 2017 using the Forest Vegetation Simulator. Forest data were combined with parcel and riparian management zone data to create a spatially explicit database of forest condition, owner class, and management zone. Tree component biomass for stems, bark, branches, foliage, and roots were calculated by applying national biomass estimators (Jenkins et al., 2003) and the U.S. Forest Service's Forest Inventory and Analysis (FIA) component ratio method to the tree lists. C-BREC also accounts for the difference in decay and fire behavior across material size classes and disposition (scattered or piled). A given residue base is therefore modeled at 0 percent, 30 percent, 50 percent, and 70 percent piled disposition to account for this variability.

Figure 1: Example of Forest Residue Base



Example residue base data layer across a section of California. This map presents the residue resulting from thinning activity removing 40 percent of total standing basal area from below (that is, selecting for smaller diameter trees). Modeled at 30-meter spatial resolution.

Source: Schatz Energy Research Center, 2018

Scope and System Boundary

A key question underpinning LCAs for uses of forest residuals is how to account for the emissions associated with the primary forest management activity that generated those residues, and for any change in forest carbon stock or flow rate driven by that forest management. A common approach in LCA is to allocate any "upstream" emissions to the different products emerging from the system (often called co-products) on the basis of their relative economic value. In a case where sawtimber and pulpwood are being harvested from the same forest, if sawtimber represented 50 percent of the value derived from a landscape

[3] https://lemma.forestry.oregonstate.edu/data

and pulpwood the other 50 percent, one would allocate half of the emissions associated with the primary forest management activity to the lumber and half to the pulp.

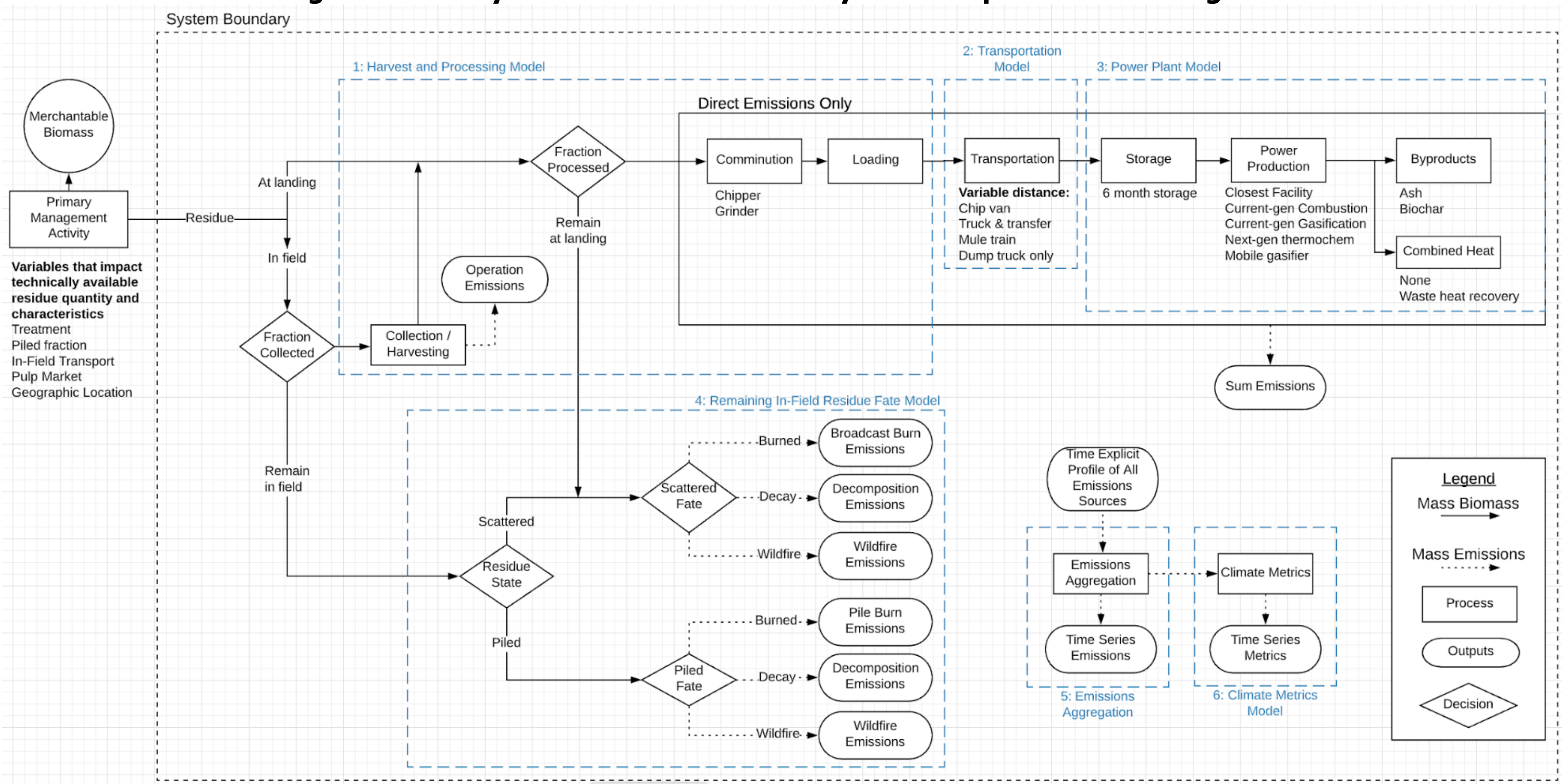
In California, primary forest management activities are conducted to extract sawtimber, improve forest health, or reduce wildfire risk. The branches, treetops, and foliage that comprise the harvest residue base are typically left to decay or are burned on site. Since the residues represent none of the net economic value derived from the primary management activity, they are considered a “true waste” and are allocated none of the emissions or sequestration associated with that activity. As such, C-BREC does not allocate any of the primary harvest emissions (those emerging from the harvest activity itself) - nor any of the forest carbon stock and flow implications of the primary harvest - to the biopower pathway.

This is made slightly more complex by the fact that fire risk reduction and forest carbon sequestration are not conventional financial products, meaning that conventional value-fraction-based co-product allocation is not possible. However, when an entity (usually the government) pays for forest management to reduce the risk of a catastrophic wildfire, it is paying for the "product" of fire risk reduction, not for the residue that will be produced by that activity. These residues currently bear no market value as revealed by the fact that they are not currently removed from the field, and in fact represent a net expense to land owners. In circumstances where residues are purchased by an entity that has been subsidized to accept this material, this is not considered a true economic value of the residue, but rather a subsidy for the primary treatment via a different market pathway.

As emissions associated with primary forest management decisions are excluded from this analysis, the LCA of the harvested residues covers only those emissions directly related to their removal (use case) or to their retention on the landscape (reference case). As indicated in Figure 2, this includes emissions associated with:

- Collection, processing, transportation, storage, and conversion of biomass residues into electricity.
- Controlled burn of residues (pile and broadcast burning).
- Decomposition of any remaining residues out to 100 years.
- Exposure of any remaining residues to wildfire.

Figure 2: Life Cycle Assessment Boundary and Component Flow Diagram



Mass flow diagram of the C-BREC forestry model analytical framework

Source: Schatz Energy Research Center, 2018

Residue Mobilization and Use

C-BREC users are able to specify treatment type, harvest practices, feedstock collection and handling methods, post-harvest treatments, feedstock management pathways, conversion technologies, and other characteristics. Mobilization and conversion of biomass residues into electricity are covered in the following three steps:

- *Collection and Processing*: This includes emissions from fuel use associated with gathering, handling, and loading the residues from their initial piled or scattered disposition into the processing stage followed by comminution (chipping or grinding), hauling to a transfer point, then loading onto hauling equipment. These steps include both fixed and variable emissions. Fixed emissions are associated with bringing collection and processing equipment to the field and do not vary by treatment size or total residue base. Variable emissions represent the operation of collection and processing equipment and off-road haulers and loaders, and therefore are quantified as mass of emissions per bone-dry metric ton of biomass. All variable emissions are a function of terrain steepness, residue density (tons per acre), residue type and disposition, forest density, residue cleanliness, and moisture content.
- *Transportation*: Round-trip travel of hauling processed residues between the transfer point and the power plant. The vehicle type used in a given harvest scenario is a function of residue type, amount, and ease of access. Emissions from transportation vary by vehicle type and depend on the distance to the power plant, characterized in C-BREC for either the nearest existing biomass power facility to a given harvest site or a user-specified distance to the use location. Hauling trips are either volume or weight-limited based on moisture content.
- *Energy Conversion*: Operations and production of electricity at a power plant. C-BREC is parameterized with specifications and performance of existing, generic, next generation, and novel biomass power plants. Specifications of existing power plants in California are based on data reported to the California Energy Commission and California Air Resources Board. All other power plant specifications are derived from literature. Emissions are based on a specific existing generator or one of a set of "generic" facility types - current generation combustion plant, next generation integrated gasification/combustion plant, next-generation thermochemical gasification facility, and small (<1 megawatt) mobile gasifier/generator. Facility performance is also a function of the energy density of the specific biomass type (for example tree species) at a given treatment location. Energy content is reduced via dry matter loss over a variable storage period prior to combustion in the power plant.

Reference Biomass Fate

The “reference case” or “counterfactual fate” of the biomass describes the emissions associated with a given ton of biomass residue if it is not removed from the field for energy production.

Modeling Emissions from Fire

Emissions from wildfire and prescribed burns of forest residues are modeled using the "activity" fuels equations from the Consume software, version 4.2, created by the U.S. Forest Service (Prichard et al., 2006). The activity fuels equations were developed for fuels that were "resulting from or altered by forestry practices such as timber harvesting or thinning" (Prichard et al., 2006), and are thus directly applicable to this use case. The activity fuels equations calculate consumption and emissions estimates for scattered (that is, non-piled) fuels. These equations provide estimates of fuel consumption for each fuel size class, weighted by combustion phase: flaming, smoldering, and residual. The consumption estimates are then multiplied by emission factors specific to each emissions species (for example CO, CO_2) taken from the Bluesky modeling framework (Larkin et al., 2010).

Fuel Characteristic Classification System (FCCS) (Riccardi et al., 2007) data are used to represent the initial fuel loads. FCCS data are available in raster format through Landfire.gov. Additional fuel loading resulting from treatments is derived from the CBI Project's biomass resource base projections and is added to the original fuel loading data. The emissions impact of residue removal was estimated by running Consume with and without this additional fuel on site. Fuel consumption and emissions estimates are delivered in spatially explicit (raster) format for integration into the C-BREC model framework.

Both emissions and fire behavior models require inputs for fuel moisture and mid-flame wind speed. To characterize these parameters, C-BREC uses 4 km resolution GRIDMET gridded surface meteorological data set (Abatzoglou, 2013; Abatzoglou & Brown, 2012) augmented with additional fuel moisture parameters (Cohen & Deeming, 1985) and treatment-specific wind adjustment factors (Andrews, 2012). For wildfire simulations, 97th percentile conditions are assumed for all climate variables spanning the months of June through September for all years from 2000 to 2017. For prescribed fire simulations, the model assumes 37.5th percentile conditions for all climate variables constrained to September and October (the typical fall prescribed fire season) from the same time period. For material burned in piles, the researchers assume the 90 percent consumption rate that is the CONSUME default. For scattered material, consumption rate varies as a function of fuel moisture and fire weather.

The approach described above enables us to model the emissions from a wildfire if it were to occur on the landscape at any point in the next 100 years, both with and without forest residues left in the field. However, it is of course not possible to predict when a fire will occur at a given site. C-BREC therefore annualizes emissions from wildfire at each location in each year by taking the product of the expected emissions from a wildfire in that year and the probability of it occurring — each of which changes over time. This quantifies the expected annual emissions from wildfire *on average,* which is accurate at a landscape scale, but will differ from actual emissions at any specific site, where wildfire will occur at a single point in time rather than spread over time on a probabilistic basis. Current and projected wildfire probability in California is derived from the Cal-Adapt dataset[4] (Westerling, 2018). For the future wildfire probability projections, C-BREC uses the HadGEM2-ES (Warm/Drier) climate model results with representative concentration pathway (RCP) 4.5 emissions trajectory and business as usual population growth assumptions.

Decomposition

As is typical in the LCA literature on solid biomass (Giuntoli et al., 2016; Gustavsson et al., 2015; Madsen & Bentsen, 2018) C-BREC characterizes decay using a negative exponential model (Olson, 1963). The literature on biomass decomposition identifies three main drivers for

[4] cal-adapt.org/tools/wildfire

decay rate variability: species composition, size class and disposition of material, and climatic factors. As such, C-BREC models these decomposition mechanisms using annual decay constants that vary across these parameters (Blasdel, 2020). An example of the spatial variability of decay factors for forest material is shown in Figure 3.

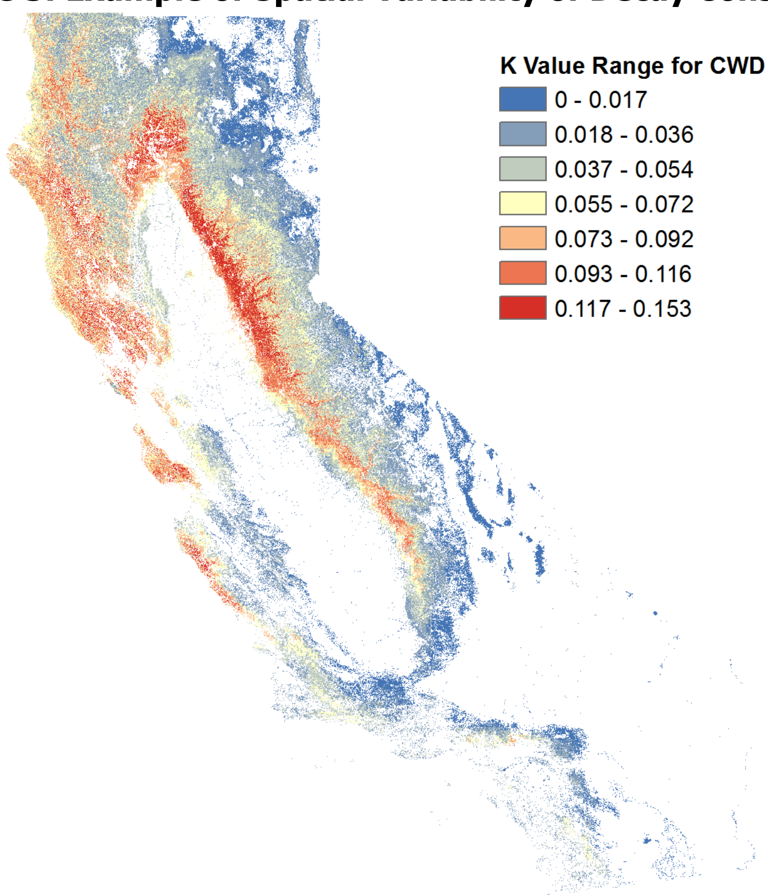
Species Composition

An array of primary literature sources and meta-analyses (Laiho & Prescott, 2004; Mackensen & Bauhus, 1999; Weedon et al., 2009; Yin, 1999) was used to develop a database of average residue decomposition constants varying by species and size class at a given location as described in (Blasdel, 2020).

Size Class and Disposition

Decomposition rate of biomass in the forest varies by size class and between scattered and piled material (Edmonds et al., 1986; Erickson et al., 1985; Wagener & Offord, 1972), with material in contact with the ground exposed to conditions and organisms that hasten decay. Where material is piled, these piles are assumed to be of a consistent size and geometry, and the bottom fraction of the piled mass is treated as though it were scattered because it is in contact with the ground.

Figure 3: Example of Spatial Variability of Decay Constants



Decay rates (k) for coarse woody debris (CWD) across the forestlands of Northern California. Fine woody debris decay exhibits a similar spatial pattern.

Source: Schatz Energy Research Center, 2019

Climate

Temperature and moisture are the two most important climatic factors affecting the decay of biomass (Sierra et al., 2015). Temperature controls the rate of heterotrophic cell respiration while moisture can be a limiting factor for decay if material becomes too dry. To capture these effects in C-BREC, a mechanistic model is used to alter the exponential annual decay constant in a given area based on the recent historical record of temperature and soil moisture at that site. A variation on the Demeter equations for climate effects (adapted from (Foley, 1995) was used to derive a climate modifier for decay as a function of temperature and moisture. The decay rate for each 30x30 m grid cell is determined by the average of the climate-modified decay rates for each species present weighted by that species' fraction of total tree biomass in that cell (using the proxy of aggregate trunk diameter by species).

Scenario Case Pairings

As described, residue from a given forest treatment in C-BREC is modeled at 0 percent, 30 percent, 50 percent, and 70 percent piled disposition to account for the variability in forest harvest and residue management practices. A forest manager then faces three options: remove the residue for bioelectricity generation, burn it, or leave it on site. In the use case, C-BREC models removal of piles only and removal of all technically recoverable biomass. For prescribed burn reference cases, these pile fraction and removal types influence the type of burn that is allowed to occur because the model assumes the residue removal and the counterfactual prescribed burn are intended to target the same material. Where only piles are removed in the use case, C-BREC assigns a pile burn as the reference case prescribed burn option. Where all technically recoverable material is removed in the use case, C-BREC models pile (if piles are present) *and* broadcast burn prescription as the reference case. Where no piles are present, C-BREC models a broadcast burn. Land managers typically either collect residue *or* conduct a prescribed burn, and C-BREC therefore does not allow prescribed burns in the use cases.

Accounting for Time

A key challenge in the emissions accounting for the framework described here is the fact that bioelectricity emissions occur in one pulse at the time of primary treatment (year zero), whereas the emissions associated with the reference fate of the biomass may occur slowly over decades of biomass decay or in some future year via wildfire. Just as financial accounting must consider the time value of money in comparing expenses or revenues at different points in time, rigorous LCA must account for the "time value" of emissions or sequestration over time in terms of their differing climate forcing effects on policy-relevant timescales.

Life cycle impact assessment in the C-BREC model uses an "emissions scenario" approach as discussed by (Myhre et al., 2013), elaborated on by (Aamaas et al., 2012), and recently implemented in several publications related to the emissions profile of biomass energy (Giuntoli et al., 2015). The result is a time-explicit absolute GWP (AGWP) and absolute GTP (AGTP) that approximate the global aggregate radiative forcing and temperature response, respectively, to a time-explicit emissions profile generated by C-BREC. The model uses these to calculate the CO_2 equivalent emissions for reporting all emissions on a uniform basis - that is the emission mass of CO_2 in year 1 that would yield the same AGWP and AGTP in year 100. This mirrors the approach taken by the Intergovernmental Panel on Climate Change (IPCC) in its calculation of CO_2 equivalent GWP values for different GHGs, except applied across time as well as across emission species.

The GWP-based metric evaluates the aggregate climate forcing experienced by the planet in the 100-year period. Since most policy analysis in California is conducted on the basis of 100-year GWP, (though typically only for normalizing across different GHGs, not across emission timings), most of the results in this report use the GWP-based approach. However, the GTP-based metric is also useful, evaluating how much hotter the climate will be 100 years in the future due to a given emission trajectory. As this is concerned with the state of the climate 100 years from now, it should be considered as a long-term metric for climate impact. Both of these metrics are useful, as both prioritize different considerations.

If policy-makers are concerned primarily about the long-term temperature of the climate system, making decisions on the basis of the GTP may be rational. However, this analysis considers one-time activities whereas forest and residue management decisions will in fact be made year after year. Moreover, some impacts of climate change — such as the loss of biodiversity — may not be reversible if global temperatures rise and subsequently fall. As such, policy made on the basis of the GWP is also a sensible approach. Rather than choosing one of these metrics, C-BREC models both to offer the most possible information and flexibility. This approach is aligned with the guidance put forth by UNEP/SETAC (Levasseur et al., 2016) and taken up by ISO standard for Life Cycle Assessment (ISO 14067:2018, 2018).

Note on Electric Power Displacement

All the carbon intensity figures presented in this report are total emissions from bioelectricity generation net of emissions from the counterfactual fate of the same biomass. However, they are gross emissions for the generation of the bioelectricity and are not credited for the avoided emissions from other sources that might be offset by bioelectricity. Biopower can operate as base load generation and can be ramped in response to intermittent renewable generation causing some analysts to assume that it is displacing natural gas power. Others point to the fact that biomass can be used in existing stoker power plants to directly displace coal. However, California utilities are also bound by renewable portfolio standard obligations to buy a certain amount of renewable electricity, so biomass could also be said to be displacing other renewables. Ultimately, the marginal power source displaced by biopower generation will be a function of local and regional power system economics and policies, which are shifting constantly. These shifts do not, however, change the emissions associated with biomass mobilization and power generation. As such, C-BREC reports the emissions from bioelectricity generation absent any assumptions about power grid and market operations, allowing policy makers and other analysts to evaluate these emissions in whatever context they deem appropriate.

California Biomass Residue Emissions Characterization Model Code and Web Tool

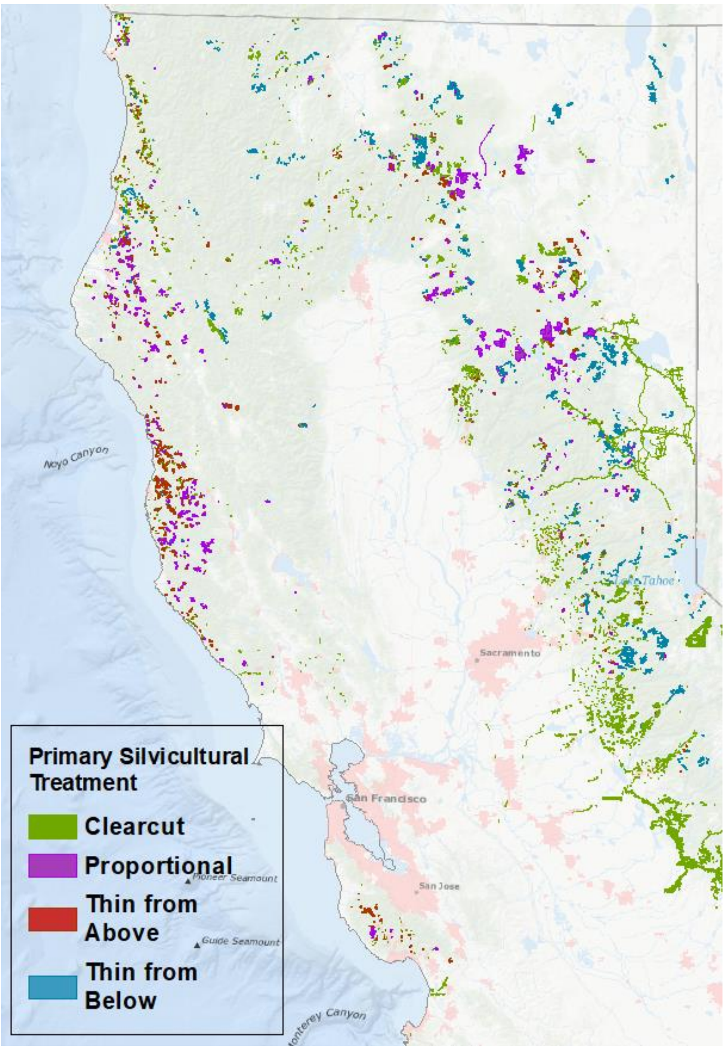
The C-BREC model enables robust, transparent accounting for the GHG and air pollutant emissions associated with residual forest biomass energy systems in California. It offers a high degree of spatial resolution. This open-source model is built using the R programming language and is available on GitHub. A limited version of the model is available for exploration via an interactive web tool. The web tool allows a user to identify a specific project area in

California and specify the key project characteristics for the use and reference fates, producing a report of biomass residue harvested, electricity generation, and net emissions. Links to the webtool and the GitHub repository for the model code and can be found at schatzcenter.org/cbrec/.

CHAPTER 3: California Biomass Residue Emissions Characterization Model Results

The C-BREC model can evaluate the impact of residue use from any forestry activity type on any forested landscape in the state. However, to investigate the range of results it generates, this report focuses on a case study of the actual treatment activities conducted in California in the years 2016-2019 (Figure 4). The results of that analysis shed light on the variable environmental performance of biomass electricity systems in California, and also the drivers of that variation.

Figure 4: Forest Treatments in California From 2016 - 2019



The 11,035 individual forest treatment activities that make up the case study detailed in this chapter. This map focuses on the northern region of California as it contains the majority of the working forests in the state and therefore almost all of the treatments evaluated for this study.

Source: Schatz Energy Research Center, 2021

To evaluate trends, the figures in this results section isolate many of the system configuration variables in C-BREC to explore the impact of others. For this report, except where otherwise noted, the following base case parameters are used for all of the systems under consideration:

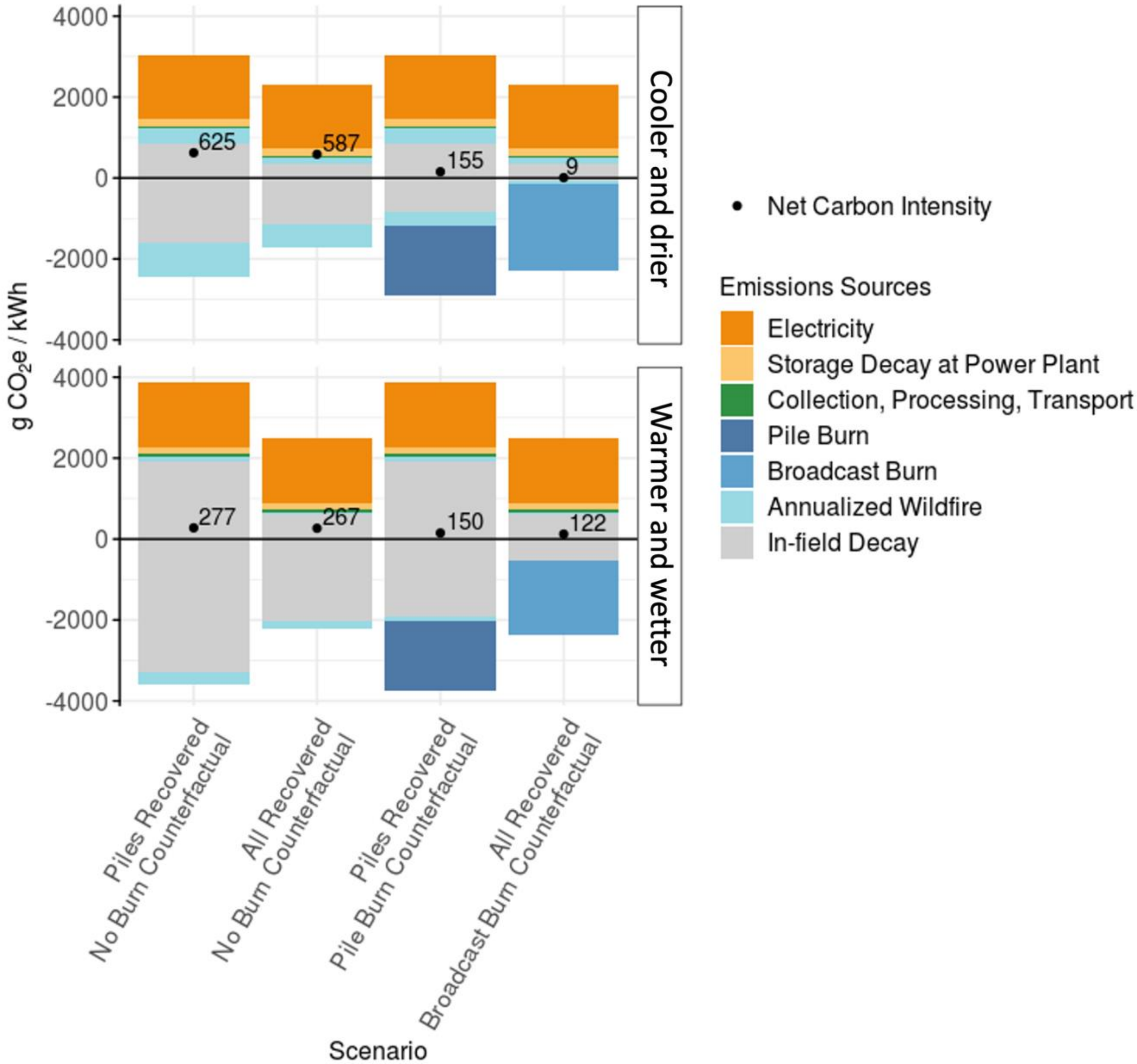
- Biopower is generated using a current-generation combustion plant of statewide average efficiency without combined heat and power (CHP) capability.
- Biomass collection is carried out using a large harvest equipment system and comminution conducted on dry wood using a grinder.
- Residue is hauled 50 km to the power generation facility.
- Emission time series are normalized to CO_2e using 100-year GWP equivalencies as discussed.
- Results are filtered to remove unrepresentative outliers, such as treatments in which <1 metric ton of total residue is estimated to be present and which are therefore unlikely to be mobilized for bioelectricity generation.
- All pile burn emissions assume material is very dirty which impacts the emissions factors assumed.

Net Carbon Intensity Results

Figure 5 illustrates the relative roles of the different contributors to reference and use-case emissions and how these vary by collection and burn scenario as well as across different climate zones in California. Use-case emissions from residue mobilization and use are arrayed above the x-axis, where reference-case emissions from the counterfactual fate of the same biomass are arrayed below the x-axis as these represent "negative" emissions, avoided by residue mobilization. The difference between the two cases is net emission from bioelectricity generation and is indicated by the black point in each column.

Figure 5 illustrates some expected, and some unexpected, trends that are being quantified by C-BREC. For example, biomass left in the field in a relatively warmer/wetter climate (below the x-axis for the "no burn counterfactual" scenarios) exhibits more emission from decay but less from wildfire than in a relatively cooler/drier climate owing to the climatic drivers of decay rate and fire return interval. In addition, warmer/wetter conditions generally lead to less complete consumption of scattered residue in a broadcast burn (far right) than is evident in relatively cooler/drier conditions. In all cases the pile-only collection scenario appears larger in both reference and use cases. This is because these emissions are calculated for the entire residue base and reported per kilowatt-hour (kWh) of power generated. Where only piles are collected, there is less total power generation, so the emissions per kWh are larger. The uncollected material is present in both use and reference cases, however, so these emissions cancel one another out when calculating net carbon intensity.

Figure 5: Example of Gross and Net Carbon Dioxide Equivalent from Mobilization of Forestry Residues



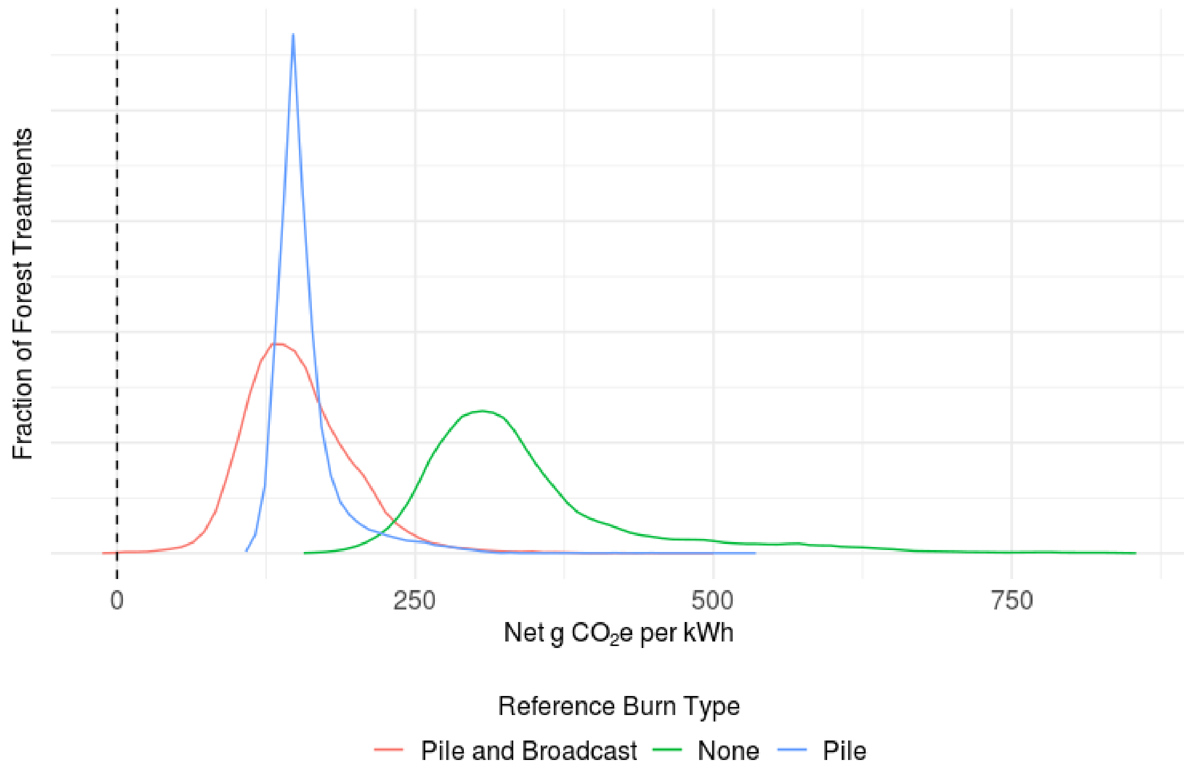
Example emissions from each source for four collection and burn scenarios in both use case (above the x-axis) and reference case (below the x-axis) at two treatment sites in California representing two different climatic zones. Net emissions from biopower generation is the difference between the two cases and is indicated by the black point in each column. All emissions are in present-day CO_2e, normalized based on 100-year GWP.

Source: Schatz Energy Research Center, 2020

The emissions displayed represent a specific and limited set of scenarios to illustrate different emission sources and variations. Model results vary across system characteristics such as forest treatment type, residue disposition, transport distance, and power plant technology as well as geographic characteristics such as residue species, decay rate, and wildfire probability. As such, considering the distribution of carbon intensities across the treatments conducted from 2016 to 2019 in California allows a better understanding of the sources of this variation and the sensitivity of biopower carbon footprint to various system characteristics and model assumptions. This provides useful insight in shaping forest and bioelectricity policy and industry going forward. Figure 6 displays the distribution of outcomes across the scenarios considered for biopower generation from the residues created by permitted forest harvest and treatment activities conducted in California in the years 2016 through 2019.

While the fate of residues from these treatments is not known, Figure 6 displays the carbon intensity of the resultant electricity if they had been mobilized for power generation. It is clear that a major driver of the net carbon footprint of biopower from woody residues is the counterfactual (or "reference") fate of the biomass - that is, whether it would have been burned or left to decay on site. As the prevalence of prescribed burning in California is not consistently tracked, the research team modeled the carbon footprint of biopower assuming several different counterfactual fates for the biomass. These different assumptions are presented as different curves on Figure 6, representing the range of possible carbon intensities for this biopower. Figure 6 and many of the following distribution figures are smoothed histograms, with carbon intensity displayed on the horizontal axis and relative prevalence of a given range of results represented on the vertical axis.

Figure 6: Net Carbon Dioxide Equivalent Intensity Results for Generic Current Generation Combustion Power Plant



Distribution of carbon intensity results (net g CO_2e/kWh) across the California recent treatments dataset disaggregated to illustrate the difference across reference case burn scenarios.

Source: Schatz Energy Research Center, 2020

In the interest of situating these values in context, note that Carnegie Mellon University calculated the US grid average carbon intensity to be 366 grams/kWh in 2020 and California's grid average at 175 grams/kWh.[5] However, it is important to note that the Carnegie Mellon analysis cited above only includes *direct* (scope 1) GHG emissions. As such, it counts sources such as solar, wind, and hydropower as having a carbon footprint of zero. The *life cycle*

[5] Scott Institute for Energy Innovation. (2020). Power Sector Carbon Index. Carnegie Mellon University, Pittsburgh, PA. Retrieved from https://www.emissionsindex.org.

carbon intensity of average power generation in the U.S. and in California is higher than reported above.

Because these figures display net emissions, higher emissions in the reference case (that is, the counterfactual fate of the residues) lead to lower values here because more of the mobilization and combustion emissions in the use case are "offset" by the counterfactual outcome. It is clear that the prescribed burn scenarios (that is, those in which residues would be burned if not mobilized for biopower generation) have a lower net biopower carbon intensity than the no-burn cases because they have higher reference-case emissions offsetting those in the use case. The research team found almost no circumstances under business as usual in which biopower from woody residues has a zero or net negative carbon intensity.[6] This is because the avoided emissions of methane and N_2O that can emerge from prescribed burns are typically more than offset by the fact that those burns do not completely consume the residue, leaving uncombusted wood and char material in the field.

The shapes of the different distributions are also instructive. Scenarios in which only piled material would be collected, and a pile burn is therefore the reference fate (blue curve), exhibit the least variability. This is because pile burns are relatively uniform in their combustion dynamics. In broadcast burning (red curve) more wood is exposed to fire, but the dynamics of that fire vary significantly across residue types and conditions. At the opposite extreme, the greatest variability is evident in the "no burn" cases where residues would be left in place if not removed (green curve). The climate, species, and treatment-type drivers of decay as well as the conditions and frequency of wildfire lead to variable emissions in the reference case, and therefore a large spread in net emissions for biopower generation.

In addition, long "tails" are evident, especially in the no burn scenario distribution, with a small number of cases showing carbon intensities reaching out towards 1,000g CO_2e/kWh. These outlier treatments are predominantly those with very low total residue base and/or very low residue density (T/ac). In such cases, the fixed emissions associated with mobilizing collection equipment to field locations can become a dominant source of greenhouse gas emissions since these emissions are distributed across a very small number of total kWh. In addition, these low residue densities tend to occur in areas where climatic factors such as low rainfall rate yield not only low biomass production but also very low decay rates and therefore a larger climate impact from burning wood that would otherwise have been left in situ. These outlier cases are likely not logistically or economically viable for residue mobilization and use but are worth noting as they may occur where residue removal rather than prescribed burn or scatter is deemed necessary, such as in roadside clearing.

As discussed, the single largest driver of the net carbon intensity of biopower from woody residues is the counterfactual fate (displayed as different colored curves in Figure 6). However, there is also significant variation within each of those curves. This variation is largely driven by geographic factors such as the species and size class characteristics of the residue base as well as the climatic drivers of decay and wildfire emissions. Mapping the net emissions from biomass use (Figure 7) allows these geographic variations to be assessed. Each map displays the variation across treatments conducted from 2016 to 2019 in California.

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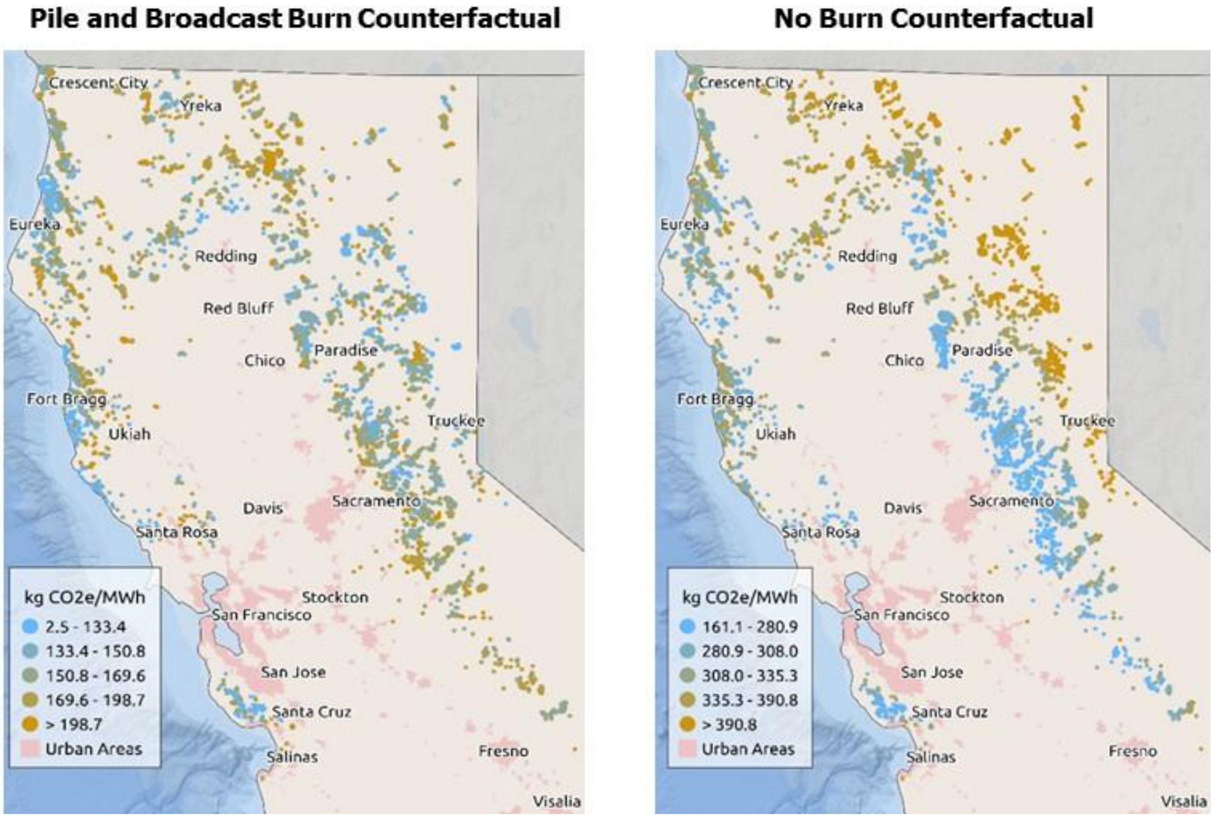
[6] With the possible exception of a facility employing efficient combined heat and power to offset natural gas heating

Figure 7: Example Spatial Variability of Biopower Carbon Intensity



Carbon intensity for two specific scenarios mapped across California to illustrate the spatial variation in results in a given scenario (within each map) and how it is influenced by the reference burn scenario (across the two maps). All results assume 50 percent of residue is piled and all technically recoverable residue is mobilized in the use case.

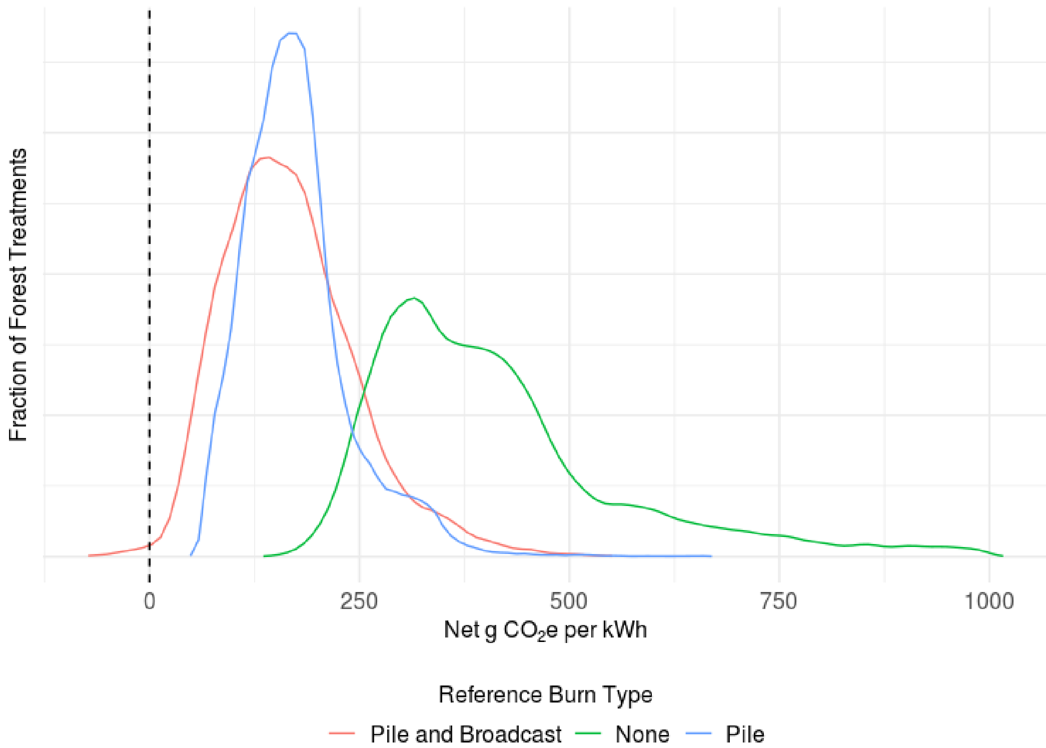
Source: Schatz Energy Research Center, 2020

The map on the left displays the range in carbon intensity of biopower generation from forest treatment residue if that residue would otherwise have been subject to a prescribed burn. The spread in carbon intensity stems from variation in emissions from prescribed burning owing to residue species, size class distribution, and climate. The map on the right displays the range in carbon intensity of biopower from residues of the same treatments if those residues would otherwise have been left in place, subject to decay and wildfire. The spread in carbon intensity stems from climatic and residue type variables driving differing decay rates and wildfire probability.

Most of the figures in this report characterize net emission distributions for woody residues if converted to biopower in a generic current-generation combustion plant and a uniform distance of 50 km from the forest treatment. This enables investigation of the variation stemming from feedstock type, source location, and counterfactual fate. However, C-BREC is populated with the location, efficiency, and emission characteristics of all existing biopower facilities in California.

Figure 8 displays net emissions intensity distributions comparable to those shown previous figures, but with residues sent to the *nearest existing* biopower facility.

Figure 8: Net Carbon Dioxide Equivalent Intensity Results for Existing Power Plants



Distribution of carbon intensity results (net g CO_2e/kWh) across the California recent treatments dataset if used in the nearest biomass power facility — disaggregated to illustrate the difference across reference case burn scenarios.

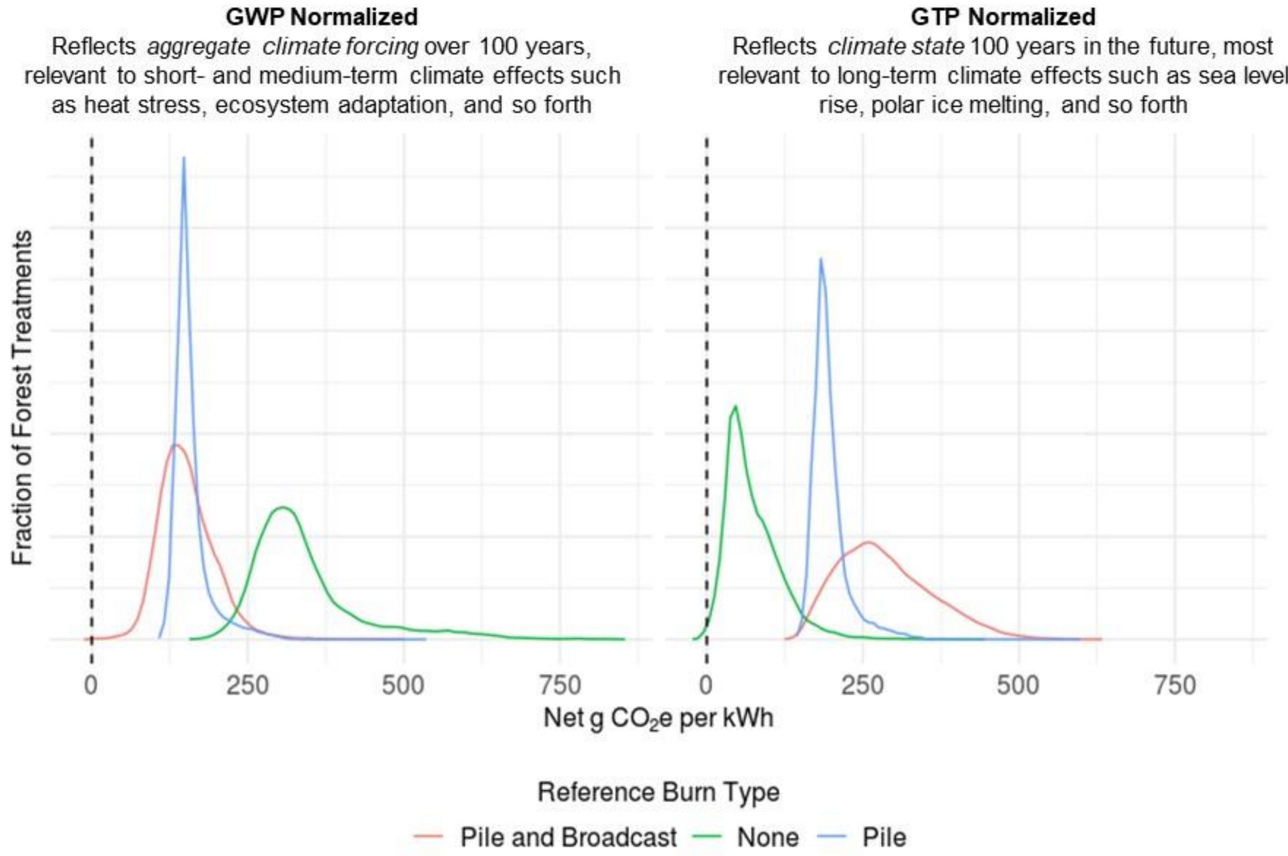
Source: Schatz Energy Research Center, 2021

This leads to more skewed carbon intensity distributions, with longer "tails" evidencing more high-intensity outliers. This is attributable to the fact that some treatments occur much more than 50 km from the closest biopower facility, leading to higher transport emissions, and some biopower facilities have much lower thermodynamic efficiency, leading to higher emissions *per kWh generated*.

Investigating Different Climate Metrics

The C-BREC model can calculate carbon intensity values for biopower generation using two different climate metrics. These differ in how they account for the present-day CO_2e of a modeled emissions time series. The first alternative — and that which is used in the results reported above—is to normalize emissions based on the 100-year GWP. In this case, C-BREC calculates the present-day emissions of CO_2 that would yield the same aggregate radiative forcing over a 100-year time period as the GHG emission trajectory in question and reports that as CO_2e. Because this is an aggregate metric, it is often considered the relevant approach to evaluating near and medium-term climate impacts. Another alternative is to normalize emissions using the GTP. As this approach is an instantaneous metric, and therefore concerned with the state of the climate in 100 years but not any intervening warming, it is often considered the relevant approach for evaluating long-term climate impacts (Levasseur et al., 2016). Figure 9 displays the distribution curves for net carbon intensity across the California recent treatments dataset broken out by reference biomass fate in both GWP- and GTP-normalized CO_2e.

Figure 9: Net Carbon Dioxide Equivalent Intensity Results for Global Warming Potential and Global Temperature Potential



Distribution of carbon intensity results (net g CO_2e/kWh) across the California recent treatments dataset with emission profile over time normalized to CO_2e on the basis of the 100-year Global Warming Potential (GWP, left) and 100-year Global Temperature Potential (GTP, right).

Source: Schatz Energy Research Center, 2021

Further explanation is warranted as it offers key insights into the differences between the climate metrics reported. Recall that higher emissions in the reference case lead to lower net emissions because more of the mobilization and combustion emissions in the use case are offset by the counterfactual outcome. In the GWP-normalized figure on the left, it is clear that the prescribed burn scenarios (that is, those in which residues would be burned if not mobilized for biopower generation) have a lower net biopower carbon intensity than the no-burn cases because they have higher reference-case emissions offsetting those in the use case. However, the long-term, GTP-normalized forcing values display the opposite trend, with the "no burn" reference cases having lower carbon intensities than those with prescribed burns.

There are two key reasons for this difference: 1) the GWP metric represents aggregate climate impacts whereas the GTP metric represents instantaneous impacts, and 2) it takes decades for the full impact of CO_2 to be “felt” by global ecosystems. Therefore, delaying reference-case emissions by leaving material to decay means they have less total forcing impact in the 100-year period, bringing the net GWP-normalized carbon intensity of biopower up. However, it also means that more mass of GHGs is present in the atmosphere at year 100 because they were emitted later, driving the net GTP-normalized carbon intensity of biopower today down.

Criteria Air Pollutant Results

Beyond greenhouse gases, the C-BREC model also quantifies net emissions of VOCs, CO, NO_x, and SO_2, and particulates at 2.5- and 10-micron scales ($PM_{2.5}$ and PM_{10}) including black carbon. Results vary across system characteristics such as forest treatment type and residue disposition as well as geographic characteristics such as residue species, decay rate, and wildfire behavior and probability. As such, considering the distribution of net emission profiles across the treatments conducted in California over the four-year case study period allows a better understanding of the sources of this variation and the sensitivity of biopower criteria pollutant emissions to various system characteristics and model assumptions. This provides useful insight in shaping forest and bioelectricity policy and industry going forward.

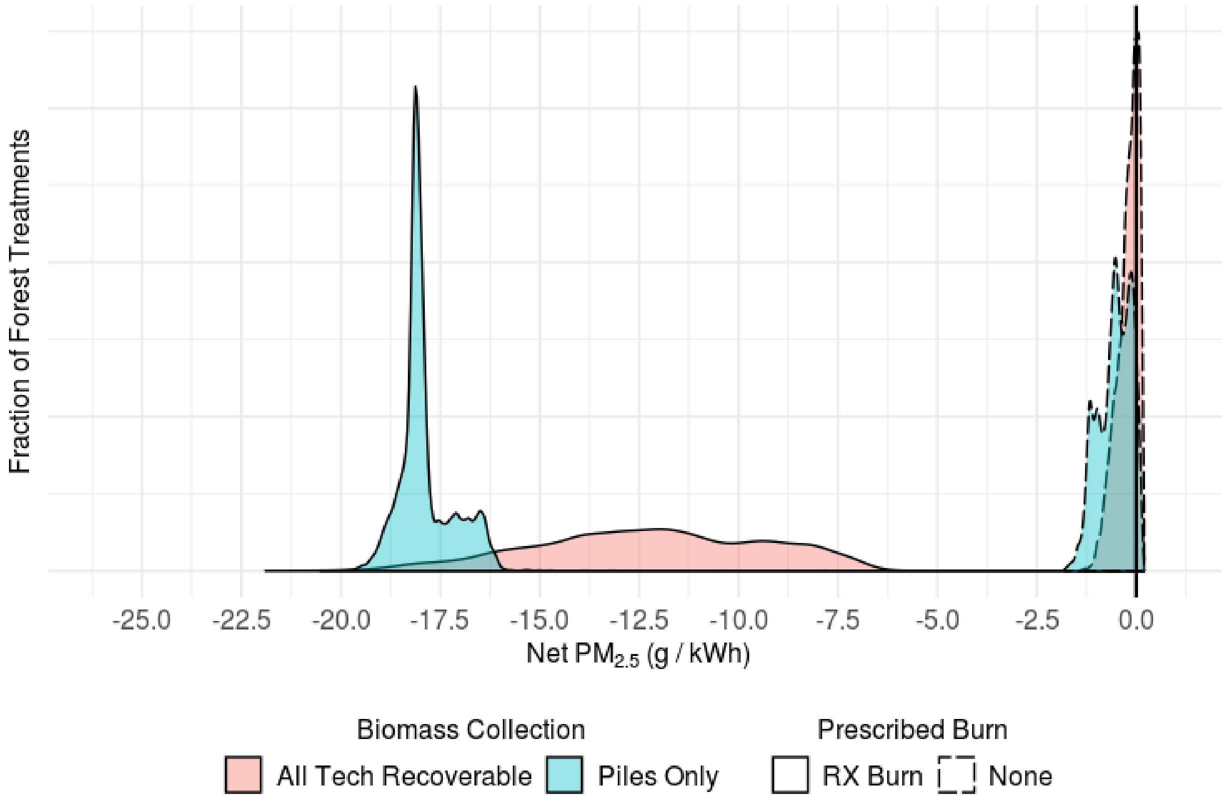
The distributions presented here report aggregate criteria pollutant emissions over the 10-year period following residue generation. In accounting for greenhouse gas emissions, it is possible to normalize an emission time series to year-1 CO_2e as described above. For criteria pollutant emissions, actual emission mass is reported as there is no equivalency basis for normalizing different emissions species or emissions at different times. The following figures therefore report 10-year aggregate criteria pollutant emissions as a compromise between reporting first-year or full 100-year aggregate emissions, which underestimate or overestimate the average impact of wildfire emissions respectively across all statewide activities.

Results indicate that mobilizing forestry residues for biopower generation typically leads to a reduction in emissions of health-harming criteria air pollutants. Figure 10 shows this effect for the case of direct emissions of $PM_{2.5}$, a particularly harmful pollutant. These figures are for primary emissions only, and don't include secondary formation of $PM_{2.5}$ in the atmosphere.

Because these figures display the *net* emissions associated with residue mobilization and use, higher emissions in the reference case lead to lower (or more negative) values. The reduction in criteria air pollutants from biomass use is unsurprisingly strongest where biomass would otherwise have been burned in the field. By removing this material to an engineered combustion chamber, and one where emissions are tightly controlled, the particulate emissions from a ton of biomass are significantly reduced compared to burning that same ton in the field. Where residue would have been left in the field rather than subjected to a prescribed burn, mobilization for biopower generation generally yields slightly lower $PM_{2.5}$ emissions over 10 years (because of probabilistic exposure to wildfire), though the results are mixed.

It is worth noting here that while mobilization of this woody biomass may reduce the total mass of particulates emitted per ton of residue, it also aggregates this emission to a point source, and one that may be closer to human populations. This report does not evaluate the human exposure to these pollutants, nor the equity of distribution of that health burden across populations. This is an important area for future research that will be enabled by the modeling tools and datasets developed under this project.

Figure 10: Net 10-Year Cumulative Particulate Matter 2.5 Impacts

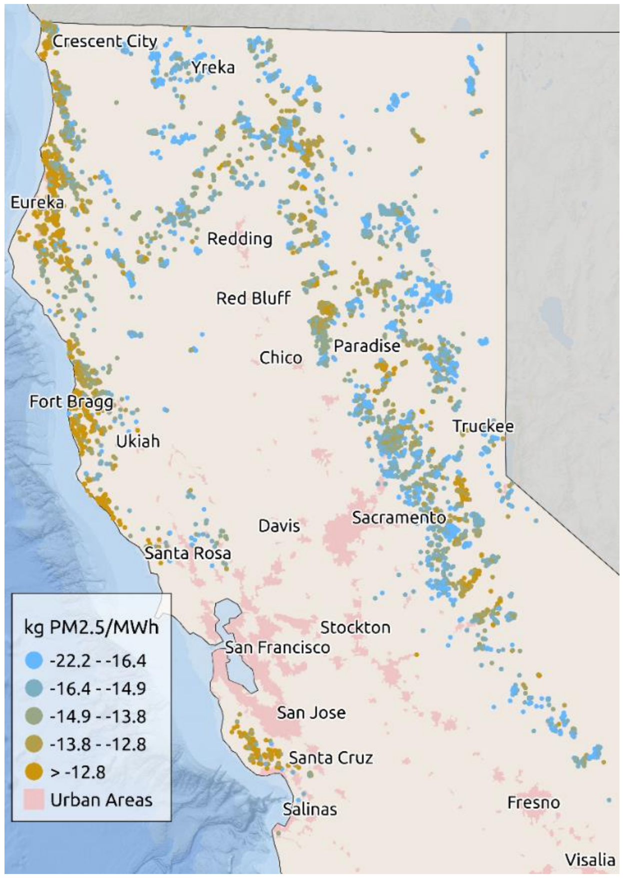


Distribution of 10-year aggregate direct $PM_{2.5}$ emissions from different residue mobilization and counterfactual scenarios across the recent California treatments dataset. The average $PM_{2.5}$ emission factor for all existing power plants in California is 0.299 g/kWh.

Source: Schatz Energy Research Center, 2021

A great deal of the variation seen within each of the distribution curves is attributable to spatially-variable emissions dynamics associated with leaving or burning residues in the field. This is because the many forest treatments being evaluated differ in their residue base characteristics as well as in their climatic drivers of the probability of wildfire occurrence as well as the dynamics of a fire when it occurs. For example, larger, more moist material will tend to smolder. This has a significant effect on the emissions associated with that burning. Mapping the net emissions from biomass utilization allows an assessment of these geographic variations, thereby lending insight into where biomass utilization might offer the most and least air quality mitigation potential. Figure 11 illustrates these spatial trends by exhibiting the mapped distribution in net 10-year aggregate emissions of $PM_{2.5}$ in cases where residue would otherwise have been exposed to prescribed burn.

Figure 11: Example Spatial Variation in Net 10-Year Cumulative Particulate Matter 2.5 Emissions

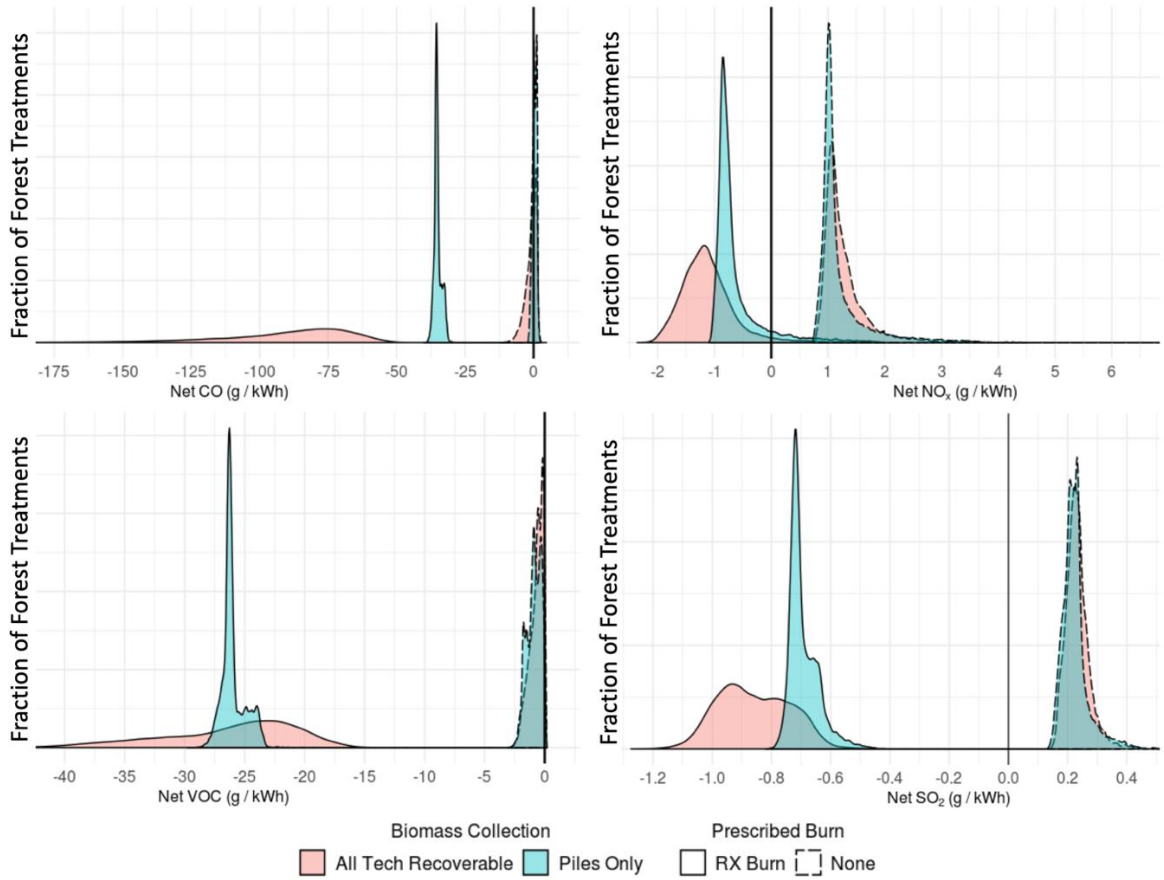


Net direct emissions of $PM_{2.5}$ mapped across California to illustrate the spatial variation in results in a given scenario. Illustrated here is the scenario in which residue would have been expose to a broadcast burn if not removed. These results assume 50 percent of residue is piled and all technically recoverable residue is mobilized in the use case.

Source: Schatz Energy Research Center, 2020

$PM_{2.5}$ is a very important air pollutant, especially because it is implicated in many of the most important human health effects of degraded air quality. However, many other air pollutant constituents are also important for human health and environmental degradation, and are therefore are also tracked by C-BREC. Emission distributions for four key criteria pollutants are displayed in Figure 12.

Figure 12: Net 10-Year Cumulative Impacts from Carbon Monoxide, Oxides of Nitrogen, Volatile Organic Compounds, and Sulfur Dioxide



Source: Schatz Energy Research Center, 2021

The net effect of biopower generation on emissions of these different criteria pollutants exhibits trends that illustrate the varying impact of woody residue mobilization on air quality. The emissions distributions are all similar in that diverting residues that would otherwise have been burned offers more significant emission avoidance than where residues would have been left in place. This is to be expected, as open prescribed burning generates higher emission of criteria pollutants than combustion of the same material in a power plant. The shapes of the distributions are also instructive. Scenarios in which only piled material would be collected and a pile burn is therefore the reference fate (solid-line curves shaded blue) exhibit much less variability than those in which a broadcast burn is the reference fate (solid-line curves shaded red). This is because pile burns are relatively uniform in their combustion dynamics, whereas in broadcast burning more wood is exposed to fire but the dynamics of that fire vary significantly across residue types and conditions.

However, these emissions distributions also differ in some significant ways. First, they differ in whether removing piled material that would otherwise have been subjected to a pile burn offers more or less emission avoidance than scattered material that would otherwise have been subjected to broadcast burning. This is due to the differing fire behavior and emission dynamics between these two prescribed burn types. Smoldering fires typically emit more criteria pollutants than flaming fires, and broadcast burns smolder more than pile burns due to the effects of fuel moisture and fire weather. For the same set of reasons, however, broadcast burning also typically consumes less of the exposed material than pile burning. The differential in emissions between smoldering and flaming varies by pollutant type, and for some pollutants (for example NO_X, SO_2, CO) this differential is large enough to outweigh the lower total consumption of broadcast burning to yield a higher total emission rate per ton of material exposed to fire. For other pollutants (for example $PM_{2.5}$ and PM_{10}), the reduced consumption rate in broadcast burning has a larger effect, yielding lower total emissions than for the same material exposed to a pile burn. More detail on the approach and the models used in characterizing fire for the C-BREC model can be found in the model framework (Carman et al., 2021) and fire modeling (Kane & Wright, 2020) reports available at schatzcenter.org/cbrec/.

Another notable difference in the distributions of these different criteria pollutants is in the sign of the net emissions from biopower when material would otherwise have been left in situ. There are criteria pollutants present in both reference and use cases of this analysis. In the use case, criteria pollutants emerge from collection, distribution, and power generation where in the reference case, these emissions mostly stem from uncontrolled combustion. Where a prescribed burn is the reference case, those fire emissions far exceed the comparatively small emissions from the use case, leading to the significantly negative numbers discussed. Where biomass would be left in situ, there is more variation. For most of the pollutants tracked by C-BREC (PM, CO, and VOCs), the expected emissions from wildfire over a 10-year period are enough to exceed the emissions from the use case, leading to a slightly negative net emission rate. The exceptions are SO_2 and NO_X. These pollutants are particularly tied to fossil fuel consumption, which is only present in the use case. As a result, biopower generation from residues that would otherwise be left in the field was found to lead to higher emissions of SO_2 and NO_X.

Treatment of Black Carbon

Black carbon (BC) is a component of particulate matter (PM) emerging from incomplete combustion and is important because it is both a powerful climate forcer and an air pollutant that affects air quality and human health. While the toxicity of the pollutant mixture may vary, PM sources are generally detrimental to health, and their reduction is a common, and important, air quality goal. The climate impact of black carbon emission is much more complex. Because of its low albedo, BC is a strong absorber of sunlight. Although a particle rather than a gas, it is the second largest driver of climate change in today's atmosphere, following CO_2 (Bond et al., 2013). Although BC remains in the atmosphere for only a few days, one gram of it can have a climate impact hundreds of times greater than one gram of CO_2 does over 100 years (Myhre et al., 2013).

However, sources of BC also emit other particles and gases that impact climate, but not always in the same direction. For example, organic carbon (OC) and sulfate aerosol precursors, are typically co-emitted with BC via combustion and are known to have a net cooling effect due to their role in increasing atmospheric reflectance (Bond et al., 2013; Myhre et al., 2013). It is entirely possible — especially in woody biomass management — to reduce a source of BC while having a net warming impact due to the attendant reduction in co-occurring emissions species.

Because of the large uncertainties inherent in the quantification of the climate forcing effects of BC as well as the fact that it co-occurs in varying concentrations with climate-cooling pollutants, neither BC nor other particulates are included in calculations of life cycle climate forcing in the C-BREC model. This is aligned with the existing LCA literature on biopower from woody biomass. However, unlike many existing LCA models, total net BC emissions are reported by C-BREC. This would enable the model to integrate BC into its climate impact calculations pending further convergence in LCA protocols or policy guidance.

Model Sensitivities

The C-BREC model enables a rigorous evaluation of the extent to which these emission estimates depend on specific characteristics of the system being modeled and the assumptions underlying the model itself. Key sensitivities were found to include characteristics such as power plant generation technology, biomass storage period, and methane emission rate from biomass decay both in the field and during storage at the power plant. A detailed exploration of these and other sensitivities can be found in the *LCA Results Report* and the *Criteria Air Pollutant Impacts Report* available at schatzcenter.org/cbrec/.

CHAPTER 4: Conclusions and Recommendations

Climate mitigation strategies commonly promote biopower , especially when generated from forest wastes and residues. In a 2018 Special Report, the IPCC estimated that bioelectricity systems — in particular those employing carbon capture and sequestration — would need to make up a median of 26 percent of primary energy supply in 2050 to achieve a maximum warming of 1.5°C (Rogelj et al., 2018). The bioelectricity sector, therefore, is expected to play a significant role in a carbon-constrained energy future, and policy makers should structure it to ensure that it delivers the intended climate and environmental performance.

Most policies that support biopower are predicated on the assertion that the pathways being promoted offer a climate benefit compared to a scenario in which this biopower was not produced. However, the C-BREC model has shown that the climate performance of biopower from forest residues is highly variable. It is therefore incumbent upon policymakers in California and elsewhere to design bioelectricity and woody residue utilization policies that deliver specifically those pathways offering significant climate and/or other environmental benefits.

The C-BREC model offers the most rigorous and transparent accounting of the life cycle GHG and criteria pollutant impact of forest residue-to-electricity systems to date. As demonstrated in this report, C-BREC results reveal significant variation across supply chains, feedstock types, and geographies in California. Given this variation, the C-BREC model can be useful in shaping the biomass energy system and other uses for woody residues, enabling activities to be targeted to where they offer the greatest benefit. In particular, the C-BREC model can:

- Identify the geographic locations and forest treatment types in which utilization of residuals offers the greatest climate and air pollution benefit in order to structure incentives accordingly.
- Evaluate other use cases for woody residues with additional model development. This would aid in shaping residue mobilization and conversion supply chains to minimize emissions by identifying what improvements will offer the greatest life cycle emissions reduction potential.
- Provide insights to legislators and the CEC to inform implementation of Assembly Bill 322 (Salas, Chapter 229, Statutes of 2021)— Electric Program Investment Charge program: biomass. AB 322 directs the CEC to "consider, in the investment planning process for the EPIC program, funding for eligible biomass conversion to energy projects." The findings from this study sheds light on the variable climate and air quality impact of these projects, and C-BREC could be used to target investments where they would carry the most benefit.
- Provide project-level analysis for policies aiming to reduce GHG emissions from California's forestlands and energy systems. For example, it could be used by the Air Resources Board in formulating woody biomass pathways under California's Low Carbon Fuel Standard and by the California Public Utilities Commission in its ongoing effort to apply climate impact criteria to the BioMAT program.

- Generate screening tools for programs - such as CAL FIRE's Forest Health Grant program and California Air Resources Board's (CARB) broader California Climate Investments program - that seek to manage forestlands for carbon sequestration and fire risk reduction.
- Streamline CAL FIRE's review process under the California Environmental Quality Act for approving forest activities integrating residue removal and utilization.

C-BREC typically found net positive emissions from bioelectricity generation, even where prescribed burn is avoided. However, bioelectricity does not need to have a negative carbon footprint to offer a benefit, as there are very few products or processes in existence that can make that claim. Biopower from residues that would otherwise have been burned on site can have a lower carbon intensity than California grid average electricity on a GWP-normalized basis, though higher than other renewables such as wind and solar power. In addition, the air quality benefits offered by mobilizing residues that would otherwise have been burned may be substantial and should be considered alongside climate, wildfire, and ecosystem impact.

This analysis does not account for carbon emissions or sequestration implications of the primary treatment activity that yields the woody residues in question. This is because there is no evidence of a market for residues driving those activities. If biomass removal is a necessary part of forest management activities that reduce fire risk or improve the carbon storage on the landscape or both, biopower that facilitates these activities by offering an outlet for residues could provide further climate benefit not quantified. However, these benefits do not accrue uniquely to bioelectricity, and state policymakers should consider alternate uses such as biochar, liquid fuels, or durable wood products that may provide stronger climate performance alongside or as an alternative to biopower generation.

Areas for Future Research

While the model results reported here and the C-BREC tool offer key insights into the climate and air quality performance of bioelectricity systems in California, the researchers have also identified some important research questions that warrant further investigation:

- *Empirical studies of targeted emissions sources*: C-BREC modeling has identified key system sensitivities that warrant closer evaluation and further study. For example, field measurement of methane generation from biomass piles would aid in stronger empirical parameterization of the model. In addition, the most significant sensitivity in bioelectricity carbon intensity is the counterfactual fate of the biomass being used. There is little organized record-keeping on prescribed burning of forest residues, and further research is needed to rigorously and transparently estimate the fraction of residue that has historically been burned on different working landscapes in California.
- *Air emissions health burden*: While mobilization of woody biomass typically reduces the total mass of criteria pollutants emitted per ton of residue, it also aggregates this emission to a point source, and one that may be closer to human populations. It was beyond the scope of this research to evaluate the human health burden associated with these emissions or the equity of the distribution of this burden. However, this is an important area for future research that will be enabled by the modeling tools and datasets developed under this project.
- *Expansion to other use-cases for woody biomass*: In addition to electricity, residual biomass could be used as a feedstock for other end uses such as liquid fuels, biochar,

or durable wood products. Policy and industry decision-making in the broader wood products space could be better informed if impact assessments were harmonized. Expanding C-BREC to incorporate other pathways for residue utilization would offer key insights and could be accomplished via integration with existing LCA tools such as the GREET model for liquid fuels.

- *Integration of Biopower with Carbon Capture and Storage (BECCS) in California*: BECCS is one of the more practical negative emissions electricity generation technologies available. By removing the most significant emission source in the use case of the pathways evaluated here (biomass combustion for electricity generation), it would lead to uniformly negative biopower carbon intensity. C-BREC could be a useful tool in locating and evaluating the potential of BECCS facility development in California.
- *Integration with broader land-use modeling frameworks*: This project considers forest management activities as exogenous to the biomass residue supply chain. As such, C-BREC does not quantify any carbon cycling implication of these activities. There are promising opportunities to integrate C-BREC with forest carbon modeling tools to evaluate the landscape-level climate implications of different land management scenarios including biomass utilization. For instance, linking C-BREC with the CALAND model (Di Vittorio et al., 2021) could provide a more detailed and complete analysis of the carbon effects of both forest/land management strategies and the biopower pathway.
- *Incorporation of biomass resource economic modeling*: The C-BREC framework enables the evaluation of the emissions implications of mobilizing residues from notional harvests in California but does not identify where those harvests will occur in practice. By integrating elements evaluating the economics of forest harvest and biomass mobilization, researchers would be able to robustly evaluate the landscape-scale implications of, for example, new biopower facility construction or subsidies to biomass mobilization in the state.
- *Incorporating the Climate Forcing Effect of Black Carbon*: As noted in Chapter 3, there are large uncertainties in the quantification of the climate forcing effects of BC. The role of BC needs to be resolved by the international atmospheric science community, and then accounting protocols must be worked out for LCA protocols. Because total net BC emissions are reported by C-BREC, it would be straightforward to integrate BC into its climate impact calculations once these scientific issues are resolved.

CHAPTER 5: Knowledge Transfer Activities

Knowledge transfer activities during the project period aimed to reach the following audiences:

- Federal agencies (United States Department of Energy, U.S. Environmental Protection Agency, U.S. Department of the Interior [including parks], the U.S. Department of Agriculture, especially U.S. Forest Service).
- State agencies (California Environmental Protection Agency, California Air Resources Board, California Public Utilities Commission, California Natural Resources Agency, Office of Planning and Research).
- Air Districts/California Air Pollution Control Officers Association.
- Industry (energy facilities, commercial forestry, mills, commercial wood products, agricultural industry).
- Academia (University of California [UC] Berkeley, UC Davis, UC Merced).
- Nongovernmental organizations (environmental justice, environmental [traditional]).
- Industry/trade associations in forest industry.
- The Technical Advisory Committee, consisting of expert representatives from government, utilities, industry, environmental non-profits, and scientific research institutions.

The types of information shared with stakeholders include:

- Emission-related policy questions (CO_2 emissions/bone-dry ton residue diverted). How this emission intensity varies spatially, what supply-chain characteristics drive emission variability, and clarity on counterfactual fate drivers of net carbon intensity results.
- Alignment with state methods and policies.
- Recommendations for integration of this work into relevant state efforts.
- Demonstration webtool of the C-BREC model to allow stakeholders to interact with the model.

Education, outreach and knowledge transfer activities included:

1. In-person and remote participation in workshops, conferences, webinars and other knowledge transfer activities.
2. Preparation, publication and distribution of project documents, including:
    a. Factsheet
    b. Detailed project brief
    c. Project reports
3. Outreach to legislators and regulatory agency staff to aid in shaping policies and outcomes in the forest biomass space.

The project conducted numerous outreach and knowledge transfer efforts (Table 1). The project has maintained a website throughout the project period and a webpage has been launched for the C-BREC Model to enable the project team to continue disseminating the project results and extend the impact of the project beyond the project period. In addition, the project team released a blog post during the project kick off.

- CBI Project Page: schatzcenter.org/cbip
- CBI Project Blog Post: https://schatzcenter.org/2017/10/california-biopower-impact-project-creating-a-life-cycle-assessment-for-bioenergy-systems/
- C-BREC Model Page: schatzcenter.org/cbrec

Table 1: List of Knowledge Transfer Activities Conducted for This Project

Event/Stakeholder Name	Date	Project Team Participants	Location	Audience (description, size)	Presentation Name/Topic
Ad-hoc CA Forest Biomass Working Group	6/21/2017	Kevin Fingerman and Jerome Carman	Sacramento, CA	20+, stakeholders in California's forest industry	Overview of the CBI Project
DOE Bioenergy Technologies Office	9/14/2017	Kevin Fingerman	Remote	3 DOE/BETO staff	Overview of the CBI Project
Technical Advisory Committee kick-off meeting	12/7/18 – 12/8/18	Most staff, all TAC members	Eureka, CA	TAC members	Introduced the project to a global audience of LCA and forestry specialists
Ad-hoc CA Forest Biomass Working Group	6/20/2018	Kevin Fingerman and Jerome Carman	Sacramento, CA	20+, stakeholders in California's forest industry	Overview of the CBI Project, specific questions, and discussion of areas of collaboration and overlap
CA Air Resources Board	6/21/2018	Kevin Fingerman and Jerome Carman	Sacramento, CA	5 CARB staff members	Overview of the CBI Project, specific questions, and discussion of areas of collaboration and overlap
CA Public Utility Commission	6/20/2018	Kevin Fingerman and Jerome Carman	Sacramento, CA	3 CPUC staff members	Overview of the CBI Project, specific questions, and discussion of areas of collaboration and overlap
CAL FIRE	6/21/2018	Kevin Fingerman and Jerome Carman	Sacramento, CA	3 CPUC staff members	Overview of the CBI Project, specific questions, and discussion of areas of collaboration and overlap

Event/Stakeholder Name	Date	Project Team Participants	Location	Audience (description, size)	Presentation Name/Topic
CA Biomass Energy Association	6/21/2018	Kevin Fingerman and Jerome Carman	Sacramento, CA	10+, private industry stakeholders in California's forest industry	Overview of the CBI Project
CSU Agricultural Research Institute Principal Investigator's Meeting	9/19/2018	Sintana Vergara and Cassidy Barrientos	Sacramento, CA	100+ professors and students in the CSU system.	Presentation and poster session on literature review of emissions profiles of processed biomass at powerplant facilities
Beta Test of NREL's new Feedstock Production Emissions to Air Model (FPEAM)	9/19/18 – 9/21/18	Mark Severy	Golden, CO	10 – 15 academics and government regulators	Staff engaged in beta testing a new NREL tool, focusing on bringing understanding and expertise on forest residue utilization
Who Will Own the Forest? Conference by the World Forestry Center	9/25/18 – 9/27/18	Andrea Tuttle	Portland, OR	100+ U.S. and global forest industry representatives	Participated on a panel entitled Forest Investments in Conservation and Carbon – Forestry and Carbon. Discussed CBI Project and CA activities to a geographically broad audience.
UC Davis Biological and Agricultural Engineering Seminar	11/7/2018	Jerome Carman	Davis, CA	Unknown	Presenting on details of LCA work to date to professors and students

Event/Stakeholder Name	Date	Project Team Participants	Location	Audience (description, size)	Presentation Name/Topic
Comments to CPUC on BioMAT Review and Staff Proposal	12/7/2018	Kevin Fingerman and Jerome Carman	--	BioMAT Proceedings Parties	Among other comments, recommendations on how to leverage the C-BREC model for the BioMAT program.
California Bioresources Economy Summit	January 29, 2019	Kevin Fingerman	Berkeley, CA	100+, was also webcast	Overview of project
Argonne National Laboratory GREET Team	4/3/2019	Kevin Fingerman and Jerome Carman	Remote	3 staff	Introduction to project and LCA methods, discussion of collaboration potential with GREET model
CPUC Workshop: Evaluating Potential Programmatic Changes to the Bioenergy Market Adjusting Tariff (BioMAT) Program	July 19, 2019	Kevin Fingerman and Jerome Carman	Sacramento, CA	Public meeting plus remote attendance. 30+ in person and unknown number of remote attendees.	California Biomass Residue Emissions Characterization (C-BREC) Model
CAL FIRE staff	8/1/2019	Kevin Fingerman and Jerome Carman	Sacramento, CA	4 CAL FIRE staff	Overview and update on C-BREC model
CARB Fuels staff	8/1/2019	Kevin Fingerman and Jerome Carman	Sacramento, CA	3 ARB staff	Overview and update on C-BREC model. Collaborative presentation with GREET model representative

Event/Stakeholder Name	Date	Project Team Participants	Location	Audience (description, size)	Presentation Name/Topic
CEC liquid biofuels staff	8/2/2019	Kevin Fingerman and Jerome Carman	Sacramento, CA	3 CEC staff	Overview and update on C-BREC model. Collaborative presentation with GREET model representative
California Biomass Energy Alliance	11/2019	Kevin Fingerman and Jerome Carman	Remote	CBEA Membership	Update on status of project and initial results.
Sustainable Futures Speaker Series	11/14/2019	Kevin Fingerman and Jerome Carman	Arcata, CA	Humboldt County residents, HSU faculty, staff, and students	Overview of project and preliminary findings.
Comments to CARB on the Forest Health GHG Quantification Methodology	11/22/2019	Kevin Fingerman and Jerome Carman	--	Public	Recommendations on how to leverage the C-BREC model for CARB quantification efforts.
Copernicus Institute of Sustainable Development – Utrecht University	2/10/2020	Kevin Fingerman	Utrecht, Netherlands	University faculty	Overview of project, methods, and preliminary findings
Conversation with California Assembly member Rudy Salas' Staff	2/12/2021	Kevin Fingerman	Remote	Legislative staff	Overview of project and initial results
Discussion with CARB Fuels Evaluation Section, Industrial Strategies Division staff	3/3/2021	Kevin Fingerman and Jerome Carman	Remote	3 staff	Discuss project results and status, discuss how C-BREC could be leveraged for LCFS pathway analyses.

Event/Stakeholder Name	Date	Project Team Participants	Location	Audience (description, size)	Presentation Name/Topic
California Biomass Working Group	3/17/2021	Kevin Fingerman and Jerome Carman	Remote	Estimate 20+ attendees	Overview of project results and status
CPUC BioMAT Technical Working Group	4/2021 - ongoing	Kevin Fingerman	Remote	varies	Provide guidance and recommendations on CPUC's goal to develop project-specific GHG reduction model for the BioMAT program
Argonne National Laboratory GREET Team	4/8/2021	Kevin Fingerman and Jerome Carman	Remote	4 staff	Overview of project results and status, discussion of ways to leverage C-BREC in GREET to improve LCFS pathways and other applications.
Discussion with CARB Fuels Evaluation Section, Industrial Strategies Division staff	4/19/2021	Kevin Fingerman and Jerome Carman	Remote	3 staff	Continue discussion of how C-BREC could be leveraged for LCFS pathway analyses.
Joint Institute for Wood Products Innovation	4/23/2021	Kevin Fingerman and Jerome Carman	Remote	Estimate 20+ attendees	Overview of project results and status
Argonne National Laboratory GREET Team	6/3/2021	Kevin Fingerman and Jerome Carman	Remote	3 staff	Discuss alignment of climate metric methodologies between C-BREC and GREET

Event/Stakeholder Name	Date	Project Team Participants	Location	Audience (description, size)	Presentation Name/Topic
Coordinating Research Council Workshop on LCA of Transportation Fuels. US Department of Energy	10/20/2021	Kevin Fingerman	Remote	~100 energy industry representatives and researchers	Life Cycle Analysis of energy products from forest residues in California

Source: Schatz Energy Research Center, 2021

CHAPTER 6: Benefits to Ratepayers

The CBI project has generated critical knowledge necessary to ensure that the biomass residue-to-energy economy in California develops in an environmentally sustainable fashion. This should help the state achieve stated goals at the nexus of forest management, wildfire risk abatement, renewable energy, air quality, and climate. Using C-BREC to assess the life cycle emissions from forest residue biopower will help define an appropriate end use for fuel from high-hazard zones, promoting a responsible wildfire prevention plan. Furthermore, establishing the true GHG impact of bioelectricity generation from forest residue will determine the extent to which California can depend on biomass to provide renewable power and to support California's renewable energy portfolio goals. Newfound demand for forest residue feedstock could also provide economic support for removing overstocked fuels from the state's forested landscapes, reducing the cost burden for ratepayers facing wildfire risk from adjacent forestland.

Developing responsible fire management plans and expanding sustainable biopower promote improved grid reliability. Increased resilience to wildfires not only protects millions of Californians, it also defends critical grid infrastructure. Furthermore, given that transportation costs can create a barrier to biopower systems (Pan et al., 2008), distributed power stations may be a viable alternative—creating a more locally robust electric grid. Insights from the CBI project could be used to locate small-scale biomass-fueled generators or microgrids in locations where they offer the greatest climate and air quality benefit. This would create more opportunities for sustainable localized power, increasing community choice in power production, reducing transmission infrastructure costs, providing an added layer of grid resiliency, and potentially reducing transmission-based fire ignitions in forested regions by reducing the strain and dependence on transmission infrastructure.

However, these systems should not be uniformly promoted. This research reveals and quantifies the significant variation in the climate and air quality impact of biopower from forest residues across feedstock types and geographies in California. It is therefore incumbent upon policymakers in California and elsewhere to design biopower and woody residue utilization policies that deliver specifically those pathways offering significant climate and/or other environmental benefits.

The C-BREC model offers the most rigorous and transparent accounting of the life cycle GHG and criteria pollutant impact of forest residue-to-electricity systems to date. It could be useful in shaping the biomass energy system and other uses for woody residues, enabling activities to be targeted to where they offer the greatest benefit. This will benefit Californians not only through climate and air pollution mitigation, but also by enabling policymakers to promote systems specifically where they can offer enhanced forest management, fire risk reduction, rural economic development, and power grid resilience.

This research has generated valuable datasets identifying the location and physical characteristics of the forest residue base in California. This dataset has already been put to use in carbon accounting for California's natural and working lands, and C-BREC could be used to identify and target the geographic locations and forest treatment types in which utilization of residuals offers the greatest climate and air pollution benefit in order to structure incentives accordingly.

The model could provide project-level analysis for policies aiming to reduce GHG emissions from California's forestlands and energy systems. For example, it could be used by the California Air Resources Board in formulating woody biomass pathways under California's Low Carbon Fuel Standard and by the California Public Utilities Commission in its ongoing effort to apply climate impact criteria to the BioMAT program. In addition, it could be applied as a screening tool for programs—such as CAL FIRE's Forest Health Grant program and CARB's broader California Climate Investments program—that seek to manage forestlands for carbon sequestration and fire risk reduction.

GLOSSARY AND LIST OF ACRONYMS

Term	Definition
AB	Assembly Bill
AGTP	Absolute global temperature potential
AGWP	Absolute global warming potential
BC	Black carbon
BECCS	Biopower with carbon capture and storage
Bioenergy	A form of energy derived from recently living organic materials (collectively termed "biomass"). Can include transportation fuels, heat, electricity, or other energy carriers
Biopower (or bioelectricity)	Electricity generated from biomass. A subset of bioenergy.
CARB	California Air Resources Board
Case	The fate of a given mass of residue. It can either be removed for biopower (use case) or left in the field (reference case). The difference between the emissions in these two cases is the net carbon footprint of biopower
CBI	California Biopower Impacts Project
C-BREC	California Biomass Residue Emissions Characterization model
CCI	CAL FIRE California Climate Investments Program
CEC	California Energy Commission
CH_4	Methane
CHP	Combined heat and power
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent, or the amount of CO_2 that would yield the same climate impact as the climate forcing agent under investigation
Comminution	The process of breaking down biomass (or other material) into small pieces for transport and use
CWD	Coarse woody debris
Disposition	Physical placement of residue following the silvicultural treatment — whether piled or scattered. This affects the residue collection system in the use case, and decay and fire dynamics in the reference case.
EPIC	Electric Program Investment Charge
FCCS	Fuel Characteristic Classification System
FIA	Forest Inventory and Analysis
FPEAM	Feedstock Production Emissions to Air Model
GHG	Greenhouse gas

Term	Definition
GREET	Greenhouse Gas Regulated Emissions and Energy use in Technologies
GTP	Global temperature potential – a climate metric focused on assessing the state of the global climate at some point in the future. This study uses 100 years.
GWP	Global warming potential – a climate metric focused on assessing the aggregate radiative forcing caused in the global climate up to some point in the future. This study uses 100 years.
IPCC	Intergovernmental Panel on Climate Change
kWh	Kilowatt-hour
LCA	Life Cycle Assessment – the analytical process of quantifying the aggregate impact (on some parameter of concern – GHG and criteria pollutants are the parameters studied here) of a system or product across its life cycle.
LCA	Life cycle assessment
LEMMA	Landscape Ecology, Modeling, Mapping and Analysis
Mobilization	As used in this report, the process of removing woody residue from the field for use
N_2O	Nitrous oxide
NO_x	Oxides of nitrogen
OC	Organic carbon
PM_{10}, $PM_{2.5}$	Particulate matter
RCP	Representative concentration pathway
Reference case	Fate a given mass of residue if not removed from the field for use in energy systems. Sometimes referred to as "counterfactual" case. Includes ongoing decay of residues as well as exposure to prescribed burns and wildfire.
Residue	Tree tops, branches, or other non-merchantable woody waste material resulting from forest treatment
Scenario	Any specific combination of reference and use cases
SO_2	Sulfur dioxide
Thin from above	Forest management selecting for larger diameter trees. Typical of selective commercial harvest.
Thin from below	Forest management selecting for smaller diameter trees. Typical of forest health or fire risk reduction treatments.
Treatment	The primary harvest or other forest management activity resulting in the residue being investigated.
UC	University of California
UNEP/SETAC	United Nations Environment Programme / Society for Environmental Toxicology and Chemistry

Term	Definition
Use case	The case in which the residues are removed from the field for biomass energy use. A given use case will have numerous supply-chain characteristics, including transport distance, equipment utilization, and end-use facility technology.
VOCs	Volatile organic compounds

REFERENCES

Aamaas, B., Peters, G. P., & Fuglestvedt, J. S. (2012). A synthesis of climate-based emission metrics with applications. *Earth System Dynamics Discussions*, *3*(2), 871–934. https://doi.org/10.5194/esdd-3-871-2012

Abatzoglou, J. T. (2013). Development of gridded surface meteorological data for ecological applications and modelling. *International Journal of Climatology*, *33*(1), 121–131. https://doi.org/10.1002/joc.3413

Abatzoglou, J. T., & Brown, T. J. (2012). A comparison of statistical downscaling methods suited for wildfire applications. *International Journal of Climatology*, *32*(5), 772–780. https://doi.org/10.1002/joc.2312

Andrews, P. L. (2012). Modeling wind adjustment factor and midflame wind speed for Rothermel's surface fire spread model. *Gen. Tech. Rep. RMRS-GTR-266. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 39 p.*, *266*. https://doi.org/10.2737/RMRS-GTR-266

Blasdel, M. (2020). *Decay of woody residues as the counterfactual treatment to mobilization for bioelectricity generation* [Thesis, Humboldt State University]. https://digitalcommons.humboldt.edu/etd/420

Bond, T. C., Doherty, S. J., Fahey, D. W., Forster, P. M., Berntsen, T., DeAngelo, B. J., Flanner, M. G., Ghan, S., Kärcher, B., Koch, D., Kinne, S., Kondo, Y., Quinn, P. K., Sarofim, M. C., Schultz, M. G., Schulz, M., Venkataraman, C., Zhang, H., Zhang, S., … Zender, C. S. (2013). Bounding the role of black carbon in the climate system: A scientific assessment. *Journal of Geophysical Research: Atmospheres*, *118*(11), 5380–5552. https://doi.org/10.1002/jgrd.50171

Brack, D. (2017, February 23). *The Impacts of the Demand for Woody Biomass for Power and Heat on Climate and Forests*. https://www.chathamhouse.org/2017/02/impacts-demand-woody-biomass-power-and-heat-climate-and-forests

Buchholz, T., Hurteau, M. D., Gunn, J., & Saah, D. (2016). A global meta-analysis of forest bioenergy greenhouse gas emission accounting studies. *GCB Bioenergy*, *8*(2), 281–289. https://doi.org/10.1111/gcbb.12245

California Air Resources Board. (2021). *California Climate Investments Funded Programs*. https://ww2.arb.ca.gov/our-work/programs/california-climate-investments/california-climate-investments-funded-programs

California Department of Forestry and Fire Protection, Resource Management, Forest Practice Program. (2017). *California Forest Practice Rules*.

Carman, J., Severy, M., Barrientos, C., Blasdel, M., Geronimo, C., Harris, A., Hsu, C.-W., Kane, J., Rios-Romero, S., Wright, M., & Fingerman, K. (2021). *California Biomass Residue Emissions Characterization (C-BREC) Model Framework: Version 1.2* (EPC-16-047). Schatz Energy Research Center.

Cherubini, F., & Strømman, A. H. (2011). Life cycle assessment of bioenergy systems: State of the art and future challenges. *Bioresource Technology*, *102*(2), 437–451. https://doi.org/10.1016/j.biortech.2010.08.010

Cohen, J. D., & Deeming, J. E. (1985). The national fire-danger rating system: Basic equations. *Gen. Tech. Rep. PSW-82. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 16 p*, *082*. https://doi.org/10.2737/PSW-GTR-82

Collins, B. M., Das, A. J., Battles, J. J., Fry, D. L., Krasnow, K. D., & Stephens, S. L. (2014). Beyond reducing fire hazard: Fuel treatment impacts on overstory tree survival. *Ecological Applications*, *24*(8), 1879–1886. https://doi.org/10.1890/14-0971.1

Cornwall, W. (2017). The burning question. *Science*, *355*(6320), 18–21. https://doi.org/10.1126/science.355.6320.18

Di Vittorio, A. V., Simmonds, M. B., & Nico, P. (2021). Quantifying the effects of multiple land management practices, land cover change, and wildfire on the California landscape carbon budget with an empirical model. *PLOS ONE*, *16*(5), e0251346. https://doi.org/10.1371/journal.pone.0251346

Edmonds, R. L., Vogt, D. J., Sandberg, D. H., & Driver, C. H. (1986). Decomposition of Douglas-fir and red alder wood in clear-cuttings. *Canadian Journal of Forest Research*, *16*(4), 822–831. https://doi.org/10.1139/x86-145

Erickson, H. E., Edmonds, R. L., & Peterson, C. E. (1985). Decomposition of logging residues in Douglas-fir, western hemlock, Pacific silver fir, and ponderosa pine ecosystems. *Canadian Journal of Forest Research*. https://doi.org/10.1139/x85-147

Foley, J. A. (1995). An equilibrium model of the terrestrial carbon budget. *Tellus B: Chemical and Physical Meteorology*, *47*(3), 310–319. https://doi.org/10.3402/tellusb.v47i3.16050

Forest Climate Action Team. (2018). *California Forest Carbon Plan: Managing Our Forest Landscapes in a Changing Climate* (p. 178).

Giuntoli, J., Agostini, A., Caserini, S., Lugato, E., Baxter, D., & Marelli, L. (2016). Climate change impacts of power generation from residual biomass. *Biomass and Bioenergy*. https://doi.org/10.1016/j.biombioe.2016.02.024

Giuntoli, J., Caserini, S., Marelli, L., Baxter, D., & Agostini, A. (2015). Domestic heating from forest logging residues: Environmental risks and benefits. *Journal of Cleaner Production*, *99*, 206–216. https://doi.org/10.1016/j.jclepro.2015.03.025

Gustavsson, L., Haus, S., Ortiz, C. A., Sathre, R., & Truong, N. L. (2015). Climate effects of bioenergy from forest residues in comparison to fossil energy. *Applied Energy*, *138*, 36–50. https://doi.org/10.1016/j.apenergy.2014.10.013

Helin, T., Sokka, L., Soimakallio, S., Pingoud, K., & Pajula, T. (2013). Approaches for inclusion of forest carbon cycle in life cycle assessment—A review. *GCB Bioenergy*, *5*(5), 475–486. https://doi.org/10.1111/gcbb.12016

ISO 14067:2018. (2018). *Greenhouse gases—Carbon footprint of products—Requirements and guidelines for quantification*. International Organization for Standardization. https://www.iso.org/standard/71206.html

Jäppinen, E., Korpinen, O.-J., Laitila, J., & Ranta, T. (2014). Greenhouse gas emissions of forest bioenergy supply and utilization in Finland. *Renewable and Sustainable Energy Reviews*, *29*, 369–382. https://doi.org/10.1016/j.rser.2013.08.101

Jenkins, J. C., Chojnacky, D. C., Heath, L. S., & Birdsey, R. A. (2003). National-Scale Biomass Estimators for United States Tree Species. *Forest Science*, *49*(1), 12–35.

Jessica Olsen. (2017, November 7). *Agricultural Open Burning Emissions Inventory and Air Quality Impacts: Trends and Forecasts*. Central Valley Summit on Alternative to Open Burning of Agricultural Waste, Kearney Agricultural Research & Extension Center. http://valleyair.org/cvsummit/index.htm

Kane, J. M., & Wright, M. (2020). *California Biopower Impact Project: Fire Emissions and Fuels Report* (EPC-16-047). Schatz Energy Research Center.

Laiho, R., & Prescott, C. E. (2004). Decay and nutrient dynamics of coarse woody debris in northern coniferous forests: A synthesis. *Canadian Journal of Forest Research*, *34*(4), 763–777. https://doi.org/10.1139/x03-241

Larkin, N. K., O'Neill, S. M., Solomon, R., Raffuse, S., Strand, T., Sullivan, D. C., Krull, C., Rorig, M., Peterson, J., Ferguson, S. A., Larkin, N. K., O'Neill, S. M., Solomon, R., Raffuse, S., Strand, T., Sullivan, D. C., Krull, C., Rorig, M., Peterson, J., & Ferguson, S. A. (2010). The BlueSky smoke modeling framework. *International Journal of Wildland Fire*, *18*(8), 906–920. https://doi.org/10.1071/WF07086

Levasseur, A., Schryver, A. de, Hauschild, M., Kabe, Y., Sahnoune, A., Tanaka, K., & Cherubini, F. (2016). Greenhouse gas emissions and climate change impacts. In *Global guidance for life cycle impact assessment indicators* (Vol. 1). United Nations Environment Programme.

Liu, B., & Rajagopal, D. (2019). Life-cycle energy and climate benefits of energy recovery from wastes and biomass residues in the United States. *Nature Energy*, *4*(8), 700–708. https://doi.org/10.1038/s41560-019-0430-2

Mackensen, J., & Bauhus, J. (1999). *The Decay of Course Woody Debris* (No. 6; National Carbon Accounting System Technical Report). Australian Greenhouse Office, Canberra.

Madsen, K., & Bentsen, N. S. (2018). Carbon Debt Payback Time for a Biomass Fired CHP Plant—A Case Study from Northern Europe. *Energies*, *11*(4), 807. https://doi.org/10.3390/en11040807

McKechnie, J., Colombo, S., Chen, J., Mabee, W., & MacLean, H. L. (2011). Forest Bioenergy or Forest Carbon? Assessing Trade-Offs in Greenhouse Gas Mitigation with Wood-Based Fuels. *Environmental Science & Technology*, *45*(2), 789–795. https://doi.org/10.1021/es1024004

Miner, R. A., Abt, R. C., Bowyer, J. L., Buford, M. A., Malmsheimer, R. W., O'Laughlin, J., Oneil, E. E., Sedjo, R. A., & Skog, K. E. (2014). Forest Carbon Accounting Considerations in US Bioenergy Policy. *Journal of Forestry*, *112*(6), 591–606. https://doi.org/10.5849/jof.14-009

Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J.-F., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura, T., & Zhang, H. (2013). Anthropogenic and Natural Radiative Forcing. In T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Doschung, A. Nauels, Y. Xia, V. Bex, & P. M. Midgley (Eds.), *Climate Change 2013—The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 659–740). Cambridge University Press. http://ebooks.cambridge.org/ref/id/CBO9781107415324A026

Olson, J. S. (1963). Energy Storage and the Balance of Producers and Decomposers in Ecological Systems. *Ecology*, *44*(2), 322–331. https://doi.org/10.2307/1932179

Pan, F., Han, H.-S., Johnson, L. R., & Elliot, W. J. (2008). Production and cost of harvesting, processing, and transporting small-diameter (<= 5 inches) trees for energy. *Forest Products Journal*, *58*(5), 47.

Prichard, S. J., Ottmar, R. D., & Anderson, G. K. (2006). Consume 3.0 user's guide. *Pacific Northwest Research Station, Corvallis, Oregon*.

Reid, W. V., Ali, M. K., & Field, C. B. (2020). The future of bioenergy. *Global Change Biology*, *26*(1), 274–286. https://doi.org/10.1111/gcb.14883

Riccardi, C. L., Ottmar, R. D., Sandberg, D. V., Andreu, A., Elman, E., Kopper, K., & Long, J. (2007). The fuelbed: A key element of the Fuel Characteristic Classification System. *Canadian Journal of Forest Research*, *37*(12), 2394–2412. https://doi.org/10.1139/X07-143

Rogelj, J., Shindell, D., Jiang, K., Fifita, S., Ginzburg, V., Handa, C., Kheshgi, H., Kobayashi, S., Kriegler, E., Mundaca, L., Séférian, R., & Vilariño, M. (2018). Mitigation pathways compatible with 1.5°C in the context of sustainable development. In V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, & T. Waterfield (Eds.), *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* (pp. 93–174). IPCC/WMO. https://www.ipcc.ch/site/assets/uploads/sites/2/2019/05/SR15_Chapter2_Low_Res.pdf

Sierra, C. A., Trumbore, S. E., Davidson, E. A., Vicca, S., & Janssens, I. (2015). Sensitivity of decomposition rates of soil organic matter with respect to simultaneous changes in temperature and moisture. *Journal of Advances in Modeling Earth Systems*, *7*(1), 335–356. https://doi.org/10.1002/2014MS000358

Springsteen, B., Christofk, T., Eubanks, S., Mason, T., Clavin, C., & Storey, B. (2011). Emission Reductions from Woody Biomass Waste for Energy as an Alternative to Open Burning. *Journal of the Air & Waste Management Association*, *61*(1), 63–68. https://doi.org/10.3155/1047-3289.61.1.63

Sterman, J. D., Siegel, L., & Rooney-Varga, J. N. (2018). Does replacing coal with wood lower CO 2 emissions? Dynamic lifecycle analysis of wood bioenergy. *Environmental Research Letters*, *13*(1), 015007. https://doi.org/10.1088/1748-9326/aaa512

Ter-Mikaelian, M. T., Colombo, S. J., & Chen, J. (2015). The Burning Question: Does Forest Bioenergy Reduce Carbon Emissions? A Review of Common Misconceptions about Forest Carbon Accounting. *Journal of Forestry*, *113*(1), 57–68. https://doi.org/10.5849/jof.14-016

Wagener, W. W., & Offord, H. R. (1972). *Logging Slash: Its breakdown and decay at two forests in northern California* [Research Paper]. USDA Forest Service - Pacific Southwest Forest and Range Experiment Station.

Weedon, J. T., Cornwell, W. K., Cornelissen, J. H. C., Zanne, A. E., Wirth, C., & Coomes, D. A. (2009). Global meta-analysis of wood decomposition rates: A role for trait variation among tree species? *Ecology Letters*, *12*(1), 45–56. https://doi.org/10.1111/j.1461-0248.2008.01259.x

Westerling, A. L. (2018). *Wildfire Simulations for California's Fourth Climate Change Assessment: Projecting Changes in Extreme Wildfire Events with a Warming Climate* (No. CCCA4-CEC-2018–014; California's Fourth Climate Change Assessment, California Energy Commission, p. 57). University of California, Merced. cal-adapt.org/tools/wildfire

Yin, X. (1999). The decay of forest woody debris: Numerical modeling and implications based on some 300 data cases from North America. *Oecologia*, *121*(1), 81–98. https://doi.org/10.1007/s004420050909