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FINAL PROJECT REPORT

Forest Resource and Renewable Energy Decision Support System:

An Online Application for Decision Support in Siting Woody Biomass to Electricity Facilities 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 EPIC Program is funded by California utility customers under the auspices of the California Public Utilities Commission. The CEC and the state's three largest investor-owned utilities—Pacific Gas and Electric Company, San Diego Gas and 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.

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 Energy Research and Development Division at ERDD@energy.ca.gov.

ABSTRACT

Decisions to build biopower facilities, like those for most other infrastructure developments, are made within a complex framework of technical, environmental, ecological, social, political, financial, and economic considerations. With data and prior experience often limited, modeling to explore sensitivities to solution alternatives can help support and contribute to the decision processes, particularly when attempting to quantify technoeconomic and environmental qualifications that affect project feasibility. Biomass resources associated with California's extreme tree mortality, not only represent major ecological concerns but also represent opportunities to increase renewable energy supplies as part of improved management approaches. Toward this end, a decision support system (DSS) model was developed for lifecycle technoeconomic and environmental assessments that quantify the potential impacts of electricity generation. This web-based Forest Resource and Renewable Energy Decision Support System (FRREDSS) provides site-specific project development guidance on potential feedstock availability, as well as estimated economic and environmental performance. The model enables users to assess short- and longer-term feedstock availability and the potential economic feasibility and environmental impacts of biopower facilities in California. The current resource database derives from the U.S. Forest Service (USFS) national data collection for the Sierra Nevada region. The spatial analysis integral to the model yields proximity to feedstock, landings, and road networks, along with estimated delivered costs of feedstock at the facility, and the overall levelized cost of energy (LCOE) as electricity transmitted to the nearest substation. Included in the spatial analysis are related attributes including defined fire hazard zones where wildfire mitigation may have relevance to project siting. The model provides preliminary information to help inform more detailed engineering, environmental, and other studies critical to the final determination of overall project feasibility and decisions that must be made to proceed. The model is flexible toward future enhancements to expand the types of facilities considered, the available resource data and resource uncertainties, and many other factors influencing decision outcomes.

Keywords: forest biomass, biopower, waste-to-energy, forest management, forest residue, decision support system, technoeconomic analysis, environmental impacts

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Background

California forests are increasingly threatened by extensive wildfire. During the 2020 fire season alone, more than 4.3 million acres burned with the loss of 33 lives while incurring nearly half a million emergency responses (CAL FIRE, 2021), and losses continue. In 2023, CAL FIRE reported 7,109 wildfires, 324,745 acres burned, and 71 structures either damaged or destroyed. Over the past decade, unprecedented drought and insect outbreaks have also led to large-scale tree mortality, greatly impacting the forest ecosystem and further increasing the likelihood of even more hazardous wildfire. To help mitigate these effects, woody biomass derived from sustainable forest management practices and timber harvesting operations can serve as feedstock for electricity generation, biofuels, and other valuable products that contribute to the state's renewable energy and zero net carbon climate goals. These benefits together can help improve forest health, spur economic development, create jobs, and increase resilience to climate change and other influences. In attempting to secure public and regulatory approval and financing for these practices, woody biomass energy projects must quantify anticipated economic and environmental impacts. More precise forest biomass data on current and future woody biomass availability, assessment of feedstock transportation and available bioenergy technology for converting woody biomass to electricity, and detailed lifecycle emissions data would all help address these issues.

Project Purpose and Approach

The purpose of this project was to develop a web-based facility siting application, the Forest Resource and Renewable Energy Decision Support System (FRREDSS), which allows users to quickly evaluate the potential economic feasibility and environmental impacts of implementing biopower facilities at particular sites. As part of a large regional initiative to assess the feasibility of a hybrid poplar-tree-based biofuel industry in the Pacific Northwest,[1] a comprehensive web-based decision support tool had already been developed.[2] The University of California, Davis, and its partners leveraged this work and built a web-based application by integrating detailed forest biomass data from the U.S. Forest Service that integrates its Forest Inventory and Analysis (FIA) data, the Forest Vegetation Simulator (FVS), and the Field and Satellite for Ecosystem Mapping (FastEmap) (Huang et al., 2017) to simulate how forests change over time under both natural succession and vegetation management (Huang et al., 2018). The FRREDSS model was developed using primarily open-source software and integrates user-defined inputs with a number of analysis modules representing the elements of a forest-based biopower supply chain including forest biomass harvesting cost evaluation adapted from the Fuel Reduction Cost Simulator (FRCS) (Fight et al., 2006) optimized feedstock transportation

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[1] Advanced Hardwood Biofuels Northwest (AHB: http://hardwoodbiofuels.org/) project supported by the USDA Agriculture and Food Research Initiative (AFRI) Competitive Grant no. 2011-68005-30407 from the USDA National Institute of Food and Agriculture (NIFA).

[2] The AHB Decision support tool: http://willow.bioenergy.casil.ucdavis.edu/

employing the Open Source Routing Machine (OSRM)[3] and a transportation cost estimator developed in association with the Advanced Hardwood Biofuels project (Bandaru et al., 2015), the comprehensive technoeconomic assessment adapted from the California Biomass Collaborative[4] to provide the estimated levelized cost of energy over the facility's economic lifetime, and lifecycle assessment to estimate criteria pollutants, greenhouse gas emissions, and other environmental effects.

Key Results

The Forest Resource and Renewable Energy Decision Support System provides guidance on potential feedstock availability for site-specific forest biomass-to-electricity project development and allows users to conduct preliminary economic assessment and environmental performance assessments for potential biopower facilities. The project team at UC Davis, along with partners at UC Berkeley and the University of Maryland, developed this system to support project development decisions related to more detailed and costly engineering, siting, and other planning studies needed for actual project implementation. The tool may be used to inform policy development and community engagement activities as well. Distributed bioenergy as a dispatchable renewable generation resource can help mitigate intermittent energy supply from other renewables while simultaneously supporting wildfire risk mitigation as part of integrated sustainable forest management practices. The model offers potential ratepayer benefits by helping facilitate greater reliability in the state's renewable electricity generation portfolio, lowering costs for renewable biopower, increasing public safety from wildfire reduction or mitigation, and supporting key Electric Program Investment Charge (EPIC) goals. In addition, preliminary assessments of environmental benefits associated with the use of woody biomass may help reduce project development costs, increase the cost competitiveness of renewable energy systems, inform policy, and develop strategies that promote development of biopower facilities within the state. Through improved understanding of the development potential of new biopower facilities, model analyses may help support other societal and ratepayer benefits including watershed protection, air quality benefits, and greenhouse gas reductions, among others.

Knowledge Transfer and Next Steps

The development of the Forest Resource and Renewable Energy Decision Support System was guided by a technical advisory committee made up of representatives of various governmental agencies (CAL FIRE, Placer County Air Pollution Control District, California Air Resources Board, utilities (Sacramento Municipal Utility District and the California Public Utilities Commission), academia (UC Berkeley, Cal Poly Humboldt) non-profit organizations (Sierra Institute for Community and Environment, the Watershed Research & Training Center) and private industry (TSS Consultants). The model and its development have been presented at various biomass working group meetings as well as through seminars and meetings with academic and other institutions and organizations. The FRREDSS user guide (Yeo et al., 2022) provides users with step-by-step instructions on how to use the model, and the model website allows for continu-

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[3] http://project-osrm.org

[4] https://biomass.ucdavis.edu/tools/energy-cost-calculator/

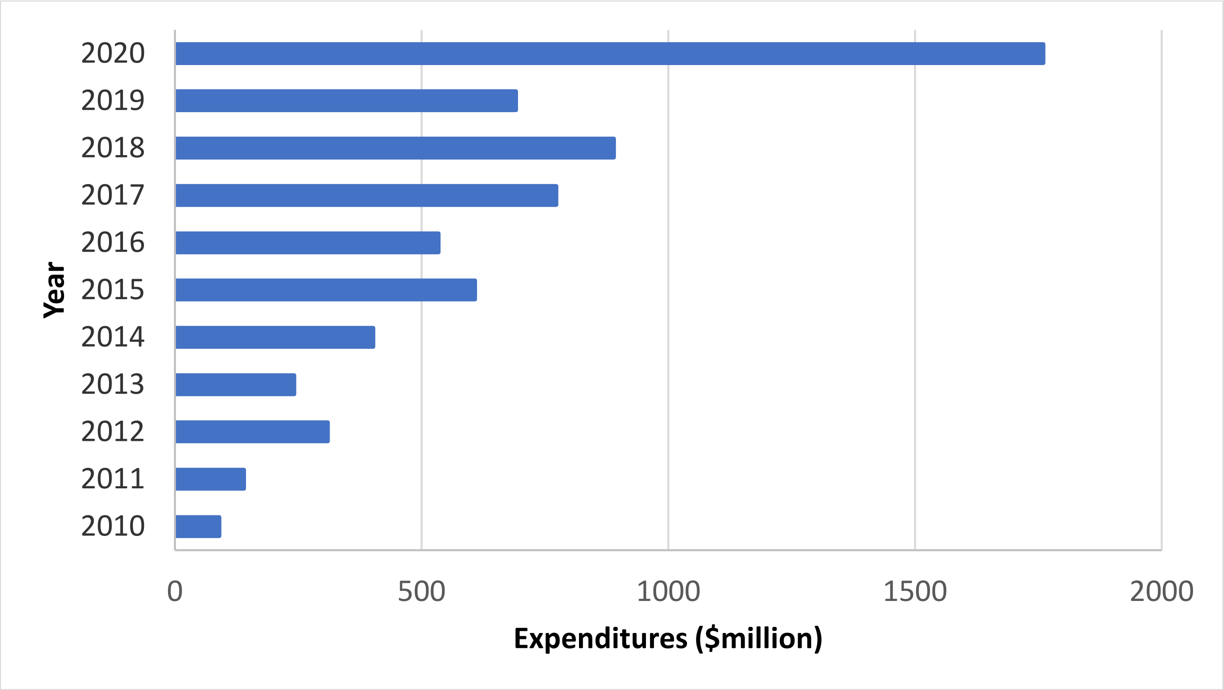
ous updates as well as sharing relevant case studies and results. Model development and results have been published and will continue to be published in academic journals and other media.

The model has to date received attention and interest from different governmental agencies, private industry, and academic institutions by either directly using the application for project development or furthering research and development. The successful development of the model has provided the basis for further expansion, utilization, and development. The California's Governor's Office of Planning and Research is funding five pilot projects to develop regional strategies that establish reliable access to woody feedstock; one of the tasks of the pilot projects is to test new mechanisms for developing long-term supply feedstock contracts. That office supports this effort through the development of an online digital marketplace for woody biomass by leveraging existing web-based tools including FRREDSS as well as the California Biomass Residue Emissions Characterization model of Cal Poly Humboldt, both developed through investments made by the California Energy Commission. Leveraging the achievements of these projects, additional research support has been provided to Cal Poly San Luis Obispo, Cal Poly Humboldt, and UC Davis to develop this online digital marketplace tool in order to connect buyers and sellers of forest biomass and enhance the market development for innovative wood-based products and renewable energy in California, which together may further enhance the model framework to support critical decision making around bioenergy and forest and other biomass resource management.

Chapter 1: Introduction

Forests are an essential natural resource of California, making up a third of the state's land-cover. The forest industry is an important sector of the state's economy, with nearly 60,000 in direct employment and earnings of close to $4 billion (Marcille et al., 2020), in addition to other regional economic benefits. Unprecedented drought and insect outbreaks have caused large-scale tree mortality, however, which greatly affects the forest ecosystem and increases fire hazards. Frequent and intense wildfires not only cost lives and destroy property, infrastructure, and services, but release large amounts of greenhouse gases (GHG) and air pollutants into the atmosphere. In the past decade, tree mortality has increased dramatically due to drought, bark beetle infestation, and wildfires. According to the California Department of Forestry and Fire Protection, over 147 million dead trees across 9.7 million acres of land in California were reported from 2010 to 2018 (CAL FIRE, 2019). Climate change is a key driver of these outcomes. Climate change leads to warmer spring and summer temperatures and earlier spring snowmelt, creating longer and more intense dry seasons (CAL F, 2021a). Among other effects, increased forest fires are products of global warming, as are significant impacts on ecosystems due to increased areas burned, fire intensity, and severity (Flannigan et al., 2000). According to the statistics published by CAL FIRE, there has also been a sharp rise in fire suppression expenditures over the past decade (Figure 1).

Figure 1: Fire Suppression Expenditures Have Increased Sharply From 2010 to 2020



Source: CAL FIRE, 2021.

Forest management philosophies and approaches are shifting (Reed et al., 2023). Utilizing sustainably sourced woody biomass (for example, woody residue from forest thinning) to produce bioenergy would help meet California's renewable energy and GHG emission reduction goals while reducing wildfire risk. Understanding and identifying consensus in sustainable management are important to these developments. Forest thinning is a means of restoring forest health and resilience by the planned removal of small trees, shrubs, and brush in overcrowded forests. Due to the large number of dead and dying trees, their removal can also help reduce susceptibility to wildfires (Stephens et al., 2018). Trees harvested via forest thinning and management, based on commercial value, can be divided into merchantable and unmerchantable categories. Merchantable trees are processed into sawlogs that are transported to pulp mills or sawmills. Unmerchantable small trees and tops and limbs from merchantable large trees are either disposed of via pile burning, left on the ground to decompose, or in some cases used for feedstock. According to the 2016 Billion-ton report of the United States Department of Energy (DOE), the approximate quantities of forest resources in the U.S., primarily logging residues and whole-tree biomass, ranged between 21 and 116 million dry tons in 2017 (U.S. Department of Energy, 2016). One way to utilize these residues is as feedstock to generate electricity in biomass power plants.

Using forest biomass for electricity generation, from both economic and environmental perspectives, has been extensively studied. Efforts have been made in the development of decision support systems for bioenergy production, incorporating spatial analysis (Frombo et al., (2009); Esteban and Carrasco (2011); Zambelli et al., (2012); Paredes-Sanchez et al., (2016); and Merz et al., (2018). However, little research has been done to incorporate spatial analysis, economics, and environmental assessments over the lifetime of a potential bioenergy facility, which could allow the specification of fine details such as forest prescription, harvesting system, conversion technology, and economic, technical, and financial parameters that would provide insights into the economic and environmental impacts of potential bioenergy facilities. To help address these needs, the project team developed a framework model called the Forest Resource and Renewable Energy Decision Support System (FRREDSS) for conducting the lifecycle technoeconomic and environmental assessments of generating electricity using forest biomass residues.

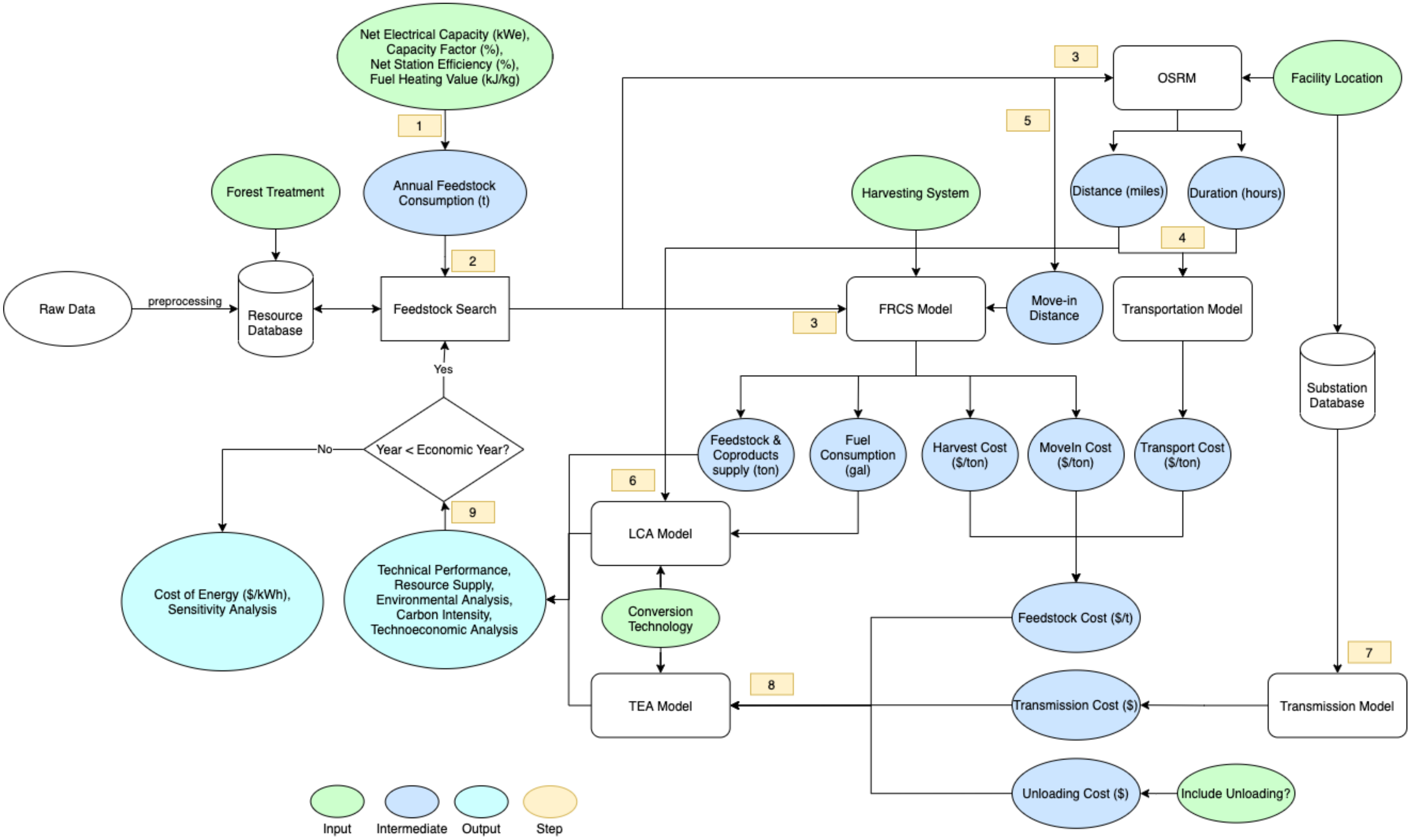
Chapter 2:
Project Approach

The FRREDSS model was designed to assess preliminary economic feasibility and partial environmental impacts over the full facility lifecycle from feedstock harvesting and transportation to energy conversion. FRREDSS also considers the availability of economically feasible woody biomass resources while considering the spatial and temporal dimensions of involved in acquiring the biomass feedstock. Spatial analysis with respect to resource distribution and availability, and actual transportation routes, are key features of the model required and are necessary to help evaluate the economic and environmental performance of a bioenergy facility over its lifetime.

FRREDSS Model Structure

The FRREDSS integrated model application was developed for open public access to expand availability of a more comprehensive, detailed decision support for forest-based renewable energy systems. The application is structured to integrate forest biomass resource data, forest harvesting cost projections adapted from methods of the Fuel Reduction Cost Simulator (FRCS) (Fight et al., 2006), transportation, technoeconomic assessment (TEA), transmission, and life cycle assessment (LCA) models yielding information on the cost of energy and potential environmental impacts (Figure 2). Full details on the model workflow and required user inputs and user accessible outputs from the model are included in the accompanying user guide and associated publications (Yeo et al., 2022; Li, 2022; Li et al., 2023).

Figure 2: Model Framework Showing How Forest Biomass Resource Data, Harvesting, Transportation, Conversion, Electricity Transmission, Technoeconomic Assessment, and Life Cycle Assessment Models Are Integrated Within FRREDSS



Forest Biomass Dataset

This tool draws spatial forest resource data in the Sierra Nevada region of California from the 2016 United States Forest Service (USFS) F^3 modeling framework, which presents the data in pixel format with 30x30 meter resolution (Huang et al., 2018). Statewide forest resource data and time-series data for future forest biomass resource estimation are not yet available from the USFS. The dataset contains nine biomass-type categories with information on the number and volume of trees, the amount of stem and crown biomass, and basal area for six size classes (Tables 1 and 2). Size classes, as defined by F^3, delineate trees by diameter. The nine biomass type categories and the six size classes together yield 54 variables or attributes for every pixel in the dataset in addition to the location data.

To improve computation speed, pixel-level data were aggregated into 360 by 360-meter clusters (or harvest units) to yield a more manageable size for the model. The resulting clusters have mostly a standard square 12.96 hectares[5] (32.02 acres) configuration, although this varies to some extent in proximity to feature boundaries such as lakes, rivers, and other terrain characteristics. The F^3 variables in the pixel data were similarly aggregated to cluster-level, on an area-weighted basis.

Table 1: List of Variables in the F3 Modeling Framework

Variable	Description	Unit
TPA	Live trees	number of trees/acre
SNG	Snags for all species and all decay classes	number of trees/acre
BMCWN	Branchwood and foliage plus unmerchantable portion of stemwood above a 4-inch diameter for live trees	BDT/acre
BMSTM	Stem biomass of live trees	BDT/acre
DBMCN	Branchwood and foliage plus unmerchantable portion of stemwood above a 4-inch diameter for snags	BDT/acre
DBMSM	Stem biomass of snags	BDT/acre
VOL	Volume of live trees	ft^3/acre
VMSG	Volume of snags	ft^3/acre
BA	Basal area of live trees	ft^2/acre

Table 2: List of Variables in the F3 Modeling Framework

Size Class	Diameter (inches)
2	$1 \leq DBH < 5$
7	$5 \leq DBH < 10$

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[5] One hectare (ha) equals 10,000 square meters or approximately 2.47 acres.

Size Class	Diameter (inches)
15	10 ≤ DBH < 20
25	20 ≤ DBH < 30
35	30 ≤ DBH < 40
40	DBH ≥ 40

Source: Data from USFS F^3, 2022

Tree Categories

Under FRCS, trees are categorized into three types: chip trees, small log trees, and large log trees. Chip trees are the trees chipped for board products or fuel, small log trees are trees with less than 80 cubic feet volume that can be mechanically felled and processed into logs, and large log trees are trees with 80 cubic feet or greater volume that are felled manually with chainsaws. Both chip trees and small log trees have volumes less than 80 cubic feet and, together, are categorized as small trees. Small log trees and large log trees together are categorized as log trees.

Forest Treatments

Activities that change forest stand structure and composition require forest practice prescriptions that document a planned series of treatments to be prepared before implementation (U.S. Forest Service, 2021). Ten forest treatments were modeled in consultation with the California Forest Practice Rules (CAL FIRE, 2020) and experts in public and private forest management (Tompkins, Ryan, personal communication, 2019; York, Robert, personal communication, 2019).The modeled treatment types are listed in Table 3. These treatment categories encompass the primary harvest types that result in forest biomass residue on both public and private land while constraining model complexity by binning all harvest types into ten categories. Most of the public forest land in California is federally managed, so public land treatment categories were crafted to match common treatments performed on national forests, such as commercial thinning. Some harvest types, such as clearcut, occur only on private land. Tree diameter thresholds may also vary between private and public land within a treatment type. Land type refers to the type of land on which a treatment is performed, both private and public. The specification of each treatment is summarized (Table 3) and discussed in terms of land types and tree categories.

1. **Clearcut** harvests all log trees on private land, and 60 percent of the chip trees with 1-5” diameter at breast height (DBH), and 90 percent of the chip trees with 5-10” DBH on private land.
2. **Commercial Thin** harvests only live log trees of mixed conifer and pine on private land. The harvest consists of certain percentages, starting with small ones closest to 10” until a certain residual basal area is reached, which is based on size class (see Appendix A. for a more detailed calculation of the Commercial Thin Forest Treatment).

3. **Commercial Thin with Chip Tree Removal** is the same as **Commercial Thin**, but with the additional removal of chip trees. On private land, 50 percent of the chip trees with 1-5″ DBH and 80 percent of the chip trees with 5-10″ DBH are harvested; on USFS land 85 percent of the chip trees with 1-5″ diameters at DBH, typically measured at 4.5 feet above ground DBH and 90 percent of the chip trees with 5-10″ DBH are harvested.
4. **Timber Salvage** harvests all dead log trees on both private and USFS land for timber.
5. **Timber Salvage with Chip Tree Removal** is the same as **Timber Salvage** but with the additional removal of chip trees. On private land, 60 percent of the chip trees with 1-5″ DBH, and 90 percent of the chip trees with 5-10″ DBH, are harvested; On USFS land, 85 percent of the chip trees with 1-5″ DBH and 90 percent of the chip trees with 5-10″ DBH are harvested.
6. **Selection Forest Treatments** harvest only live log trees on private land. The harvest consists of certain percentages, starting with small trees closest to 10″ until a certain residual basal area is reached, based on size class.
7. The percentages of different size classes of trees to be removed can be determined in a similar way to that for commercial thinning while the determination of residual_{BA} is based on Table 4.
8. **Selection With Chip Tree Removal** is the same as **selection** but with the additional removal of chip trees on private land. 50 percent of the chip trees with 1-5″ DBH and 80 percent of the chip trees with 5-10″ DBH are harvested.
9. **Ten Percent Group Selection** applies **Clearcut** to 10 percent of the area of a harvest unit and Selection to the rest of the area.
10. **Twenty Percent Group Selection** applies **Clearcut** to 20 percent of the area of a harvest unit and Selection to the rest of the area.
11. **Biomass Salvage With Chip Tree Removal** is essentially the same as **Timber Salvage With Chip Tree Removal**, except that it considers stems of log trees as part of the biomass feedstock.

Table 3: Specifications of the 10 Forest Treatments in FRREDSS

Treatment		Land Type	Log Trees		Chip Trees
#	Type		Live	Dead	Both Live and Dead
1	Clearcut	Private	100%	100%	1-5″ DBH – 60%
					5-10″ DBH – 90%
2	Commercial Thin	Private	calculated %		
3	Commercial Thin CT	Private	calculated %		1-5″ DBH – 50%
					5-10″ DBH – 80%
		USFS			1-5″ DBH – 85%
					5-10″ DBH – 90%
4	Timber Salvage	Private		100%	
		USFS		100%	
5	Timber Salvage CT	Private		100%	1-5″ DBH – 60%
					5-10″ DBH – 90%
		USFS		100%	1-5″ DBH – 85%
					5-10″ DBH – 90%
6	Selection	Private	calculated %		
7	Selection CT	Private	calculated %		1-5″ DBH – 50%
					5-10″ DBH – 80%
8	Ten Percent Group Selection	Private	Combination of Treatment 1 and 7. Applies clearcut to 10% of the area of a harvest unit and selection to the rest of the area.		
9	Twenty Percent Group Selection	Private	Combination of Treatment 1 and 7. Applies clearcut to 10% of the area of a harvest unit and selection to the rest of the area		
10	Biomass Salvage CT	Private		100%	1-5″ DBH – 60%
					5-10″ DBH – 90%
		USFS		100%	1-5″ DBH – 85%
					5-10″ DBH – 90%

* USFS = U.S. Forest Service; CT = chip tree removal.

Table 4: Basal Area that Should Remain for the Selection Forest Treatment Under Different Size Classes

Size Class	Residual Basal Area (ft2/ac)
1	100
2	75
3	75
4	50
5	50

Source: CALFIRE, 2020

Adaptation of the Fuel Reduction Cost Simulator

The Fuel Reduction Cost Simulator (FRCS) model was developed originally for the USFS as a Microsoft Excel™,[6] spreadsheet used to estimate the costs of harvesting trees from stump to truck based on machine costs and production equations from existing studies (Fight et al., 2006). The original FRCS model used a year 2000 cost basis (year 2000 constant dollars). These costs, including wages, equipment costs, and diesel fuel prices, were later updated to December 2007, and included three new FRCS variants categorized by region: west, north, and south, developed with newly added production equations to estimate harvesting costs in the Western, Northern, and Southern United States, respectively (Dykstra et al., 2009). The FRCS west variant was used in FRREDSS, with updated cost data for California. An allocation method is implemented in FRREDSS to estimate the cost and fuel consumption associated with acquiring feedstock. New inputs were added to improve model flexibility, and new outputs were added to provide insights on the yield, cost, and fuel consumption associated with feedstock. Additionally, the limits of the FRCS model on tree volumes were revised. The cost of harvesting large trees is modeled for volumes beyond the original limits. The adapted FRCS west variant was further converted to JavaScript and published as a node package manager (npm) package (https://www.npmjs.com/package/@ucdavis/frcs), and a user-friendly web application (https://frcs.ucdavis.edu) was created for stand-alone use, application programming interface (API) integration in FRREDSS, and potentially for other applications.

Harvesting Systems Represented in FRCS

The FRCS harvesting systems are divided into two categories: whole-tree (WT) systems and log-length systems. In whole-tree systems, small log trees are felled at the stump and processed into logs at the landing; in log-length systems log trees are felled, limbed, and bucked into logs at the stump. Based on how trees are harvested at the stump, the systems can be categorized as manual felling or mechanized felling. Trees can be felled manually with chainsaws or mechanically by feller bunchers or harvesters. The mechanized log length systems are also known as cut-to-length (CTL) systems where a harvester is used. Based on how trees are delivered to the landing, the systems can be categorized as ground based, cable yarding, and helicopter yarding. Ground-based harvesting systems are used in areas accessible by road and

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[6] Mention of a specific tradename does not constitute an endorsement by the University of California.

where slopes are lower than 40 percent. Cable yarding and helicopter-yarding systems are applied to areas inaccessible by road or with slopes greater than 40 percent. The specifications of the ten harvesting systems in FRCS are summarized in Table 5.

1. **Ground Based Mechanized Whole-Tree System (Ground Mech WT):** At the stump, small trees are felled and bunched by mechanical feller bunchers. Large log trees are manually felled, limbed, and bucked into logs with chainsaws. Bunches from small trees and the logs from large log trees are transported to the landing by mechanical skidders. At the landing, log trees are processed into logs by portable processors and loaded onto trucks. Tree tops and limbs and chip trees are chipped and loaded onto chip vans.
2. **Ground Based Manual Felling Whole-Tree System (Ground Manual WT):** At the stump, small trees are felled with chainsaws. Large log trees are felled, limbed, and bucked into logs with chainsaws. The small trees and the logs from large log trees are transported to the landing by skidders. At the landing, log trees are processed into logs by portable processors and loaded onto trucks. Tree tops and limbs and chip trees are chipped and loaded onto chip vans.
3. **Ground Based Manual Felling Log-Length System (Ground Manual Log):** At the stump, trees are chainsaw-felled, limbed, and bucked into logs. The logs are transported to the landing by skidders. At the landing, logs from log trees are loaded onto trucks, and logs from chip trees are chipped into chip vans.
4. **Ground Based Cut-to-Length System (Ground CTL):** At the stump, trees are felled, limbed and bucked into logs by a harvester. Logs are transported to the landing by mechanical forwarders. At the landing, logs from log trees are loaded onto trucks, and logs from chip trees are chipped into chip vans.
5. **Cable Yarding Manual Felling Whole-Tree System (Cable Manual WT):** At the stump, small trees are felled with chainsaws. Large log trees are felled, limbed, and bucked into logs with chainsaws. Small trees and logs from large log trees are transported to the landing by cable yarders. At the landing, small log trees are processed into logs by portable processors and loaded onto trucks. Small log treetops and limbs and chip trees are chipped into chip vans.
6. **Cable Yarding Manual Felling Whole-Tree/Log-Length System (Cable Manual WT/Log):** At the stump, chip trees are felled with chainsaws. Log trees are felled, limbed, and bucked into logs with chainsaws. Chip trees and logs are transported to the landing by cable yarders. At the landing, logs from log trees are loaded onto trucks. Chip trees are chipped into chip vans.
7. **Cable Yarding Manual Felling Log-Length System (Cable Manual Log):** At the stump, trees are chainsaw felled, limbed, and bucked into logs. The logs are transported to the landing by cable yarders. At the landing, logs from log trees are loaded onto trucks, and chip trees are chipped into chip vans.
8. **Cable Yarding Cut-to-Length System (Cable CTL):** At the stump, trees are felled, limbed and bucked into logs by harvesters. Logs are transported to the landing

by cable yarders. At the landing, logs from log trees are loaded onto trucks, and logs from chip trees are chipped into chip vans.

9. **Helicopter Yarding Manual-Log System (Helicopter Manual Log):** At the stump, trees are chainsaw-felled, limbed, and bucked into logs. The logs are transported to the landing by helicopters. At the landing, logs from log trees are loaded onto trucks, and logs from chip trees are chipped into chip vans.
10. **Helicopter Yarding Cut-to-Length System (Helicopter CTL):** At the stump, trees are felled, limbed, and bucked into logs by harvesters. Logs are transported to the landing by helicopters. At the landing, logs from log trees are loaded onto trucks, and logs from chip trees are chipped into chip vans. 1401

Table 5: List of Forest Harvesting Systems in the FRCS Model

	Ground-Based				**Cable**				**Helicopter**	
	MechWT	**CTL**	**Manual WT**	**Manual Log**	**Manual WT/Log**	**Manual WT**	**Manual Log**	**CTL**	**Manual Log**	**CTL**
Fell&Bunch: trees <=80 cf	✓									
Manual Fell, Limb, Buck: all trees				✓			✓		✓	
Manual Fell, Limb, Buck: all log trees					✓					
Manual Fell, Limb, Buck: trees >80 cf	✓		✓			✓				
Manual Fell: trees <=80 cf			✓			✓				
Manual Fell: chip trees					✓					
Harvest: trees <=80 cf		✓						✓		✓
Skid Bunched: all trees	✓									
Skid Unbunched: all trees			✓	✓						
Forward: trees <=80 cf		✓								
Yard Unbunched: all trees					✓	✓	✓		✓	
Yard CTL: trees <=80cf								✓		✓
Process: log trees <=80 cf	✓		✓			✓				
Load: log trees	✓		✓	✓	✓	✓	✓		✓	
Load CTL: log trees <=80 cf		✓						✓		✓
Chip: chip whole trees	✓		✓		✓	✓				
Chip: chip tree boles				✓			✓	✓	✓	✓
Chip CTL: chip tree boles		✓								

Source: Dykstra et al., 2009.

Feedstock Characteristics Used in FRCS

Woody biomass feedstock is made up of wood chips processed from chip trees, tops, and limbs of small log trees. This is different from how the original FRCS defined residues, which included only tops and limbs of trees (crown biomass). Large log trees do not constitute feedstock because they are felled, limbed, and bucked with chainsaws at the stump, and only logs are transported to the landing with separate operations to retrieve any residues. Logs from log trees are usually considered high-value material to be processed into lumber.

Feedstocks recovered from various FRCS harvesting systems have different characteristics (Table 6). The stem biomass of chip trees is always fully recovered because both whole-tree and log-length systems harvest chip tree boles and stems; whole-tree systems are designed to harvest and deliver whole trees to the landing; and in log-length systems, trees are cut into logs at the stump and only the logs are delivered to the landing. The crown biomass of trees is only partially recovered because of loss during delivery to the landing; also, a portion of biomass may be left on the ground for conservation purposes. For the whole-tree systems, FRCS assumes that a portion of tops and limbs are left onsite, and that the remaining fraction of the crown biomass, referred to as a "residue recovery fraction" in FRCS, is recovered as feedstock. For the log-length systems, tops and limbs left on the ground are generally not recovered, but for the ground-based cut-to-length system additional harvesting equipment, such as a bundler and a forwarder where slopes allow, can be brought to the harvest site and used to collect and deliver biomass to the landing. A smaller fraction of crown biomass is recovered in the ground-based cut-to-length system compared with whole-tree systems. Cable- and helicopter-based log-length systems are applied where the terrain is steep and ground-based harvesting equipment cannot easily be brought in, so no crown biomass is recovered in those systems. The amount of feedstock is computed by the adapted FRCS model.

Table 6: Feedstock Recoveries Under Different Forest Harvesting Systems

Biomass	Ground Mech WT	Ground CTL	Ground Manual WT	Ground Manual Log	Cable Manual WT/Log	Cable Manual WT	Cable Manual Log	Cable CTL	Helicopter Manual Log	Helicopter CTL
CT stem	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
CT crown	80%	50%	80%	0%	80%	80%	0%	0%	0%	0%
SLT crown	80%	50%	80%	0%	0%	80%	0%	0%	0%	0%

* CT = chip trees. SLT = small log trees.

The feedstock for biopower facilities includes both the crown and stem of chip trees and only the crowns of log trees. The only treatment that considers the stem of log trees as feedstock is treatment 10: biomass salvage with chip tree removal. The losses of biomass during harvesting are considered by FRCS by setting percentages, subject to the type of harvesting system, for the fraction of biomass actually harvested.

FRCS Inputs

The original FRCS required the specifications of a series of parameters and inputs to run simulations and generate logging costs including system type, cut type, location, yard/skid/forward slope distance, percent slope, and elevation. Other parameters included whether to include loading costs, whether to include move-in costs, the area treated, one-way move-in distances, and whether or not to include the costs of collecting and chipping residues. Tree characteristics included green wood density, residue fraction, and the hardwood fraction of chip trees, small log trees, large log trees, the number of trees per acre, and the average volume per tree with respect to chip trees, small log trees, and large log trees. Details regarding these input parameters are included in the user guide (Yeo et al., 2022) and in Li (2022).

In the original FRCS implementation, moisture content, residue recovery fraction for whole-tree systems, and residue recovery fraction for CTL were assumed to be 50 percent, 80 percent, and 50 percent, respectively. But these critical parameters can heavily affect the harvest cost and the amount of residue recovered. These are established as inputs in FRREDSS to allow users to enter better information, if available, based on local conditions. Default values, however, remain the same as in the original implementation.

Current cost data in the model (Appendix B, Table B1[8]) apply to California although these vary over time. Using FRCS in other states in the western region requires corresponding local cost data. New inputs in FRREDSS for labor and fuel costs were added as part of the API implementation. When the option of biomass salvage harvesting is selected, all types of trees are acquired as feedstock, including logs or stem biomass assumed to be chipped at the landing. (See "Biomass Salvage Option" in Appendix B for more details.)

FRCS Outputs

In addition to standard FRCS outputs of harvesting cost (in dollars per hundred cubic feet, dollars per green ton of trees, and dollars per acre of harvest unit), FRREDSS also computes biomass yield and fuel consumption for diesel, gasoline, and helicopter (aviation) fuel (Table 7, Appendix B), for both total biomass and feedstock biomass.

Allocation of Harvesting Cost and Fuel Consumption to Feedstock

FRCS was customized in FRREDSS based on the algorithm developed for estimating harvesting costs for feedstock alone and the fuel consumption for both total biomass and feedstock. The original FRCS considers chips from chip trees and logs from log trees as primary products and only tops and limbs from log trees as residues. FRREDSS considers chip trees plus residues (as defined by FRCS) as feedstock. There are four components of total harvest cost estimates: stump-to-truck cost for primary products, move-in cost for primary products, on-to-truck cost for residues, and move-in cost for residues (See Appendix B for details on how these costs allocate as feedstock costs). Residues in the various components refer to tops and limbs from log trees for consistency with the names of the variables in the original FRCS.

Table 7: Additional Harvesting Output Variables

Component	Variable	Unit
Total Biomass	Yield	GT
	Harvest Cost	$/acre
		$/CCF
		$/GT
	Diesel	$/acre
		$/CCF
	Gasoline	$/acre
		$/CCF
	Jet fuel	$/acre
		$/CCF
Feedstock	Yield	GT
	Harvest Cost	$/acre
		$/CCF
		$/GT
	Diesel	$/acre
		$/CCF
	Gasoline	$/acre
		$/CCF
	Jet fuel	$/acre
		$/CCF

1. Stump-to-truck cost for primary products involves the cost of harvesting trees at the stump, transporting them to the landing, and chipping chip trees into chips, also at the landing.
2. Move-in cost for primary products is the cost of transporting harvesting equipment for primary timber products to a harvest site.
3. On-to-truck cost for residues is the cost of collecting residues, which refers to tops and limbs from log trees, transporting them to a landing, and chipping them at the landing.
4. Move-in cost for residues only exists for the ground-based cut-to-length system where a bundler is required to be transported to the harvest site for collecting residues, and a forwarder is required for transporting those residues. For feedstock, a chipper is also required and is included separately in move-in costs for that option.

Only ground-based mechanized whole-tree, ground-based manual whole-tree, cable-yarding whole-tree, and ground-based cut-to-length systems have on-to-truck cost because in whole-tree systems residues are transported along with trees to the landing, and in the ground-based cut-to-length system a bundler and a forwarder can be used to collect and transport residues. Residues in the other systems are left unharvested. The on-to-truck cost for whole-tree systems only includes the cost of chipping residues at the landing, while that for the ground-based cut-to-length system includes the cost of bundling residues onsite, forwarding them to a landing, and chipping them at the landing.

Limits of the Tree Volumes in the FRCS Model

The original FRCS set limits on tree volumes. By definition, chip trees and small log trees are smaller than 80 cubic feet, and large log trees are greater than or equal to 80 cubic feet. Also, FRCS set maximum volumes for large log trees, all log trees (small log trees + large log trees), and all trees (chip trees + small log trees + large log trees). Inputs that exceeded the tree volume maximums triggered input validation errors that prevented FRCS from computing the results.

Harvesting Trees Beyond Limits

FRCS simulates harvesting large log trees up to 250 cubic feet volume. Harvest costs per unit volume of trees decrease as average tree volume increases because of efficiencies in moving to the landing. To estimate the costs of harvesting large log trees with an average volume greater than 250 cubic feet, the harvest cost per hundred cubic feet of trees greater than 250 cubic feet volume is assumed equal to that of trees with 250 cubic feet volume.

Transportation Model

Feedstock is collected, chipped at the landing, loaded onto trucks, and assumed to be directly transported to a conversion facility. The cost estimate for transporting biomass to the facility uses a transportation model similar to that developed by Merz, et al., (2018). The model estimates transportation cost by adding up estimated labor, fuel, truck ownership costs, and other costs of traveling from the landing site to the biopower facility.

Transport distance and duration between a harvest unit and a biopower facility are obtained from Open Source Routing Machine (OSRM), which is an open source router for computing the shortest path between two coordinates using data from the OpenStreetMap project (Luxen and Vetter, 2011). Due to the complexity of OpenStreetMap data, simple tag mappings are not supported by OSRM. Scripts named OSRM profiles can instead be used to generate the desired route, as well as to transport distance and duration between two coordinates by defining, in advance, the routing behavior and rules. An OSRM profile specifies routing properties such as vehicle category, vehicle size and weight, and the speed on different types of roads, among other properties. It also levies penalties on certain road conditions such as U-turns, traffic lights, and other speed impediments. In the development here, a truck profile that enforces vehicle size restrictions and highway penalties were attached to OSRM (Project-OSRM/osrm-profiles-contrib, 2021).

Different attributes of the feedstock clusters and their locations together allow optimization of the feedstock supply using, for example, minimum cost objectives. Full optimization requires searching the potential feedstock sourcing across the entire resource database, an intensive procedure that can add substantial time to the analysis. A partial optimization procedure is included in FRREDSS that significantly reduces computation time while approaching full optimization, depending on the user selection of a search expansion factor. Further details of this procedure are provided later in the context of specific case studies. .

Biopower Facility Modeling: Technoeconomic Assessment

The California Biomass Collaborative (https://biomass.ucdavis.edu, California Biomass Collaborative, 2013) earlier developed energy cost calculators in a Microsoft Excel™ spreadsheet format used as the development basis for the technoeconomic analysis (TEA) in FRREDSS to determine the levelized costs of energy based on technical, financial, and economic assumptions for three conversion technologies: direct combustion, combined heat and power, and gasification. A revenue requirements method is applied to determine the electricity price, yielding a stipulated rate of return on equity investment. This method is often used by utilities to establish energy prices.

The three conversion technologies share a modeling framework that requires inputs categorized into capital cost, base year electrical capacity, and fuel related inputs, operating and maintenance expenses, taxes, income other than energy, escalation and inflation rates, financing, depreciation schedule, tax credit schedule, and other incentives and taxes as appropriate. The asset depreciation is based on the U.S. Federal Modified Accelerated Cost Recovery System (MACRS). A production tax credit was available at $0.013 per kWh using open-loop biomass, including forest resources. Beginning in 2022, the tax credit was no longer applicable, although changes to these rules appear periodically and credit options are retained in FRREDSS. The equivalent of one year of debt repayment can be assumed to help secure loans and is placed into a savings account (known as debt reserve), in the event an unanticipated facility outage reduces income otherwise necessary for loan repayment. The debt reserve allows payments to continue until either repairs can be made, or the reserve is exhausted.

While the same modeling framework is used for the three technologies, additional inputs are required for the other two technologies. For combined heat and power (CHP) technology, in addition to electricity generation, heat is recovered for other uses including industrial processing, district heating, and similar applications. Additional inputs for the modeling of combined heat and power are presented in Table C.2. For the gasification technology, biomass is first converted to syngas, and the syngas is then used to generate electricity through a broader range of conversion systems including engines and gas turbines as well as boilers, with future possibilities in fuel cells and other technologies. Additional inputs for the assumed gasification system are presented in Table C.3. Annual cash flows of the three technologies are computed including the lifetime levelized cost of energy (Table C.4). For comparison purposes, a constant dollar levelized cost of electricity is similarly calculated using an inflation-adjusted capital recovery factor [C4][C5].

Electricity Transmission Cost Estimation

To connect a new biopower facility to the utility electricity grid, new transmission lines are generally needed. The installation cost of new transmission lines is derived from a transmission model developed by Black & Veatch for the Western Electricity Coordinating Council (Mason et al., 2012). The transmission model takes the voltage class, line characteristics, new construction or re-conductor, terrain type, and location as inputs for computing the capital cost of installing new transmission lines. The current algorithm for the integrated model uses OSRM to compute the distance from the selected biopower facility to the nearest substation, then selects the corresponding length category. The distance of the eight terrain types must be specified: forested, scrubbed/flat, wetland, farmland, desert/barren land, urban, rolling hills (2 percent to 8 percent slope), and mountain (greater than 8 percent slope). Since OSRM only computes the distance between two coordinates and no terrain information is provided, the forested terrain option is applied by default. Without better information as to voltage class, conductor type, and structure, other default input values are applied (Table 8).

Table 8: Default Input Values of the Transmission Model

Voltage Class	230 kV Single Circuit
Conductor Type	ACSS
Structure	Lattice
New or Re-conductor	New

Source: Mason et al. (2012)

To determine transmission cost, the transmission model multiplies baseline transmission cost by various multipliers adjusted for specific design considerations (Mason et al., 2012), where both baseline transmission cost and multipliers were identified in the original model and the baseline cost was adjusted for inflation to 2021 dollars, using the U.S. Consumer Price Index.

Environmental Impact and Life Cycle Analysis

Life cycle analysis (LCA) is a technique for assessing the environmental impacts of a product, process, or service throughout its lifecycle, from raw material acquisition and processing through manufacturing, distribution, and use, to recycling or disposal (U.S. Environmental Protection Agency 2008). This analysis can also be used to compare two alternatives in terms of their environmental performance, and to identify critical concerns such as where the most energy is consumed or pollution released, thus enabling more informed decisions. It consists of four phases: goal and scope, inventory, impact assessment, and interpretation (U.S. Environmental Protection Agency 2008). The goal and scope define the purpose and the boundary of a study, including the audience, the objective, and the specific processes included in the lifecycle. Inventory quantifies the inputs and outputs throughout the lifecycle, such as fuel consumption, carbon dioxide emissions, and particulate matter releases. Impact assessment evaluates the potential environmental impacts by classifying the inventory into specific categories including global warming potential, acidification, and eutrophication. Interpretation serves to conclude the overall environmental performance of the study, identifies processes of concern, informs policymakers, investors, or local communities, and recommends what could be improved by analyzing results of the inventory and impact assessment.

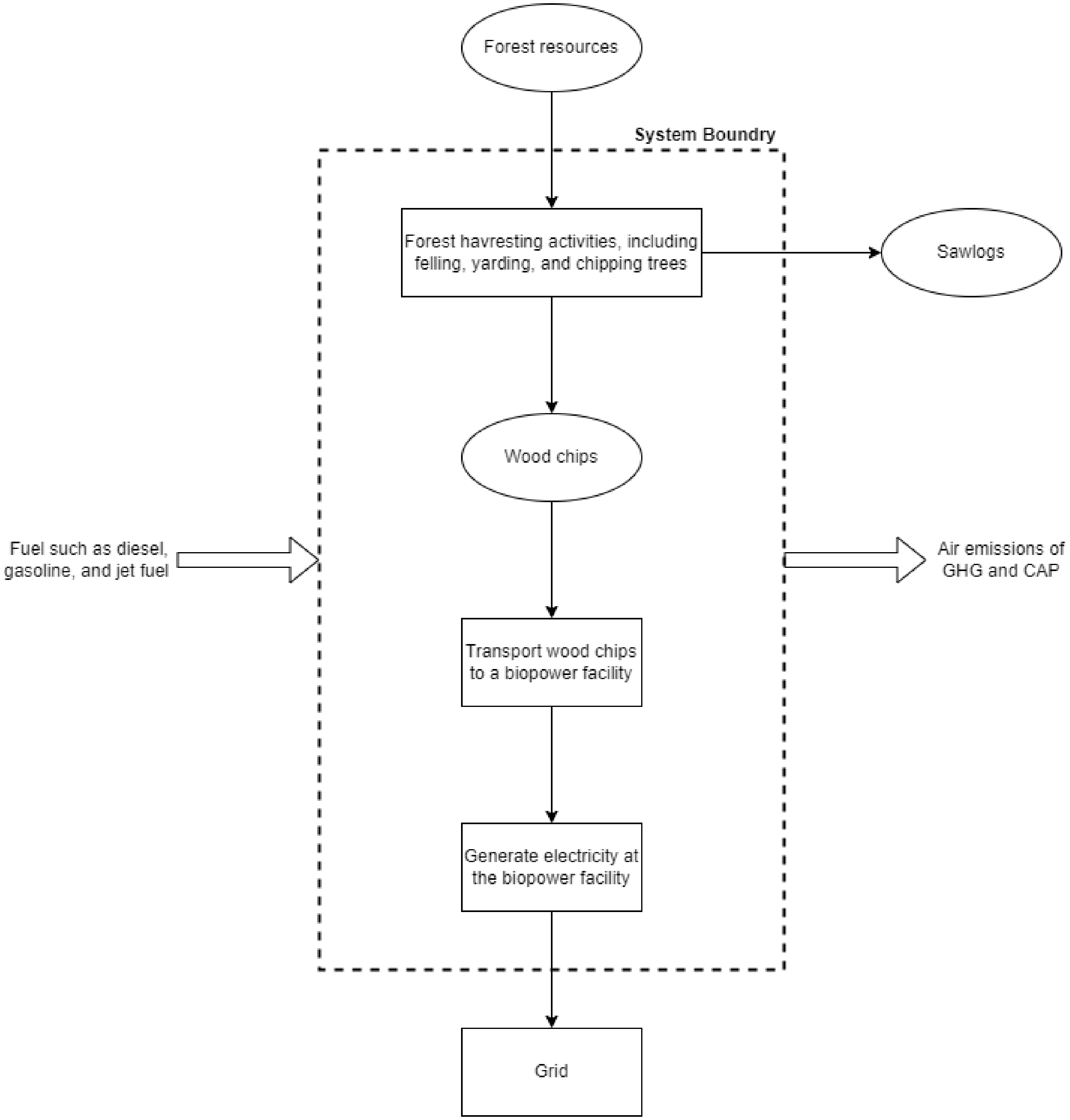
Goal and Scope of Partial LCA Model

Estimates of the emissions of greenhouse gases include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and emissions of criteria air pollutants (CAP) including carbon monoxide (CO), sulfur oxides (SO_x), nitrogen oxides (NO_x), particulate matter with an aerodynamic diameter of 10 micrometers and smaller (PM_{10}), particulate matter 2.5 micrometers and smaller ($PM_{2.5}$), and volatile organic compounds (VOC), throughout the system lifecycle. Carbon intensity, in kilograms CO_2 equivalent per MWh of electricity generation, is modeled based on emissions of CO_2, CH_4, N_2O, CO, and VOC. Environmental impacts such as global warming potential are also determined.

The system boundary is determined from forest resources at harvesting sites (stump) to the plant gate for electricity generated at a biopower facility, as shown in Figure 4. The three main phases of the lifecycle include feedstock acquisition at harvesting sites, feedstock transportation from harvesting sites to a biopower facility, and feedstock conversion at the facility. Construction of a new facility and the manufacturing of harvesting equipment are also included. The electricity transmission and distribution and the end-of-life or decommissioning of facility and harvesting equipment, which could be either disposed of or recycled, are not included in the current scope.

The functional unit of the partial LCA in the model is 1 MWh of electricity generated. The methodology is detailed in Appendix D.

Figure 3: System Boundary of the LCA Model is Taken From the Forest Resources at Harvesting Sites to the Plant Gate of the Biopower Facility



Life Cycle Inventory

Life cycle inventory (LCI) data include emission factors of GHG and CAP. Table 9 summarizes the LCIs of generating electricity via the three conversion technologies, the aggregated LCIs of the three types of fuel used (including fuel production and consumption), and the LCI of transportation using a truck tractor and trailer. Data types and sources are shown in Table 11. The LCI data for fuel production were obtained from the Greenhouse Gases, Regulated

Emissions, and Energy use in Transportation (GREET) model developed by the Argonne National Laboratory (2021). Diesel, gasoline, and jet fuel correspond to low-sulfur diesel, California reformulated gasoline (E10), and conventional jet fuel. LCI data for CAP and CO_2 emissions of diesel and gasoline were derived from the California Air Resources Board's emissions inventory (EMFAC, California Air Resources Board 2021b), where the emission factors of volatile organic compounds (VOC) were assumed to be the same as those of reactive organic gas (California Air Resources Board 2000). Emission factors of CH_4 and N_2O for diesel and gasoline were obtained from the Emission Factors for Greenhouse Gas Inventories database (U.S. Environmental Protection Agency, 2018) and are equivalent to those of gasoline and diesel for agricultural equipment. The LCI data for jet fuel, except $PM_{2.5}$, were derived from the emissions of freight aircraft in the GREET model (Argonne National Laboratory, 2021). The emission factor for $PM_{2.5}$ of jet fuel was estimated by multiplying the emission factor of PM_{10} by the average of the ratios of $PM_{2.5}$ to PM_{10} of gasoline and diesel. The LCI data of transportation, obtained from the GREET model, were converted from the well-to-wheel emission rates of low sulfur fueled heavy duty trucks.

The LCI data for the integrated gasification combined cycle (IGCC) conversion facilities were obtained from the California-specific version of the GREET model (CA-GREET) that correspond to the emission rates from biomass IGCC turbine, fueled with forest residues (California Air Resources Board, 2019). The emission factors for CO_2, NO_x, SO_x, CH_4, and N_2O, using the conventional boiler-steam cycle and CHP conversion technologies, were derived from the Emissions and Generation Resource Integrated Database (eGRID, U.S. Environmental Protection Agency 2019). Power plants located in California and categorized as non-CHP and using the primary fuel of wood or wood waste solids were first selected, and the average emission rates weighted by annual net generation were derived for the conventional boiler-stream cycle. The power plants categorized as CHP were selected to derive the emission factors for CHP. The emission rates provided by eGrid were the portion attributed to electrical energy from the plants; the electric allocation factor of each CHP plant is also provided, which is the ratio of the electric energy output to the combined total electrical and steam (or heat) energy outputs (U.S. Environmental Protection Agency, 2021). The emission factors for CO, $PM_{2.5}$, PM_{10}, and VOC were derived via the California Air Resource Board's facility search engine (California Air Resources Board 2021c), which identifies the annual emissions of criteria pollutants and air toxics from the California Emissions Inventory Data Analysis and Reporting System (CEIDARS). The most recent database year of 2019 was selected, and the portion of the annual emissions attributed to electricity was calculated using the electricity allocation factor in eGrid. Emission factors were further calculated as the average weighted by the annual net generation of the selected plants.

The LCI data of facility construction and equipment manufacturing were from the widely used Economic Input-Output Life-Cycle Assessment (EIO-LCA) web model developed by the Carnegie Mellon University Green Design Institute (2008). The 2002 purchaser price model was selected for both facility construction and equipment, which estimates impacts from resource extraction through purchase of the product. For facility construction, Construction was selected as the broader sector group, and Other Nonresidential Structures was selected as the detailed sector, which includes the construction of power and communication structures such as power plants, transmission, and substations. For equipment manufacturing, Machinery and Engines was selected as the broader sector group and Construction Machinery Manufacturing was selected as the detailed sector, which includes the manufacturing of logging equipment. Since the LCI data for facility construction and equipment manufacturing were derived from the 2002 purchaser price model, the facility capital cost input as current dollars were adjusted for inflation to 2002 dollars using the U.S. Consumer Price Index. The equipment purchase prices from FRCS were already in 2002 dollars, so no conversion was needed.

Table 9: LCI for Feedstock Acquisition, Transportation, and Conversion

Pollutant	Unit	Boiler	CHP	IGCC	Diesel	Gasoline	Jetfuel	Transport
		per kWh electricity generated			per gallon			per mile
CO_2	kg	1.59	1.11	0.95	22.72	6.25	11.48	2.67
CH_4	g	0.54	0.38	0.03	17.25	14.10	12.45	3.20
N_2O	g	0.07	0.05	0.09	0.31	0.55	0.04	0.01
CO	g	1.30	1.60	0.07	96.49	2746.44	13.40	3.60
NO_x	g	0.81	0.57	0.08	16.29	48.15	53.17	2.60
PM_{10}	g	0.13	0.07	0.02	0.73	32.31	0.75	0.04
$PM_{2.5}$	g	0.12	0.06	0.01	0.66	24.42	0.63	0.04
SO_x	g	0.18	0.12	0.41	2.66	2.31	5.08	0.15
VOC	g	0.04	0.05	0.07	3.17	52.91	3.20	0.30

Table 10: LCA Data Source and Types

Type		Pollutants	Source	Year
Boiler		CO_2, CH_4, N_2O, NO_X, SO_X	eGrid	2019
		CO, PM_{10}, $PM_{2.5}$, VOC/ROG	CARB CEIDARS	2019
CHP		CO_2, CH_4, N_2O, NO_X, SO_X	eGrid	2019
		CO, PM_{10}, $PM_{2.5}$, VOC/ROG	CARB CEIDARS	2019
IGCC		CO_2, CH_4, N_2O, CO, NO_X, PM_{10}, $PM_{2.5}$, SO_X, VOC	CA-GREET	2019
Diesel	production	CO_2, CH_4, N_2O, CO, NO_X, PM_{10}, $PM_{2.5}$, SO_X, VOC	GREET	2021
	consumption	CO_2, CO, NO_X, PM_{10}, $PM_{2.5}$, SO_X, VOC/ROG	CARB EMFAC	2021
		CH_4, N_2O	EPA	2018
Gasoline	production	CO_2, CH_4, N_2O, CO, NO_X, PM_{10}, $PM_{2.5}$, SO_X, VOC	GREET	2021
	consumption	CO_2, CO, NO_X, PM_{10}, $PM_{2.5}$, SO_X, VOC/ROG	CARB EMFAC	2021
		CH_4, N_2O	EPA	2018
Jetfuel	production	CO_2, CH_4, N_2O, CO, NO_X, PM_{10}, $PM_{2.5}$, SO_X, VOC	GREET	2021
	consumption	CO_2, CH_4, N_2O, CO, NO_X, PM_{10}, SO_X, VOC	GREET	2021
		$PM_{2.5}$	Estimated	
Transport		CO_2, CH_4, N_2O, CO, NO_X, PM_{10}, $PM_{2.5}$, SO_X, VOC	GREET	2021
Construction & Manufacturing		CO_2, CH_4, N_2O, CO, NO_X, PM_{10}, $PM_{2.5}$, SO_X, VOC	EIO-LCA	2002

Chapter 3: Results

Case studies demonstrate the use of the FRREDSS model. The first case study simulated a 25 MW_e conventional boiler-steam cycle (Rankine cycle) facility. A second simulated a 3 MW_e gasification biopower facility. The results of these two case studies provide insights into cost and emission implications for different combinations of forest treatments and harvesting systems. Levelized cost of energy (LCOE) for the conventional boiler-steam cycle case study ranged from $135 to $575 per MWh of electricity generated and from $183 to $588 per MWh for the 3 MW_e gasification case study. Estimated direct, non-offset GHG emissions range from 1,668 to 1,836 kg CO_2 equivalent per MWh for the 25 MW_e direct combustion facility, and from 1,024 to 1,188 kg CO_2 equivalent per MWh for the 3 MW_e gasification facility. Both studies show a substantial reduction in emissions from utilizing forest residue for electricity generation compared to emissions from conventional open pile burning and displacement of grid electricity based on the current mix of nonrenewable and renewable generation sources in California.

Full up-to-date statewide forest resource data, as well as time-series data for future projections, are not yet available, and the F^3 dataset was limited to the Sierra Nevada region with a reference year of 2016. For convenience, two sites were selected at locations near existing similarly sized power stations using wood fuel as feedstock, although no direct relation to these existing facilities should be assumed or inferred. Due to data limitations, the case studies used the same feedstock dataset across the lifetime of a project, assumed no forest growth in future years, and did not account for more recent wildfires that have reduced resource inventories in certain areas.

Case Study 1: 25 MW Combustion Biopower Facility

The first case study modeled a 25 MW biopower facility with an economic life of 20 years using a conventional boiler-steam cycle. This scenario assumed a capital cost of $100 million with a capacity factor of 80%. The annual operation and maintenance (O&M) cost was assumed to be $334 per kWe-year installed, with no production tax credit applied. Other than facility location, capital cost, capacity factor, and annual O&M cost, the default model technical, financial and economic information were used. The labor wages, fuel price, and producer price index (PPI) were escalated by a default inflation rate of 2.1 percent over the lifetime of the project. Inflation rates have since increased as of 2023, but different rates and other inputs can be added by the user to replace the default values and explore the sensitivity of the solution to assumed values. To realize an annual electric generation of 175,200 MWh, the estimated annual feedstock demand of the facility is 169,475 bone dry metric tons (BDMT). The nearest substation is in close proximity at less than a kilometer away from the facility.

Table 11: Facility Assumptions for a 25 Mwe Conventional Boiler Steam Cycle (Rankine Cycle) Facility

Latitude (degrees N)	37.87439642
Longitude (degrees W)	-120.4759226
Capital Cost ($)	100,000,000
Capacity Factor (%)	80
Debt Ratio (%)	75
Debt Interest Rate (%)	5
Cost of Equity (%)	15
Net Efficiency (%)	20
Labor Cost ($/y)	3,000,000
Maintenance Cost ($/y)	2,000,000
Insurance/Property Tax ($/y)	2,000,000
Utilities ($/y)	300,000
Ash Disposal ($/y)	150,000
Management/Administration ($/y)	300,000
Other Operating Expenses ($/y)	600,000
O&M Cost ($)	8,350,000
O&M Cost ($/kWe)	334

LCOE and GHG Emissions

As noted in the section on Project Approach, the 10 forest treatments and 10 harvesting systems yield 100 potential combinations. To determine the combination yielding at the lowest cost or the least environmental impact, the model was run with all combinations (Figure 4). Certain forest treatments can only be combined with a number of harvesting systems (additional detail in Li et al., 2023) and for this case study, no results were derived for any combinations with forest treatment 4 (T4, see Table 13), and the T6 + S4 (Table 13) combination because of the limited amount of biomass available within the region from timber salvage. This is not a general result however, and the options may have value for smaller facilities.

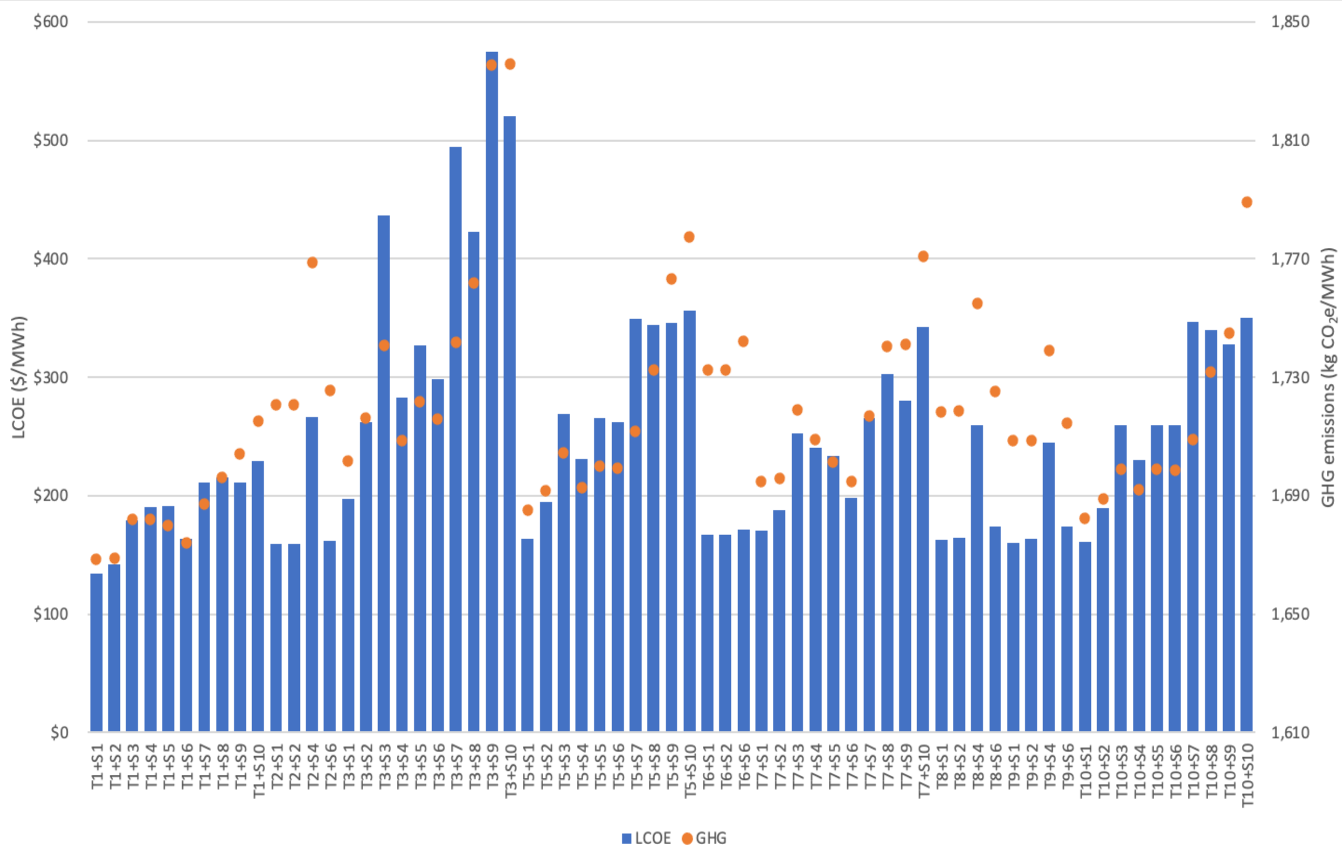
Table 12: Amount of Available Feedstock (Millions of Bone-Dry Metric Tons) and Resource Sufficiency for the Assumed Facility Capacity in the Sierra Nevada Region From Different Combinations of Forest Treatments and Harvesting Systems

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
T1	52.8	52.8	28.5	43.7	27.9	40.3	21.7	21.7	29.4	29.4
T2	6.1	6.1	0*	3.8	0*	5.0	0*	0*	0*	0*
T3	56.3	56.3	35.1	48.3	28.5	33.5	19.9	19.9	35.5	35.5

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
T4	1.3*	1.3*	0*	0.8*	0*	0.8*	0*	0*	0*	0*
T5	78.3	78.3	56.5	70.1	48.4	49.3	35.9	35.9	57.6	57.6
T6	4.5	4.5	0*	2.8*	0*	3.7	0*	0*	0*	0*
T7	19.2	19.2	10.7	16.0	11.7	15.4	8.6	8.6	11.2	11.2
T8	6.7	6.7	1.2*	4.6	1.3*	5.4	0.9*	0.9*	1.2*	1.2*
T9	8.8	8.8	2.4*	6.4	2.6*	7.1	1.9*	1.9*	2.5*	2.5*
T10	129.2	129.2	107.4	121.0	75.7	76.6	63.2	63.2	106.3	106.3

*Highlighted cells indicate insufficient resource availability relative to total resource demand.

Figure 4: LCOE and GHG Emissions Associated with Forest Treatment and Harvesting System Combinations

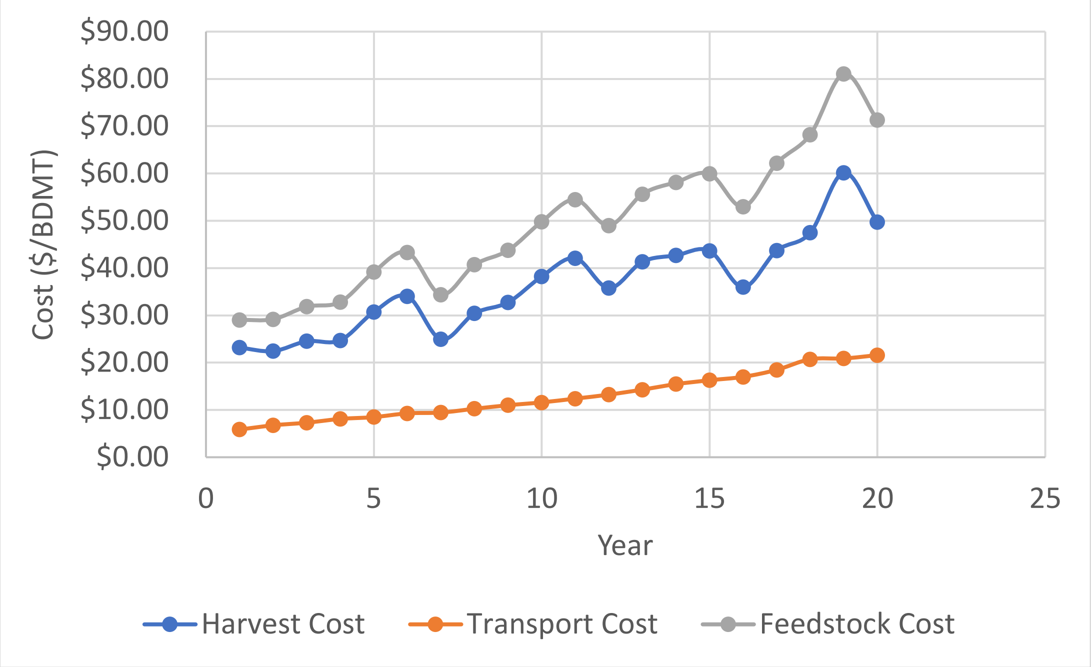


Under these assumptions, LCOE ranges from $135 to $575 per MWh and GHG emissions range from 1668 to 1836 kg CO_2 equivalent per MWh. The combination of clearcut (T1) and ground-based mechanized whole-tree system (S1) resulted in the lowest LCOE and GHG emissions and is referred to as baseline (Table 13). The LCOE for this combination is $135 per MWh of electricity generated. The average feedstock cost is $50.25 per BDMT of acquired feedstock, which consists of a harvest cost of $36.44, a transport cost of $13.80, and a small move-in cost per bone dry metric ton (BDMT) feedstock. The baseline harvests from clusters extending from the facility site (the clusters closer to the facility are assumed to be harvested first, and transport costs grow over the lifetime of the project). Figure 5 shows that the harvesting strategy leads to an increasing transport distance. In contrast, harvest cost, which on average accounts for 73 percent of the feedstock cost, is not increasing across the lifetime of the facility. The move-in cost associated with feedstock is quite small on a per BDMT acquired feedstock basis because it only accounts for the move-in of a chipper in the ground mechanized whole-tree system, and the total amount of feedstock for this facility size is large. Move-in costs of other harvesting equipment are attributed to the timber fraction.

Table 13: Forest Treatments (T) and Harvesting Systems (S)

Forest Treatment	Symbol	Harvesting System	Symbol
Clearcut	T1	Ground Mech WT	S1
Commercial Thin	T2	Ground Manual WT	S2
Commercial Thin CT	T3	Ground Manual Log	S3
Timber Salvage	T4	Ground CTL	S4
Timber Salvage CT	T5	Cable Manual WT/Log	S5
Selection	T6	Cable Manual WT	S6
Selection CT	T7	Cable Manual Log	S7
10% Group Selection	T8	Cable CTL	S8
20% Group Selection	T9	Helicopter Manual Log	S9
Biomass Salvage CT	T10	Helicopter CTL	S10

Figure 5: Harvest and Transportation Costs Over the Economic Life of the Project, Case Study 1, Baseline Scenario



Environmental Benefits and Impact

Compared with open pile burning, the baseline bioenergy scenario realizes environmental benefits in terms of GHG and CAP reductions. All but one of the emission factors for open burning were obtained from Springsteen et al., (2015), which does not report N_2O. The emission factor for this species was obtained from the Biomass Waste for Energy Project Reporting Protocol proposed by the Climate Action Reserve (2011). The electricity produced from biomass feedstock not only avoids emissions emitted from open pile burning as an alternative fate of the biomass, but also potentially displaces an equivalent amount of electricity from the utility electricity grid if total demand is not increased due to the availability of this additional capacity. The potential emission reductions from utilizing forest biomass for electricity production are significant; GHG, CO, NO_x, $PM_{2.5}$, and VOC emissions decline between 21 percent and 99 percent (Table 14). The net GHG emissions calculated by subtracting the emissions from open pile burning and electricity displacement are negative at -440 kg per MWh electricity generated, which constitutes an overall emission reduction. A GHG intensity of 210 kg per MWh electricity generation in 2019 was reported by the California Air Resources Board (2021a). The emission factor of NO_x for the California grid was derived from the California Electricity Profile 2020, published by the U.S. Energy Information Administration (2021b), and those of CO, $PM_{2.5}$ and VOC were derived from 2017 estimated annual average emissions published by the California Air Resources Board (2022).

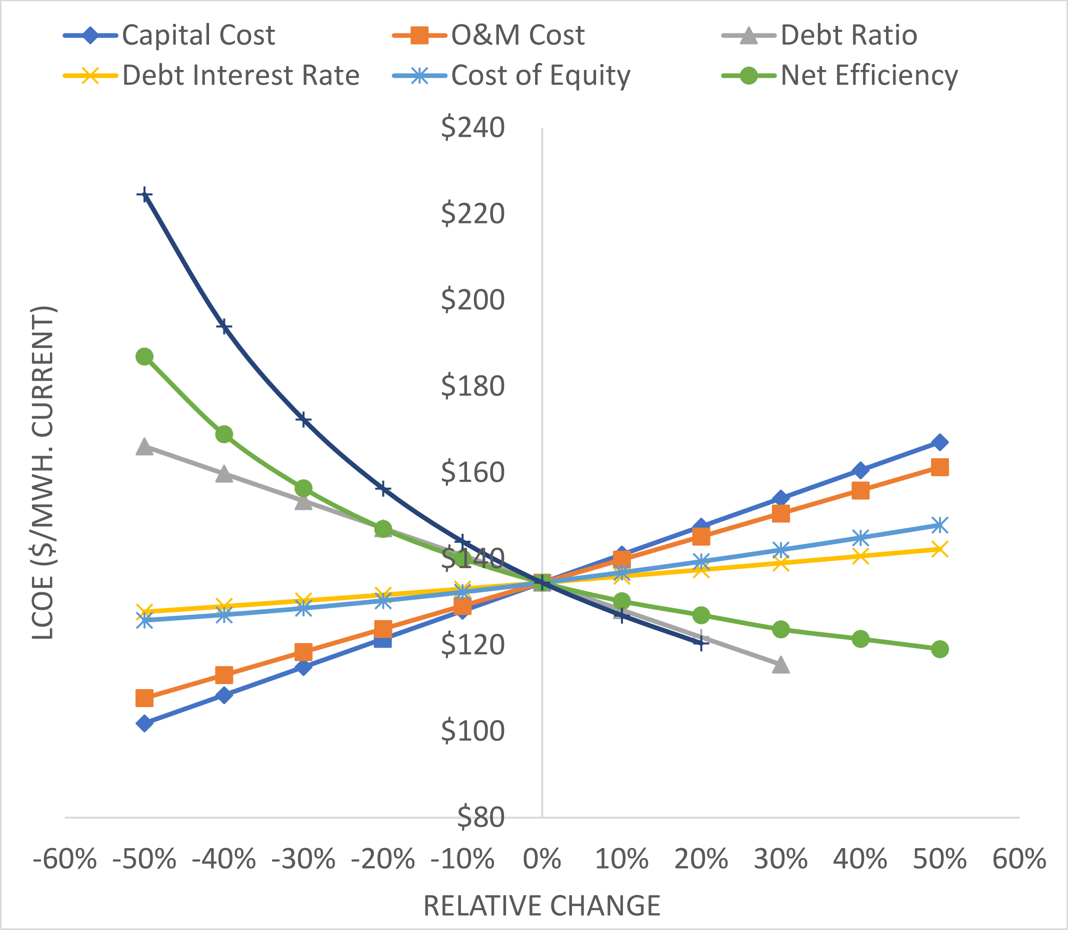
Table 14: Baseline Air Emissions Reductions From Bioelectricity Generation

Scenario	Air Emissions (kg/MWh electricity generated)				
	NO_x	$PM_{2.5}$	VOC	CO	GHG
Open pile burning	2.90	6.29	4.84	60.94	1899
Displaced power from grid	0.34	0.01	0.01	0.08	210
Forest biomass electricity	0.87	0.13	0.06	1.49	1668
Emission reductions	2.37	6.17	4.78	59.53	440
Overall reduction (%)	73	98	99	98	21

Sensitivity Analysis

Sensitivity of the LCOE to key economic parameters including capital cost, O&M cost, debt ratio, debt interest rate, cost of equity, net efficiency, and capacity factor were assessed through multiple analyses in which each parameter was varied over a range of plus or minus 50 percent from the baseline in 10 percent increments (Figure 6). Capacity factor is important to the annual electrical energy generation, and therefore partially determines the amount of feedstock to be acquired. Net efficiency directly affects the amount of feedstock to be acquired for the same electrical capacity. Assumptions around capital cost, O&M cost, debt ratio, and debt interest rate are important to the annual energy revenue requirement, but sensitivity analysis can also apply to many other factors as well.

Figure 6: Sensitivity of LCOE ($/MWh) to Different Key Economic Parameters Including Capital Cost, O&M Cost, Debt Ratio, Debt Interest Rate, Cost of Equity, Net Efficiency, and Capacity Factor



Optimization

To meet the annual feedstock needs of a user-specified bioenergy facility, the cluster selection algorithm uses a circular search centered at the facility location (or at a predefined center of resource if the facility is located outside the feedstock acquisition area). The search increases the radius in 1 km (0.6 mile) increments until the harvestable clusters within the radius can supply the annual feedstock demand. The harvest and transport costs per unit of feedstock are calculated using the FRCS and transportation models, respectively, and they constitute the feedstock cost of the clusters where the move-in cost is not included because the move-in route cannot be determined without first identifying all the clusters to be harvested for the year. The clusters are then sorted by feedstock cost and selected until the annual feedstock demand is met. With each succeeding year, the selection radius increases as clusters are assumed to be harvested only once within a typical project's lifetime. Differences in biomass yields, however, result in some clusters located at a greater distance from the facility with lower harvest costs sufficient to reduce total delivered cost even with greater transportation distances. Searching only within the area sufficient to supply the annual feedstock requirement may therefore miss these lower-cost sources beyond the annual search and constitutes a suboptimal outcome for a minimum feedstock cost objective. As mentioned earlier, full optimization of the feedstock supply requires analyzing the cost from all feasible clusters within the supply domain and was realized by segregating unused clusters from the entire cluster database, calculating feedstock harvesting cost associated with each of the remaining clusters, then sorting the clusters by feedstock cost to supply the annual feedstock demands at lowest cost, albeit increasing year to year.

The levelized cost of energy (LCOE) from full optimization is $131.88 per MWh, and direct GHG emissions are 1,668.5 kg CO_2 equivalent per MWh. As expected, feedstock cost is dynamic and consistently increases over the economic life of the project (Figure 7). On a relative cost basis, the average feedstock harvest cost per BDMT (14.4 percent), in the optimized scenario, declines slightly more than the average transport cost increases (13.8 percent), and as the harvest cost ($36.44/BDMT) is about 2.6 times the transport cost ($13.80/BDMT), there is a net reduction in total delivered cost of $3.30 (or 7 percent overall), including the increase in move-in cost (Table 15. The feedstock distribution in the optimized scenario (Figure 8) is geographically wider than that of the baseline proximity only supply scenario. Move-in cost is more than doubled in the optimized scenario compared with the baseline due to the sparse distribution of feedstock, although it is a small contribution with little impact on overall feedstock cost. The average feedstock delivered cost was reduced from $50.25/BDMT in the baseline to $46.95/BDMT through full optimization, but the reduction of net GHG emissions from the economic optimization (-440.1 CO_2e/BDMT) is slightly less than that of the baseline (-440.3 kg CO_2e/BDMT) due to the added transportation.

Figure 7: Feedstock for Nearest Proximity (Baseline) and Optimized Feedstock Supply, Case Study 1

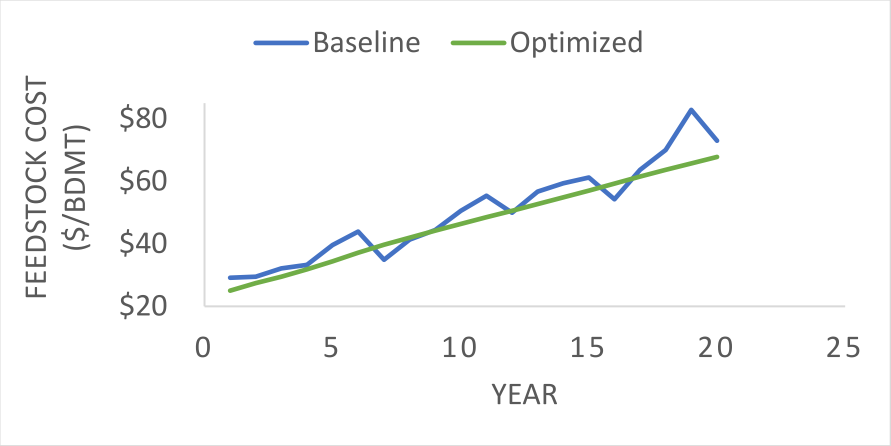
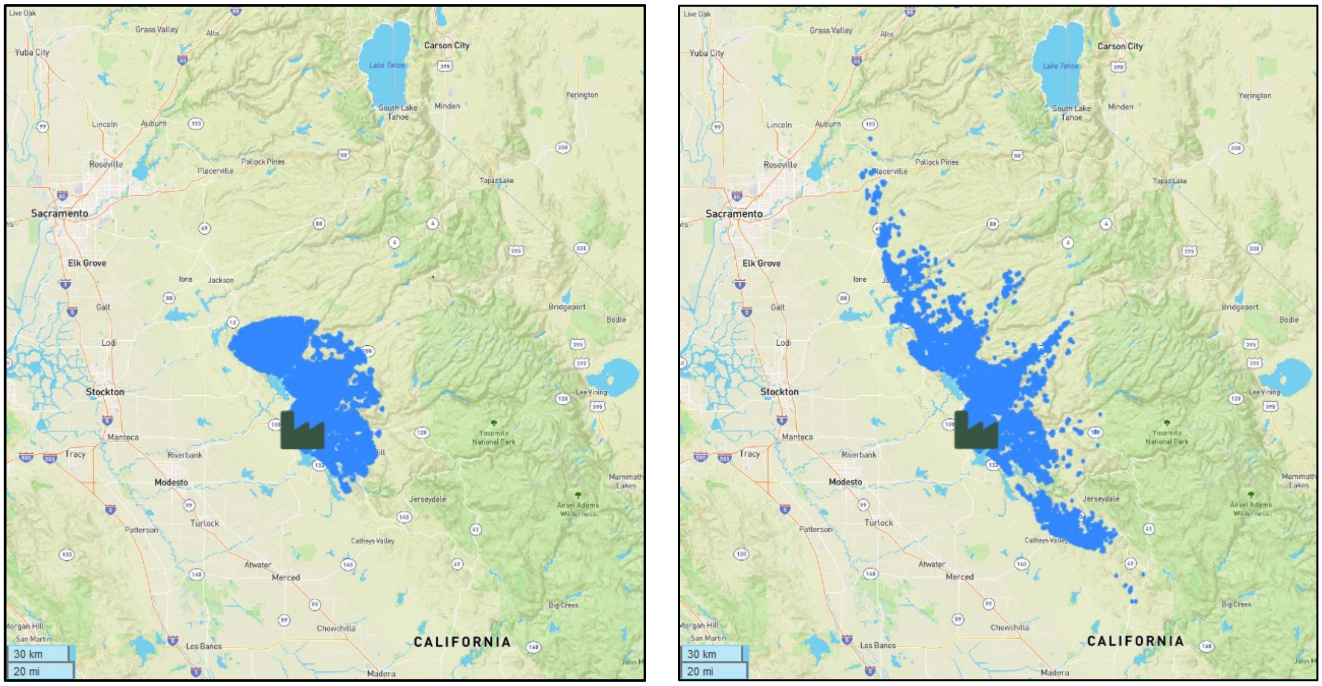


Table 15: Cost Comparison: Baseline vs. Optimized Scenarios

Category	Baseline ($/BDMT)	Optimized ($/BDMT)	Difference (%)
Harvest Cost	36.44	31.19	-14.4
Transport Cost	13.80	15.71	13.8
Move-in Cost	0.02	0.05	150
Feedstock Cost	50.25	46.95	-7

Figure 8: Feedstock Distribution is Sparser in the Optimized Scenario (Right) than in the Baseline Scenario (Left), Case Study 1



Although the optimization generates lower LCOE by minimizing feedstock cost, it is more computationally intensive, and increases both computer memory requirements and computational time. The API backend used to host FRREDSS on cloud servers was unable to process the full Sierra Nevada supply region at once, and larger statewide datasets would require additional resources. As a compromise between full optimization and practical computing times, FRREDSS also employs an approach to expand the search region in each year of the analysis beyond the closest clusters meeting the feedstock demand, but within a more limited domain to reduce the computational needs while approaching an optimal solution. This method uses an expansion factor defined as a multiplier of annual feedstock demand, or how far the radius of the search for the annual woody feedstock expands for a given biopower site location. A unity expansion factor searches only until the feedstock requirement in that year is satisfied and is subject to the non-optimal solution just described. Larger expansion factors search a larger area, to the point where a sufficiently large expansion factor achieves nearly the same cluster selection as a comprehensive search of the entire set of clusters over the full domain. Multiple runs of the model with various expansion factors demonstrate the effect on LCOE (Figure 9). As the expansion factor increases, the LCOE gradually approaches the fully optimized LCOE. The LCOE from an expansion factor of 30 is only 0.03 percent higher than the optimal LCOE, while the LCOE in the baseline of this case study with unity expansion factor is 2 percent higher. Given the uncertainties in many preliminary planning studies, this result may be adequate, but FRREDDS offers the capability to further refine the estimate at the user’s discretion. The sensitivity in net GHG emissions (Figure 10), while fairly minor, reveals that small expansion factors create a greater reduction in GHG emissions during feedstock harvest than the increase in GHG emissions from feedstock transportation. As the expansion factor increases, feedstock transportation produces a greater impact on GHG emissions than feedstock harvest, although the overall effect throughout is small. Note, however, that selection of an alternative objective function for the optimization, such as minimum emissions instead of minimum cost or use of a multi objective optimization, can yield different outcomes than those reported here.

Figure 9: As the Expansion Factor Increases, the LCOE Gradually Approaches the Ideal LCOE From a Full Optimization

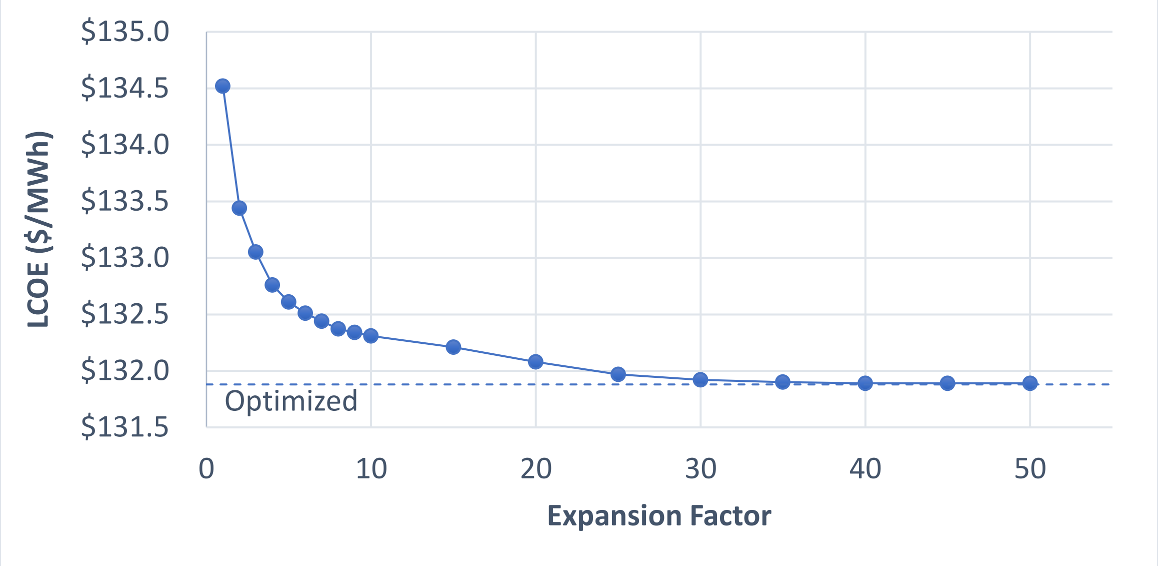
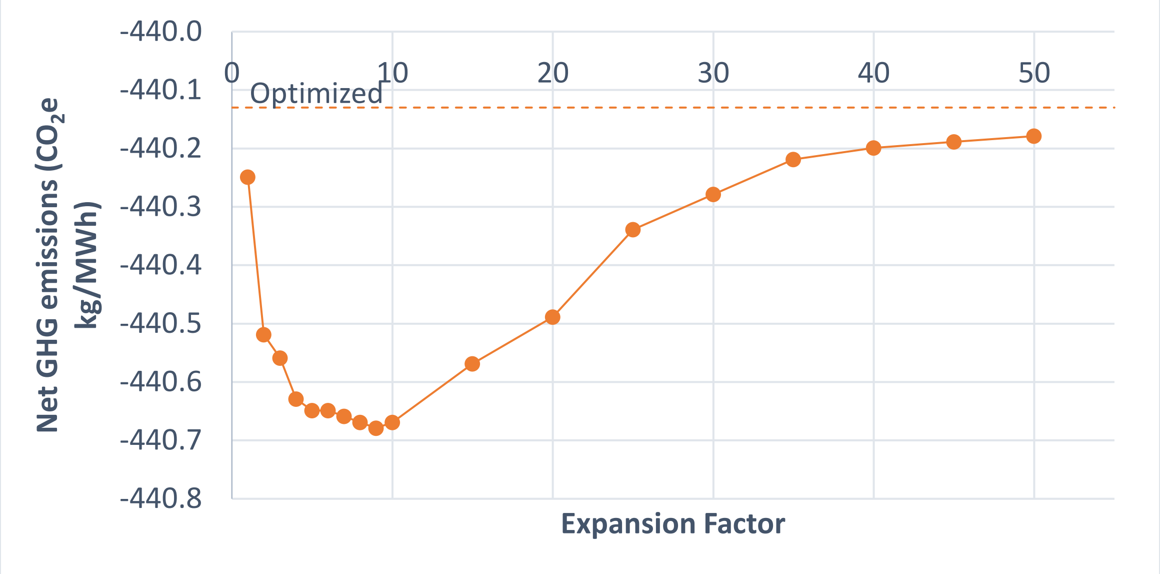
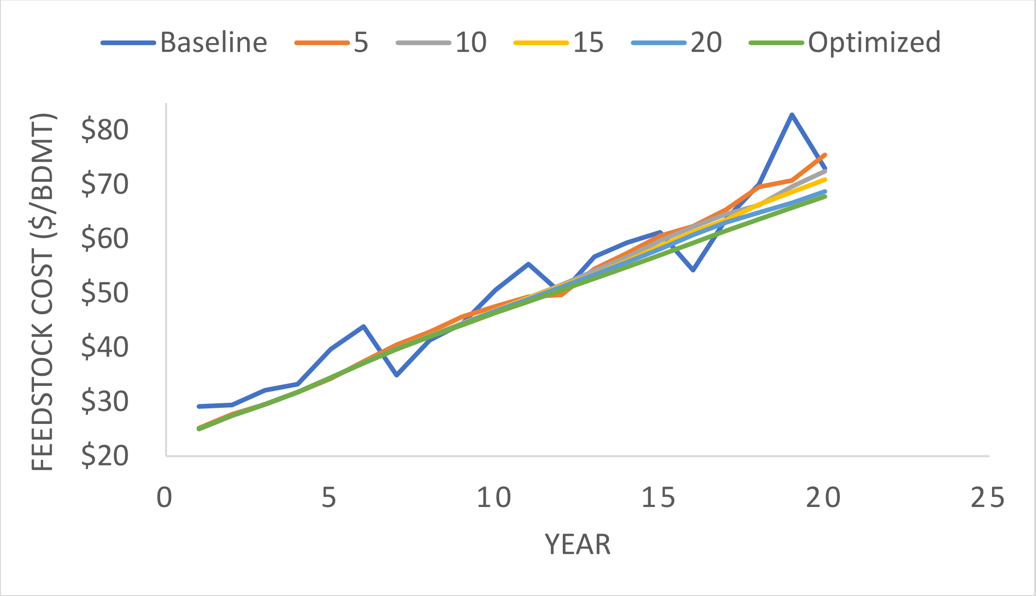


Figure 10: Net GHG Emissions Derived from Various Expansion Factors, Case Study 1



As the expansion factor increases, feedstock cost per BDMT over the economic life of the facility eventually becomes lower and more consistently increases over time as the expansion factor approaches the condition of full optimization (Figure 11). This contrasts with the sometimes quite variable annual feedstock cost when searching in closest proximity to the facility (unity expansion factor), as shown earlier (Figure 11). Gains toward feedstock cost reduction diminish with an increasing expansion factor, so there is little benefit in applying expansion factors beyond about 50, despite the reduction in computational intensity compared with full optimization. While reducing feedstock cost, GHG emissions may initially decrease and then increase in response to the tradeoff between harvest cost for higher yielding clusters and increased transportation cost for clusters located at greater distance from the conversion facility site.

Figure 11: Feedstock Cost Across the Lifetime of the Facility Derived from Various Expansion Factors, Case Study 1



Case Study 2: 3 MW Gasification Biopower Facility

The Bioenergy Market Adjusting Tariff (BioMAT) is a feed-in tariff program that supports bioenergy production by incentivizing renewable bioenergy projects through standard contracts (Rubio, 2012). At the time of this case study (2022), four forest contracts had been executed at a price of $199.72/MWh, providing a projected total of 11 MW of capacity (California Public Utilities Commission, 2021). Four 3 MW gasification biopower facilities with an economic life of 20 years were modeled at the same locations as the planned BioMAT projects (Table 16), although no direct relation to these facilities should be either assumed or inferred. The capital cost was assumed to be $18 million, the annual O&M cost $437 per kW_e-year, the capacity factor 80 percent, and the debt ratio 90 percent (Table 17). No production tax credit was applied. Other than facility location, capital cost, annual O&M cost, capacity factor, and debt ratio, the default model's technical, financial, and economic information were used. The labor wages, fuel price, and producer price index (PPI) increased by the default inflation rate of 2.1 percent over the lifetime of the projects in a manner similar to Case Study 1. The efficiency of a gasifier (Table C3) has two elements: converting feedstock to clean gas (65 percent assumed) and converting clean gas to electricity (23 percent), which yields an overall efficiency of 15 percent for converting feedstock to electricity. For these efficiencies, the annual feedstock demand of the facility is 21,765 BDMT to realize an annual electric generation of 21,024 MWh.

Table 16: Geographical Coordinates Used for the Gasification Projects

Project	Latitude	Longitude
1	38.37502373	120.5190657
2	39.19723764	121.0552327
3	37.23390696	119.4924425
4	40.90333501	121.6478209

LCOE and GHG Emissions

The levelized cost of energy (LCOE) for the lowest cost project is determined as $183/MWh of electricity generated for the assumptions used. The average feedstock cost is $39.15/BDMT of acquired feedstock, which consists of a harvest cost of $32.04, a transport cost of $7.05, and again a small move-in cost. The move-in cost per unit feedstock is larger than that in the baseline of the first study due to the smaller feedstock demand for the smaller capacity with a greater influence than the reduction in total move-in distance. The feedstock demand in this study is about 13 percent of that in the first study, while the total move-in distance is 27 percent larger.

An assessment of all combinations of forest and harvest treatments was again conducted, and the LCOE and GHG emissions for every combination with sufficient feedstock to meet demand were estimated (Figure 13).

Table 17: Biopower Facility Costs Assumptions

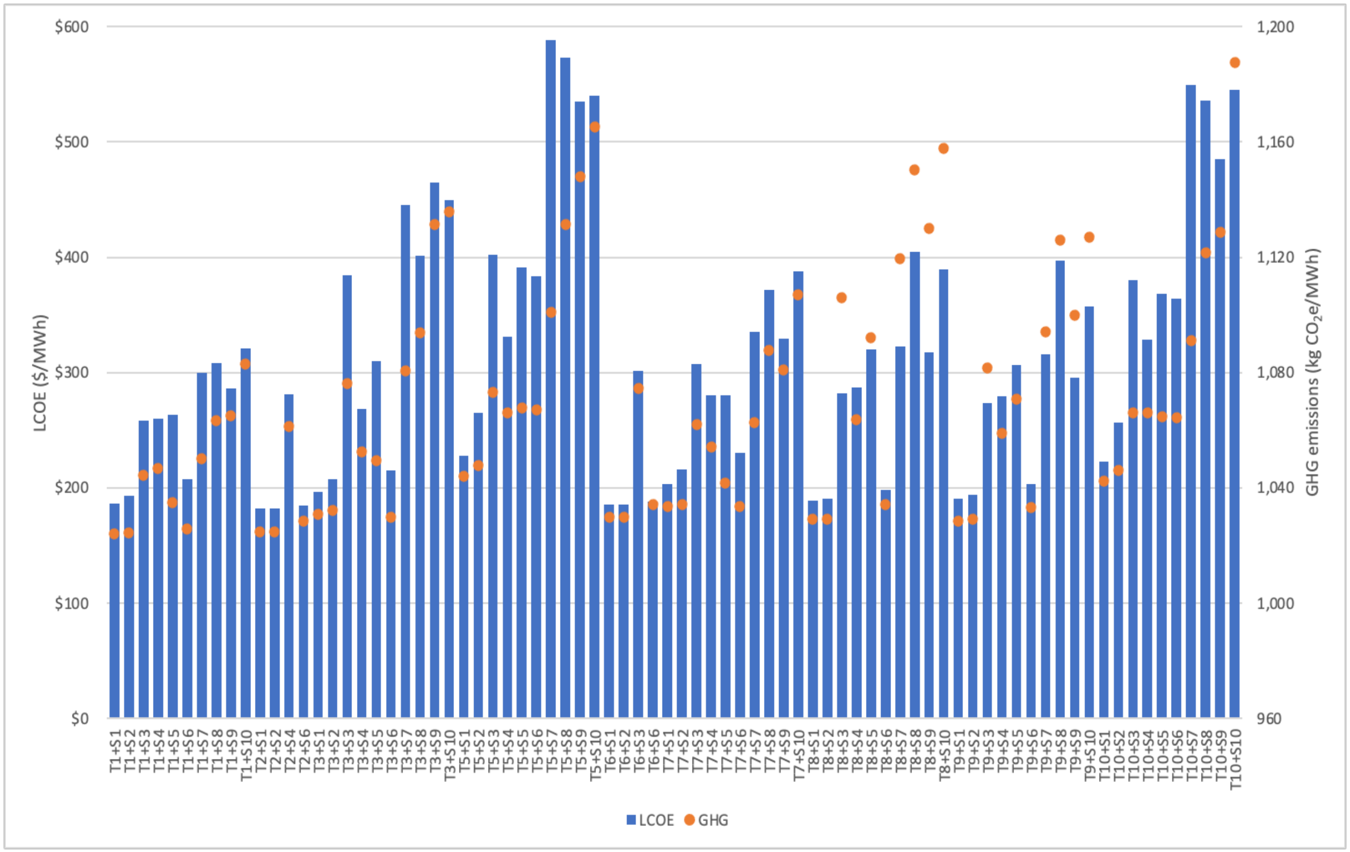
Capital Cost ($)	18,000,000
Capacity Factor (%)	80
Debt Ratio (%)	90
Debt Interest Rate (%)	5
Cost of Equity (%)	15
Net Efficiency (%)	23
Heat Price ($/kWh)	0.0207
Labor Cost ($/y)	500,000
Maintenance Cost ($/y)	100,000
Waste Treatment/Disposal ($/y)	50,000
Insurance/Property Tax ($/y)	360,000
Utilities ($/y)	100,000
Management/Administration ($/y)	100,000
Other Operating Expenses ($/y)	100,000
O&M Cost ($)	1,310,000
O&M Cost ($/kWe)	437

Table 18: Resource Sufficiency from Combinations of Forest Treatments and Harvesting Systems, Case Study 2*

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
T1	52.8	52.8	28.5	43.7	27.9	40.3	21.7	21.7	29.4	29.4
T2	6.1	6.1	0*	3.8	0*	5.0	0*	0*	0*	0*
T3	56.3	56.3	35.1	48.3	28.5	33.5	19.9	19.9	35.5	35.5
T4	1.3	1.3	0*	0.8	0*	0.8	0*	0*	0*	0*
T5	78.3	78.3	56.5	70.1	48.4	49.3	35.9	35.9	57.6	57.6
T6	4.5	4.5	0*	2.8	0*	3.7	0*	0*	0*	0*
T7	19.2	19.2	10.7	16.0	11.7	15.4	8.6	8.6	11.2	11.2
T8	6.7	6.7	1.2	4.6	1.3	5.4	0.9	0.9	1.2	1.2
T9	8.8	8.8	2.4	6.4	2.6	7.1	1.9	1.9	2.5	2.5
T10	129.2	129.2	107.4	121.0	75.7	76.6	63.2	63.2	106.3	106.3

*Highlighted cells indicate insufficient resource availability relative to total resource demand.

Figure 12: Level of LCOE and GHG Emissions Associated With Different Combinations of Forest Treatment and Harvesting Systems, Case Study 2



The LCOE ranges from $183 to $588/MWh and GHG emissions range from 1,024 to 1,188 kg CO_2 equivalent/MWh. Unlike the first case study where the combination of T1+S1 (Table 13) yields the lowest LCOE, the second case study shows that the combination of T2+S1 resulted in the lowest LCOE, while that yielding the lowest GHG emissions is T1+S1 (Table 13). Such a difference is attributed to the availability of feedstock; T2, commercial thin, only harvests live log trees from private land. In other words, feedstock is the residue from log trees. The proportion of feedstock in the total harvested biomass (including merchantable timber) in the combination T2+S1 in this case study is 23 percent while that in the first study is 15 percent, which indicates that for the combination T2+S1, feedstock is more accessible in the second case study than in the first study. The findings highlight the necessity of a comprehensive assessment of combinations of forest treatments and harvesting systems in order to determine those yielding the lowest LCOE or GHG emissions.

Table 19: Harvest Treatment-System Combinations for Minimum LCOE and GHG Emissions

	LCOE	GHG Emissions
Case Study 1 (25 Mwe)	T1+S1	T1+S1
Case Study 2 (3 Mwe)	T2+S1	T1+S1

Environmental Benefits and Impact

Similar to the assumptions made in the first case study, the baseline scenario yields environmental benefits in GHG and CAP reductions against the reference pile burning alternative. Potential emissions reductions are significant for GHG, CO, NO_x, $PM_{2.5}$, and VOC, and achieved between 51 and 99 percent reductions (Table 20). The net GHG emissions are again negative at -1084 kg/MWh. Compared with the net GHG emissions per unit output, using the conventional boiler-steam cycle and CHP technologies in the first case study, the net GHG emissions in this study for the lower CO_2 emission factors were referenced for this conversion technology (Table 21).

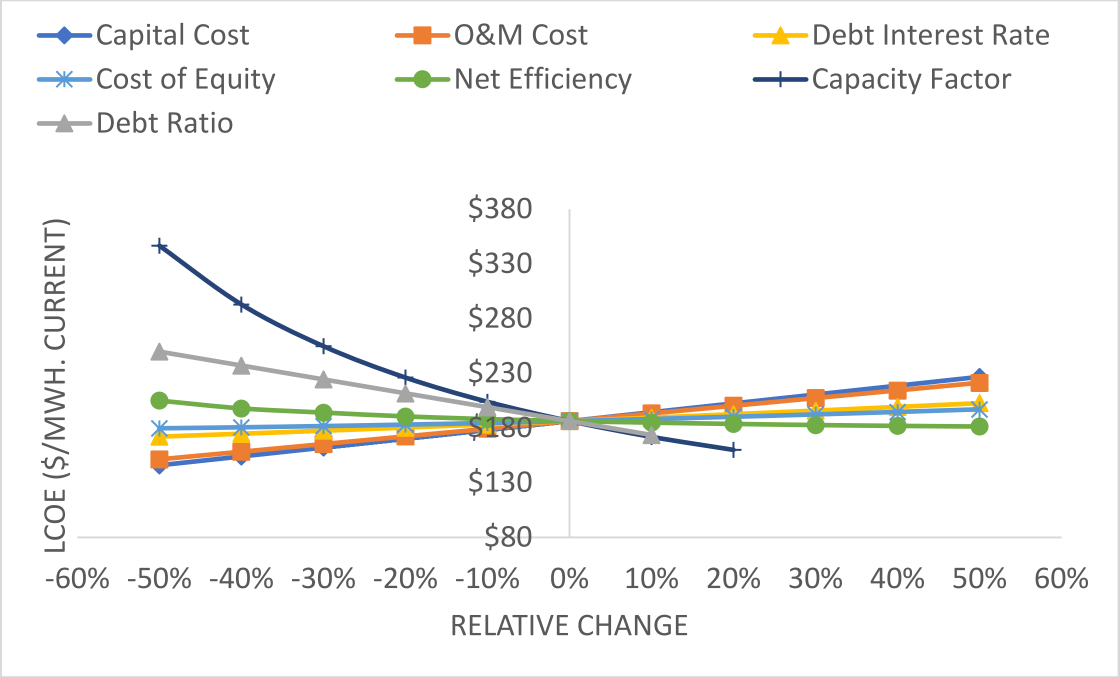
Table 20: Baseline Air Emissions Reductions From the Generation of Bioelectricity

Scenario	Air Emissions (kg/MWh electricity generated)				
	NO_x	$PM_{2.5}$	VOC	CO	GHG
Open pile burning	3.11	6.73	5.18	65.21	1899
Displaced power from grid	0.34	0.01	0.01	0.08	210
Forest biomass electricity	0.16	0.04	0.10	0.33	1024
Emission reductions	3.29	6.70	5.08	64.95	1084
Overall reduction (%)	95	99	98	99	51

Sensitivity Analysis

Sensitivity of the LCOE to key economic parameters including capital cost, O&M cost, debt ratio, debt interest rate, cost of equity, net efficiency, and capacity factor was assessed through multiple analyses. Each parameter in turn was varied in the same way as Case Study 1 over a range of ±50 percent from the baseline, in 10 percent increments.

Figure 13: LCOE ($/MWh) Varies With Different Key Economic Parameters Including Capital Cost, O&M Cost, Debt Ratio, Debt Interest Rate, Cost of Equity, Net Efficiency, and Capacity Factor



Capacity factor has the largest impact on LCOE among the seven parameters, followed by debt ratio, capital cost, O&M cost, net efficiency, debt interest rate, and cost of equity (Figure 13). The relative changes driven by the change of capacity factor and net efficiency are non-linear (Figure 13).

Similar to results from the first case study, net efficiency and moisture content (wet basis) of feedstock have little impact on GHG emissions on a per-MWh electricity generation basis, with the change ranging from -0.8 to 2.8 percent and 1.7 to -0.6 percent, respectively. A full assessment of the impacts of moisture content is not included since the model does not consider this factor within a combustion or gasification sub model to predict changes in efficiency and emissions due to changes in the chemistry, and thus only physical effects such as truck payloads are represented.

Table 21: Direct GHG Emissions From Sensitivity Analysis

Inputs	Deviation (%)	Value (%)	GHG emissions (kg CO_2e/MWh)	Relative Change (%)
Net Efficiency	50	34.5	1,016	-0.8
	-50	11.5	1,052	2.8
Moisture Content	50	75.0	1,042	1.7
	-50	25.0	1,018	-0.6

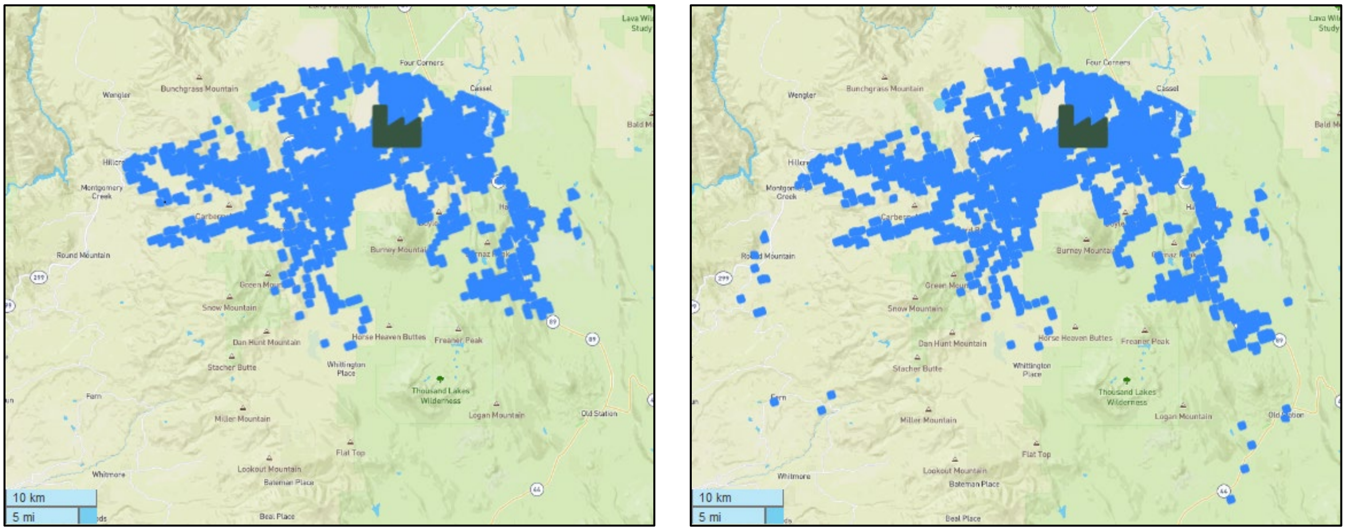
Optimization

The expansion-driven optimization based on minimum feedstock cost objective function achieved a minor impact on the LCOE and net GHG emissions (Table 22). The sensitivity of LCOE and net GHG emissions to the expansion factor at the site illustrated reveal that relatively low-cost feedstock is centered around the site instead of needing access to more distant clusters (as in the first study). The feedstock distributions at expansion factors of 1 and 50 indicate that many of the clusters with low feedstock acquisition costs is close to the selected facility site.

Table 22: Expansion Factor vs. LCOE and GHG Emissions

Expansion Factor	LCOE ($/MWh)	Net GHG emissions (CO_2e kg/MWh)
1	186.34	-1,084.44
20	185.95	-1,084.33
50	185.84	-1,084.29

Figure 14: Feedstock Distribution at an Expansion Factor of 1 (Left) and 50 (Right), Case Study 2



Discussion

Two case studies assessed the performance of a forest resource and renewable energy decision support system designed to examine the potential economic and environmental impacts from new biomass energy facilities. The case studies reveal differences among different forest treatments, harvesting systems, conversion technologies, scales, and the impact of facility location on LCOE, GHG, and other criteria air pollutant emissions. These two case studies show that substantial environmental benefits are realized from utilizing forest resources to generate electricity when compared with the common practice of open pile burning and from the displacement of utility grid electricity given the current mix of nonrenewable and renewable energy sources. The 3 Mwe gasification-type conversion facilities had lower net GHG emissions per unit of electricity generation (per MWh) than the 25 MW_e conventional boiler and CHP systems but were partly due to the much smaller assumed size (yield higher LCOE [$/MWh]). These results are preliminary, of course, since gasification and many other types of technologies are still mostly developmental for application in California, so well-documented cost and environmental data are not fully available. Incentives from carbon reductions (for example, carbon credits) by utilizing forest resources for energy production can further lower the LCOE and improve the competitiveness of forest bioenergy systems.

The LCOE is particularly sensitive to capacity factors, especially if declining below baseline assumptions representing more typical commercial values as observed from conventional boiler facilities. Feedstock cost also makes up a large share of the LCOE and optimizing feedstock sourcing at minimum delivered cost is important for reducing LCOE overall. Full optimization achieved through searching the entire high resolution spatial resource database used for each facility was computationally intensive. The use of the expansion factor to search beyond the simple annual feedstock supply in closest proximity for each year of the project life substantially reduces the model computation time and approaches the optimal solution at sufficiently high values (expansion factor of 30-50).

Chapter 4: Knowledge Transfer Activities

Activities Related to Public Outreach, Presentations, Panel Discussions, Website Development, And Publications Were Broadly Shared

Results from the model development and initial case study evaluations were disseminated in several ways including:

1. Participation workshops, webinars, and other knowledge transfer activities.
2. Preparation, publication, and distribution of project documents, including
    a. User Guide.
    b. Journal Publications.
3. Website development enabling continued updating and results dissemination as well as selected software distribution, including:

    UC Davis online web-based tool, located at: https://forestdss.ucdavis.edu/.

    CEC project website, located at: www.energizeinnovation.fund/projects/online-siting-tool-application-woody-biomass-electricity-facilities-california#tab-overview.
4. UC Davis gave a presentation to the Rural Economic Development/Wood Utilization Group's (REDS/WUG) on July 13, 2020, at the request of a representative from the Water and Rural Affairs, Governor's Office of Planning and Research. Members of the REDS/WUG included federal and state agency staff, representatives from local government, NGOs, and private consultants. Following is a brief summary of meeting outcomes.
    - The CPUC was interested in further understanding FRREDSS given its relevance to BioMAT.
    - Identifying a specific location for a biopower facility is the first input required in FRREDSS. Members were interested, however, in seeing a model where a certain number of criteria are input to the app, and in having an app provide the result on several appropriate potential biopower facility locations with the highest priority biomass availability (pre-search of supply region).
    - Members also expressed the importance of continually updating FRREDSS as development occurs, risks are assessed, and as wildfire changes the geographical availability of potential biomass.
    - Members at REDS/WUG shared that it would be useful if FRREDSS could also provide results on the numbers of employees needed for a potential biopower facility (a possible future addition).

5. California Forest Biomass Working Group Meeting (November 18, 2020)

   UC Davis presented an overview of FRREDSS and representatives from local government, federal and state agencies, and NGOs attended. Other questions and suggestions from the meeting follow.

   - It was suggested that it would be useful to expand FRREDSS to also include urban and agricultural residue, in addition to woody biomass.
   - Consistent with the comment received from various public contacts about the project, there is an interest in expanding FRREDSS to also consider other types of bioenergy (for example, hydrogen and renewable natural gas) in addition to electricity, which could be accomplished as information becomes available.
   - Interconnection cost and how it is currently modeled in FRREDSS was also discussed.

6. Tech Transfer Meeting (November 9, 2022)

   A tech transfer meeting was held on November 9, 2022, and representatives from the CEC, CAL FIRE, Spatial Informatics Group, South Tahoe Public Utilities District, and various academic institutions attended. UC Davis presented an overview of FRREDSS, explaining the inputs and output structure as well as the model's capabilities. The floor was then opened for questions. Questions and comments from the meeting included the following.

   - FRREDSS is currently designed for the user to first identify a specific location of a biopower facility; there is, however, an interest in having an app optimize the site for a biopower facility. As currently designed, users can use FRREDSS to model multiple sites individually, then compare the results across sites of interest. FRREDSS currently does not have a built-in site optimization routine, although this could be added in the future.
   - Including workforce analysis into FRREDSS was suggested as an important future enhancement.
   - Continually updating FRREDSS whenever new data becomes available will be important. While current resource data in FRREDSS may be good for some time (for example, 5-10 years), supply can change significantly over short periods of time due to wildfire, competition, and other factors. Sensitivity analysis is still recommended to assess potential impacts due to these and other conditions. Further, FRREDSS consists of stand-alone models, for example the harvest cost model and tech economic assessment, which can be used outside FRREDSS.

7. There were routine contacts with the public (for example, entrepreneurs interested in sourcing woody biomass for bioenergy, or the production of other types of wood products) and organizations (for example, local government and non-profit organizations) that have expressed interest either in directly utilizing FRREDSS for their businesses or in research collaborations to further enhance the FRREDSS model application to consider other bioproducts such as biochar, or bioenergy to expand its scope to include agricultural residues.

Chapter 5:
Conclusions and Recommendations

FRREDSS was developed to quantify potential economic and environmental impacts of generating electricity using forest resources as feedstock. Two case studies using the tool provide examples of the model performance, including an approach to optimize projected feedstock supply while maintaining acceptable computation times for assessments involving large feedstock demand. Costs and benefits vary across different combinations of harvesting system and forest treatment within the terrain, stand, infrastructure, and land distribution constraints of the supply region. Environmental benefits in the form of GHG and air pollutant reductions are apparent when compared with open-pile burning as a means of disposal, and from the displacement of utility grid electricity given current grid-associated emissions.

The model enables users to assess short- and longer-term feedstock availability and potential economic and environmental feasibilities for biopower facilities in California and can assist in preliminary planning to help inform more detailed engineering, environmental, and other studies needed for final determination of overall project feasibility. The model is flexible and can accommodate future enhancements to expand the types of facilities considered, available resource data and resource uncertainties, and many other factors that influence decision making.

While the model was developed for decision support for forest biomass electricity generation, other types of biomass feedstock such as agricultural residues could be integrated, as can other bioenergy technologies whether for power, fuels, chemicals, materials, or other products. The model also provides the basis for evaluating sensitivity to project assumptions, and to help identify additional research and development needs. The sub models and code packages developed for the FRCS, TEA, and LCA models are open-sourced and also available for incorporation into other web applications.

A primary limitation at present is the availability of relevant and up-to-date forest resource data for the entire state. Recent and ongoing wildfire, other project developments, and many other changes in resource availability and forest management influence future projections for feedstock supplies. Critically, there needs to be a more comprehensive and continuing approach to feedstock supply monitoring and prediction across the state to improve model assessments that better inform decision processes. In the meantime, development of FRREDSS and related models can support preliminary technical, policy, regulatory and market evaluations in response to urgent needs regarding both the state’s forests and energy infrastructure.

Future Research and Development

- **Competitive Analysis:** At present, FRREDSS assumes no regional competition for feedstock supply, either from facilities of the same user or from other existing or planned facilities intended for the same resource. The model can be modified to enable the user to enter the site location of multiple forest products and biomass power plants as well as their respective size, technology, and other technoeconomic variables should they be available. This will help the user better understand multiple site interactions, and also help optimize facility siting. Additionally, a routinely updated database of alternative and competing uses could be maintained for model access to assist users in evaluating potential competing demand for resources and products.

- **Risk Assessment:** The risk of forest wildfire or disease outbreak could affect the short-term and long-term biomass supply. Risk assessment methodology could be added to the model to provide greater sensitivity and uncertainty analyses around potential facility siting, development, and operating decisions. This risk assessment could help users better understand the probability of potential fluctuations in biomass supply and plan for safety nets or insurance to address potential disruptions in biomass supply. In addition to modeling the risk of wildfire affecting supply, FRREDSS could also be adapted to model the effects of price shocks; one example would be an increase in fuel prices that would affect both transportation or processing costs. Users can gain a better understanding of how sensitive the supply of biomass is with respect to a change in price and potentially be able to explore the impact of wildfire and other effects on overall feasibility.
- **Supply and Demand Analysis:** FRREDSS currently includes ten different forest treatments and ten different forest harvesting methods. The model allows users to select only one harvesting system and one forest treatment that will be applied to all the harvested clusters in one simulation. The model can be expanded to include multiple cluster-appropriate selections of harvesting systems and forest treatments, including automated selection if desired by the user to identify combinations for yielding the lowest harvest cost, environmental impact, or other factors.
- **Supply Chain and Logistics:** The feedstock supply chain of the integrated model is now onefold: feedstock is chipped at the landing and then directly transported to a conversion facility, while feedstock processing, storage, or partial conversion could occur at intermediate locations. The model could be adapted to other supply chain designs.
- **Transportation Model:** The transportation model uses the transportation distance and travel time between two coordinates generated by OSRM to estimate costs and emissions. Although OSRM generates the transportation information based on prescribed truck and route profiles; an economic and environmental model targets specific road classes along the route that could produce more accurate estimates. Other transport modes such as railway and waterway could also be modeled.
- **Transmission and Distribution:** For power transmission, the algorithm always seeks the nearest substation and assumes new transmission lines. The options of either building a new substation or otherwise interconnecting are not yet included. Also, the default input values of the transmission model, such as voltage class, structure, and conductor type, are used to estimate installation costs for new transmission lines. More

flexible and comprehensive transmission, distribution, or interconnection sub models could also be developed.

- **Technoeconomic Assessments:** The TEA model is currently configured for three power conversion technologies: conventional boiler-steam cycle, CHP, and gasifiers. FRREDSS can be expanded to include other types of systems and products, including developmental and experimental technologies where adequate data are available.
- **Lifecycle Assessment:** The LCA model uses emission factors averaged from state facilities with the same conversion technology. Emission factors, however, vary depending on the types of control devices installed and the conversion efficiency. The emissions from the construction of a facility and the manufacturing of harvesting equipment modeled through input-output analysis are only approximate, and detailed process-based LCA is recommended to model the material and energy flows from specific processes. Feedstock moisture can affect reaction processes and chemistry and therefore the facility conversion efficiency, costs, and emissions from the facility. Nor are all feedstocks of the same composition; differences in heating value, chemical composition and other properties can also influence operating performance. Further analysis should be conducted to relate changes in feedstock moisture and other properties to efficiency and emissions. In addition, the LCA model considers only air emissions, and additional research should be done to quantify the emissions in water and soil. Impacts from the end-of-life or decommissioning of a conversion facility, as well as land use and forest management, should also be assessed. To support better decision-making, a broad array of additional environmental impacts such as biodiversity, erosion and topsoil loss, soil carbon, and other changes, should be considered as well.
- **Consideration of Alternative Fates in Environmental Impact Assessment:** The environmental benefits realized from utilizing forest resources to generate electricity are compared with open pile burning for disposal. In practice, not all biomass would necessarily be burned in open piles if not used for bioenergy. Several alternatives could also be considered, for example biomass could be left on the ground to decompose, or burned in future wildfires, resulting in different environmental outcomes. Environmental implications associated with these different fates deserve more in-depth investigation to better inform decisions. The integrated model is created with an emphasis on biomass feedstock and does not model the management of coproducts (sawlogs). Subject to market demand and supply, the profit from the sales of sawlogs could enhance the potential of the biomass-to-energy market, as energy might add to the sustainability of various wood industries. In addition, the model can be generalized to utilize other types of feedstocks such as agricultural residues, and development of improved data sources could be of substantial value to the state.
- **Resource Data Flexibility:** While FRREDSS already has 2016 USFS F^3 biomass data, it would be helpful to continuously update the database as new forest biomass data become available. An additional capability can be added to the model to allow users to input resource supply and location data if they have access to this information for their specific sites.

- **Maintenance and User Support:** CEC and other state support currently provide for the model application to be hosted on UC Davis servers. Additional ongoing provisions will be needed for model updating, maintenance, and user support.

GLOSSARY AND LIST OF ACRONYMS

Term	Definition
ALT	All log trees
API	Application Programming Interface
AT	All trees
BA	Basal area of live trees (ft^2/acre)
BDMT	Bone dry metric tons
BDT	Bone dry short tons
BLS	Bureau of Labor Statistics
BMCWN	Crown biomass of live trees (BDT/acre)
BMSTM	Stem biomass of live trees (BDT/acre)
CAP	Criteria air pollutant
CARB	California Air Resources Board
CCF	hundred cubic feet
cf	cubic feet
CFPR	California Forest Practice Rules
CHP	Combined heat and power
CPI	Consumer Price Index
CPUC	California Public Utilities Commission
CT	Chip trees
CTL	Cut-to-length
DBH	Diameter at breast height, typically measured at 4.5 feet above ground
DBMCN	Crown biomass of snags (BDT/acre)
DBMSM	Stem biomass of snags (BDT/acre)
EPIC	Electric Program Investment Charge
FRCS	Fuel Reduction Cost Simulator
FRREDSS	Forest Resource and Renewable Energy Decision Support System
GHG	Greenhouse gas
GREET	Greenhouse Gases, Regulated Emissions, and Energy use in Transportation
IGCC	Integrated gasification combined cycle
LCA	Life cycle assessment
LCI	Life cycle inventory

Term	Definition
LCOE	levelized cost of energy
LLT	Large log trees
npm	node package manager
OPR	California Governor’s Office of Planning and Research
OSRM	Open Source Routing Machine
PPI	Producer Price Index
SLT	Small log trees
SNG	Number of snags (per unit area)
SMUD	Sacramento Municipal Utility District
TEA	Technoeconomic assessment
TPA	Number of live trees (per unit area)
USFS	U.S. Forest Service
VMSG	Volume of snags (volume per unit area)
VOC	Volatile organic compounds
VOL	Volume of live trees (volume per unit area)
WT	Whole tree

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Project Deliverables

Online web-based decision support system

- Forest Resource and Renewable Energy Decision Support System (FRREDSS) version 1.0, an online application for decision support in siting woody biomass to electricity facilities in California: https://forestdss.ucdavis.edu/
- Forest Resource and Renewable Energy Decision Support System (FRREDSS) version 1.0 User Guide available on the project website: https://forestdss.ucdavis.edu/

Software

- Updated and revised FRCS Javascript Version: FRCS was originally created in Excel™ and contains 30 spreadsheets, and is only available for PC. To integrate with the overall decision support system, the FRCS model was translated from the spreadsheet format into a flexible program code. FRCS was, with permission, converted to JavaScript and published as a software package registered to npm (node package manager) serving the JavaScript runtime environment Node.js. npm packages are publicly available and can be easily installed and used by developers. The FRCS npm package is at https://www.npmjs.com/package/@ucdavis/frcs and can be used to compute harvest costs and move-in costs based on the inputs described in the Project Approach section. While a npm package can be easily used by software developers, researchers and forest practitioners will not be able to leverage the software package and run forest harvesting simulations without installing the package and running the methods inside of the package in a node.js environment. A user-friendly web application was therefore created for FRCS that incorporates the FRCS npm package and computes harvest costs based on user-specified inputs such as harvesting system, cut type, tree characteristics, and other assumptions. The FRCS web application is currently hosted at https://frcs.ucdavis.edu/. The adapted FRCS west variant was converted to JavaScript and published as a npm package (https://www.npmjs.com/package/@ucdavis/frcs), and a user-friendly web application (https://frcs.ucdavis.edu) was created for both stand-alone use and API integration.
- Similar to FRCS, The model TEA analysis was converted to a npm package available at https://www.npmjs.com/package/@ucdavis/tea.
- Similar to the FRCS and TEA models, the LCA was converted to a npm package available at https://www.npmjs.com/package/@ucdavis/lca.

Publications

- Li, Kaiyan, Scott Kirkland, Boon-Ling Yeo, Carmen Tubbesing, Varaprasad Bandaru, Lan Song, Laura Holstege, Bruce Hartsough, Alissa Kendall, and Bryan Jenkins. "Integrated Economic and Environmental Modeling of Forest Biomass for Renewable Energy in

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Appendix A: Forest Treatments

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APPENDIX A: Forest Treatments

Forest Treatments

2. **Commercial thin** harvests only live log trees whose types are mixed conifer and pine on private land. The harvest consists of certain percentages starting with small ones closest to 10” until a certain residual basal area is reached, which is based on size class.

The percentages of trees to be harvested from a cluster are calculated by first determining how much basal area should remain (ft^2 acre^{-1}), denoted as $\mathrm{Residual}_{\mathrm{BA}}$, according to the California Forest Practice Rules (CFPR) (California Department of Forestry and Fire Protection, 2020), based on size class and principal forest type of the cluster (Table A-1).

Table A-1: Basal Area that Should Remain in the Commercial Thin Forest Treatment under Different Size Classes and Forest Types

Size Class	Forest Type	$\mathrm{Residual}_{\mathrm{BA}}$ (ft2/ac)
1	mixed conifer	125
1	pine	100
2	mixed conifer	100
2	pine	75
3	mixed conifer	75
3	pine	75
4	mixed conifer	50
4	pine	50
5	mixed conifer	50
5	pine	50

Source: CAL FIRE, 2020

The initial basal area of the cluster, denoted as $\mathrm{Initial}_{\mathrm{BA}}$, is calculated as

$$\mathrm{Initial}_{\mathrm{BA}} = \mathrm{BA}_{15} + \mathrm{BA}_{25} + \mathrm{BA}_{35} + \mathrm{BA}_{40} \qquad [1]$$

If $\mathrm{Initial}_{\mathrm{BA}}$ is smaller than or equal to $\mathrm{Residual}_{\mathrm{BA}}$, no trees in the cluster should be harvested, otherwise the basal area to be removed or harvested, denoted as $\mathrm{BA}_{\mathrm{remove}}$, can be calculated by subtracting $\mathrm{Residual}_{\mathrm{BA}}$ from $\mathrm{Initial}_{\mathrm{BA}}$,

$$\mathrm{BA}_{\mathrm{remove}} = \mathrm{Initial}_{\mathrm{BA}} - \mathrm{Residual}_{\mathrm{BA}} \qquad [2]$$

The fractions to be removed of different size classes of trees is determined as follows:

If $\mathrm{BA}_{\mathrm{remove}} \leq \mathrm{BA}_{15}$,

$$\mathrm{P}_{15} = \frac{\mathrm{BA}_{\mathrm{remove}}}{\mathrm{BA}_{15}}, \mathrm{P}_{25} = \mathrm{P}_{35} = \mathrm{P}_{40} = 0 \qquad [3]$$

where P is the fraction of the trees of a particular size class to be removed

If $\mathrm{BA}_{15} < \mathrm{BA}_{\mathrm{remove}} \leq \mathrm{BA}_{15} + \mathrm{BA}_{25}, \mathrm{P}_{15} = 1$,

$$\mathrm{P}_{25} = \frac{\mathrm{BA}_{\mathrm{remove}} - \mathrm{BA}_{15}}{\mathrm{BA}_{25}}, \mathrm{P}_{35} = \mathrm{P}_{40} = 0 \qquad [4]$$

If $\mathrm{BA}_{15} + \mathrm{BA}_{25} < \mathrm{BA}_{\mathrm{remove}}$ and Land Type is Private,

$$\mathrm{P}_{15} = \mathrm{P}_{25} = 1, \mathrm{P}_{35} = \mathrm{P}_{40} = 0 \qquad [5]$$

If $\mathrm{BA}_{15} + \mathrm{BA}_{25} < \mathrm{BA}_{\mathrm{remove}} \leq \mathrm{BA}_{15} + \mathrm{BA}_{25} + \mathrm{BA}_{35}$ and Land Type is FS,

$$\mathrm{P}_{15} = \mathrm{P}_{25} = 1, \mathrm{P}_{35} = \frac{\mathrm{BA}_{\mathrm{remove}} - \mathrm{BA}_{15} - \mathrm{BA}_{25}}{\mathrm{BA}_{35}}, \mathrm{P}_{40} = 0 \qquad [6]$$

If $\mathrm{BA}_{15} + \mathrm{BA}_{25} + \mathrm{BA}_{35} < \mathrm{BA}_{\mathrm{remove}}$ and Land Type is Private,

$$\mathrm{P}_{15} = \mathrm{P}_{25} = \mathrm{P}_{35} = 1, \mathrm{P}_{35} = \frac{\mathrm{BA}_{\mathrm{remove}} - \mathrm{BA}_{15} - \mathrm{BA}_{25} - \mathrm{BA}_{35}}{\mathrm{BA}_{40}} \qquad [7]$$

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Appendix B: Adaptation of Fuel Reduction Cost Simulator

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APPENDIX B:
Adaptation of Fuel Reduction Cost Simulator

FRCS Cost Updates

The costs in FRCS, including labor, fuel, and equipment costs, were updated from the original values to December 2007 by Dykstra et al. (2009). While labor costs were estimated on an hourly basis using the data of annual wage series from the Bureau of Labor Statistics (BLS) because hourly wages were not available at the time, currently the mean hourly wages of workers in the forestry industry are published by BLS every year and are used directly in FRCS. The updates of fuel and equipment costs follow the methods developed by Dykstra et al. (2009). Table B-1 summarizes the latest published cost data.

Table B-1: Cost Data for the FRCS Model

	Unit	Value	Date	Source	Region
Faller/Bucker	$/hour	35.13	May-20	BLS	CA
Other workers	$/hour	22.07	May-20	BLS	CA
Fuel	$/gallon	2.24	Oct-21	EIA	Los Angeles
PPI		284.7 (P)	Oct-21	BLS	Nationwide

* P: Preliminary; the producer price index (PPI) is subject to revision four months after original publication.

Hourly mean wages for fallers and other logging workers in California were updated to $35.13 and $22.07, respectively, according to Occupational Employment Statistics published by the BLS in May 2020. Based on the assumption of 35 percent for benefits and other payroll costs in FRCS, hourly logging wages for fallers and other logging workers in California are $47.43 and $29.79, respectively. The wholesale diesel fuel price or fuel cost in Los Angeles was $2.24/gallon (EIA, December 16, 2021). The equipment costs were updated using Equation $[\mathrm{B.1}]$ where the equipment purchase price and the PPI of year 2002 were provided in FRCS and the current producer price index (PPI) for construction machinery manufacturing was 284.7 as of October 2021 as published by the BLS.

$$\mathrm{PurchasePrice_{current}} = \mathrm{PurchasePrice_{2002}} * \frac{\mathrm{PPI_{current}}}{\mathrm{PPI_{2002}}} \qquad [\mathrm{B.1}]$$

where

$\mathrm{PurchasePrice_{current}}$ is the current purchase price of an equipment

$\mathrm{PurchasePrice_{2002}}$ is the purchase price of equipment in 2002

$\mathrm{PPI_{current}}$ is the current PPI

$\mathrm{PPI_{2002}}$ is the PPI of year 2002

FRCS Data Conversion

Harvest cost of a cluster is estimated through FRCS. The cluster-level data processed from the F^3 pixel-level data are applied in developing the FRCS inputs as described in equations $[\mathrm{B.2}]$-$[\mathrm{B.23}]$ below. Because the data do not contain the volumes of individual trees, size class by diameter is used to categorize chip trees (CT), small log trees (SLT), and large log trees (LLT). Trees with 1 ≤ DBH < 10 inches are regarded as CT, trees with a DBH between 10 inches and 20 inches are regarded as SLT, and trees with a DBH greater than or equal to 20 inches are regarded as LLT. A 20-inch DBH tree has a volume of roughly 83 ft^3 (2.34 m^3) based on Equation $[0.9]$ from the FRCS model as derived from a study by (Drews et al., 2001).

$$\mathrm{TreeVol} = \mathrm{DBH}^2 \times 0.216 - 3.675 \qquad [\mathrm{B.2}]$$

$$\mathrm{BoleWeight}_{\mathrm{CT}} = \frac{2000 \times \sum_{\mathrm{i}}^{2,7}(\mathrm{BMSTM}_{\mathrm{i}} + \mathrm{DBMSM}_{\mathrm{i}})}{1 - \mathrm{MoistureContent}} \qquad [\mathrm{B.3}]$$

where $\mathrm{MoistureContent}$ is the moisture content of biomass on a wet basis (fraction w.b.) and 2000 is used to convert short tons to pounds.

$$\mathrm{BoleWeight}_{\mathrm{SLT}} = \frac{2000 \times (\mathrm{BMSTM}_{15} + \mathrm{DBMSM}_{15})}{1 - \mathrm{MoistureContent}} \qquad [\mathrm{B.4}]$$

$$\mathrm{BoleWeight}_{\mathrm{LLT}} = \frac{2000 \times \sum_{\mathrm{i}}^{25,35,40}(\mathrm{BMSTM}_{\mathrm{i}} + \mathrm{DBMSM}_{\mathrm{i}})}{1 - \mathrm{MoistureContent}} \qquad [\mathrm{B.5}]$$

$$\mathrm{ResidueWeight}_{\mathrm{CT}} = \frac{2000 \times \sum_{\mathrm{i}}^{2,7}(\mathrm{BMCWN}_{\mathrm{i}} + \mathrm{DBMCN}_{\mathrm{i}})}{1 - \mathrm{MoistureContent}} \qquad [\mathrm{B.6}]$$

$$\mathrm{ResidueWeight}_{\mathrm{SLT}} = \frac{2000 \times (\mathrm{BMCWN}_{15} + \mathrm{DBMCN}_{15})}{1 - \mathrm{MoistureContent}} \qquad [\mathrm{B.7}]$$

$$\mathrm{ResidueWeight}_{\mathrm{LLT}} = \frac{2000 \times \sum_{\mathrm{i}}^{25,35,40}(\mathrm{BMCWN}_{\mathrm{i}} + \mathrm{DBMCN}_{\mathrm{i}})}{1 - \mathrm{MoistureContent}} \qquad [\mathrm{B.8}]$$

$$\mathrm{ResidueFraction}_{\mathrm{CT}} = \frac{\mathrm{ResidueWeight}_{\mathrm{CT}}}{\mathrm{BoleWeight}_{\mathrm{CT}}} \qquad [\mathrm{B.9}]$$

$$\mathrm{ResidueFraction}_{\mathrm{SLT}} = \frac{\mathrm{ResidueWeight}_{\mathrm{SLT}}}{\mathrm{BoleWeight}_{\mathrm{SLT}}} \qquad [\mathrm{B.10}]$$

$$\mathrm{ResidueFraction}_{\mathrm{LLT}} = \frac{\mathrm{ResidueWeight}_{\mathrm{LLT}}}{\mathrm{BoleWeight}_{\mathrm{LLT}}} \qquad [\mathrm{B.11}]$$

$$\mathrm{Volume}_{\mathrm{CT}} = \sum_{\mathrm{i}}^{2,7} \mathrm{VOL}_{\mathrm{i}} + \mathrm{VMSG}_{\mathrm{i}} \qquad [\mathrm{B.12}]$$

$$\mathrm{BoleWeight_{SLT}} = \frac{2000 \times (\mathrm{BMSTM_{15}} + \mathrm{DBMSM_{15}})}{1 - \mathrm{MoistureContent}} \qquad [\mathrm{B}.4]$$

$$\mathrm{Volume_{SLT}} = \mathrm{VOL_{15}} + \mathrm{VMSG_{15}} \qquad [\mathrm{B}.13]$$

$$\mathrm{Volume_{LLT}} = \sum_{\mathrm{i}}^{25,35,40} (\mathrm{VOL_i} + \mathrm{VMSG_i}) \qquad [\mathrm{B}.14]$$

$$\mathrm{WoodDensity_{CT}} = \frac{\mathrm{BoleWeight_{CT}}}{\mathrm{Volume_{CT}}} \qquad [\mathrm{B}.15]$$

$$\mathrm{WoodDensity_{SLT}} = \frac{\mathrm{BoleWeight_{SLT}}}{\mathrm{Volume_{SLT}}} \qquad [\mathrm{B}.16]$$

$$\mathrm{WoodDensity_{LLT}} = \frac{\mathrm{BoleWeight_{LLT}}}{\mathrm{Volume_{LLT}}} \qquad [\mathrm{B}.17]$$

$$\mathrm{Removals_{CT}} = \sum_{\mathrm{i}}^{2,7} \mathrm{TPA_i} + \mathrm{SNG_i} \qquad [\mathrm{B}.18]$$

$$\mathrm{Removals_{SLT}} = \mathrm{TPA_{15}} + \mathrm{SNG_{15}} \qquad [\mathrm{B}.19]$$

$$\mathrm{Removals_{LLT}} = \sum_{\mathrm{i}}^{25,35,40} \mathrm{TPA_i} + \mathrm{SNG_i} \qquad [\mathrm{B}.20]$$

$$\mathrm{TreeVol_{CT}} = \frac{\mathrm{Volume_{CT}}}{\mathrm{Removals_{CT}}} \qquad [\mathrm{B}.21]$$

$$\mathrm{TreeVol_{SLT}} = \frac{\mathrm{Volume_{SLT}}}{\mathrm{Removals_{SLT}}} \qquad [\mathrm{B}.22]$$

$$\mathrm{TreeVol_{LLT}} = \frac{\mathrm{Volume_{LLT}}}{\mathrm{Removals_{LLT}}} \qquad [\mathrm{B}.23]$$

As an approximation, the slope of a cluster is calculated by dividing the elevation difference between the center of biomass $[\mathrm{B}.24]$ and the landing by their distance derived from Geolib, a npm package that provides geospatial operations including distance calculation between two coordinates. OSRM was used to locate the nearest road to the cluster, with this roadside site regarded as the landing for a cluster.

Center of Mass $(\overline{\mathrm{lat}}, \overline{\mathrm{lng}})$ of a cluster is calculated as below:

$$\overline{\mathrm{lat}} = \frac{\sum \mathrm{W_i lat_i}}{\sum \mathrm{W_i}}, \overline{\mathrm{lng}} = \frac{\sum \mathrm{W_i long_i}}{\sum \mathrm{W_i}} \qquad [\mathrm{B}.24]$$

where

$\overline{\text{lat}}$ is the latitude of the center of mass of a cluster

$\overline{\text{lng}}$ is the longitude of the center of mass of a cluster

lat_i is the latitude of the ith pixel; long_i is the longitude of the ith pixel

W_i is the green weight of biomass of the ith pixel (BDT)

and the sum is taken across all pixels in the cluster.

Yarding/skidding/forwarding distance for a cluster was estimated through a pixel-weighted distance and the cluster landing:

$$\overline{\text{d}_\text{l}} = \frac{\sum \text{W}_\text{i}\text{l}_\text{i}\tau_\text{i}}{\sum \text{W}_\text{i}} \qquad [\text{B}.25]$$

where

$\overline{\text{d}_\text{l}}$ is the average yarding/skidding/forwarding distance of a cluster (ft)

τ_i is the tortuosity factor (≥ 1) of the ith pixel, $1 =$ straightline or shortest distance

l_i is the distance between the center of the ith pixel and the landing (ft)

W_i is the green weight of biomass in the ith pixel (BDT)

FRCS Fuel Consumption Modeling

All manual-felling related operations in Table 6 are carried out with gasoline-fueled chainsaws. Helicopter-yarding related operations use helicopters consuming jet fuel, and the other operations are carried out with diesel-fueled equipment such as feller bunchers, harvesters, bundlers, skidders, forwarders, cable yarders, processors, chippers, and loaders.

For forest operations that consume diesel fuel, FRCS computes associated costs on a per machine hour and per CCF basis, dynamically based on user inputs. Information on machine power rating and fuel consumption rate (gallons per horsepower per machine hour) embedded in FRCS is used to calculate the fuel consumption in gallons per machine hour of the equipment used in each harvesting system [B.26]. Fuel consumption per CCF is then computed [B.27].

where,

$\mathrm{FuelConsumptionCCF}$ is fuel consumption rate in gallons per hundred cubic feet of trees

$\mathrm{CostPMH}$ is cost per machine hour

$\mathrm{CostCCF}$ is cost per hundred cubic feet of wood

For manual-felling related operations that consume gasoline, the reported average fuel consumption of chainsaws is 0.104 liters per cubic meter (0.0778 gallons/CCF) of trees harvested (Halilović et al., 2012).

For helicopter-yarding related operations that consume jet fuel, three types of helicopters are modeled in FRCS: the Bell 204, Boeing Vertol 107 - 61A, and K-MAX. Similar helicopter types and associated fuel consumption rates in gallons per hour were published by the U.S. Forest Service as shown in Table B-2 (U.S. Forest Service, 2019). Fuel consumption (gallons/CCF) was estimated by multiplying the fuel consumption (gal/h) by the production rates (h/CCF).

Table B-2: Fuel Consumption Rates of the Helicopters Modeled in the FRCS Model

FRCS helicopter type	Bell 204 class	Boeing Vertol 107 - 61A	K-MAX
USFS helicopter type	Bell 204B (UH-1 Series)	Boeing BV-107/CH 46	KAMAN K-1200
Fuel consumption (gal/h)	86	180	86

The truck loading operation in helicopter-yarding systems is carried out by front-end loaders after logs have been deposited at the landing by helicopters. To estimate fuel consumption for loading, the fuel consumption rates (gallons/CCF) accounted for logs being handled twice: they are first moved from where the helicopter drops them on the landing to a "deck" (stack), and then from the deck to a truck.

Fuel consumption related to move-in, i.e., transporting equipment to a harvest unit, is estimated from “lowboy” truck loads, the number of trips, move-in distance, and fuel economy [0.35]. The number of equipment loads that a tractor-trailer needs to carry is equal to the number of pieces of equipment that need to be brought into harvesting site in that generally multiple pieces are too large for a single load. Table B-3 presents the number of loads and the specific equipment required for the ten harvesting systems. A chipper is included in every system by assuming that there always exist chip trees and/or residues that need to be chipped, but in scenarios where no chip trees and residues are meant to be harvested, there is no move-in cost for the biomass component although there may be for the sawlog component not ascribed to the cost of feedstock. For the ground-based CTL system, if residues are to be collected, i.e., the option of including the costs of collecting and chipping residues is selected, two more pieces of equipment, including a bundler and a forwarder, would need to be brought in, which would make the truckloads of the ground-based CTL system become 6. Usually, it takes a round trip of a truck trailer to transport a piece of equipment to a harvest unit and then return to “base”, so the number of trips for transporting a piece of equipment is 2. In general, equipment remains at a harvest unit for days, and the driver and truck trailer return to base so other equipment can be transported during that interval. In the cases where the truck tractor will travel to a different harvest unit, it is difficult to predict the overall move-in distance, so it is assumed that the number of trips for transporting a piece of equipment is always 2, i.e., the roundtrip distance.

Fuel economy is the average miles a tractor trailer travels per gallon of fuel consumed. An average of 6.0 miles per gallon (mpg) for combination trucks was reported by the Federal Highway Administration (Federal Highway Administration, 2017) and the fuel economy is assumed to be 6 mpg in the FRCS model.

$$\mathrm{FuelConsumption}_{\mathrm{move-in}} = \frac{\mathrm{MoveInDist} \times (\mathrm{NumTrips} \times \mathrm{TruckLoads})}{\mathrm{FuelEconomy}} \qquad [\mathrm{B}.28]$$

where

$\mathrm{FuelConsumption}_{\mathrm{move-in}}$ is the fuel consumption for move-in (gallons)

$\mathrm{MoveInDist}$ is the one-way distance of transporting equipment to a harvest unit (miles)

$\mathrm{TruckLoads}$ is the number of loads that a tractor-trailer needs to carry

$\mathrm{NumTrips}$ is the number of trips required for transporting a piece of equipment. It is assumed to be 2 for the roundtrip distance.

$\mathrm{FuelEconomy}$ is the average miles a tractor trailer travels per gallon of fuel consumed (assumed to be 6 mpg by default).

Table B-3: Truck Loads and Equipment Used in the Forest Harvesting Systems

Harvesting System	**Ground-Based**				**Cable**				**Helicopter**	
	Mech WT	**CTL**	**Manual WT**	**Manual Log**	**Manual WT/Log**	**Manual WT**	**Manual Log**	**CTL**	**Manual Log**	**CTL**
Truck Loads	**5**	**4**	**4**	**3**	**3**	**4**	**3**	**4**	**3**	**4**
Equipment	feller buncher skidder processor loader chipper	harvester forwarder loader chipper	skidder processor loader chipper	skidder loader chipper	yarder loader chipper	yarder processor loader chipper	yarder loader chipper	harvester yarder loader chipper	two loaders chipper	two loaders chipper harvester

The total fuel consumption is calculated by summing over the same category of fuel consumed for carrying out the relevant forest operations in the selected harvesting system (Table 6). Move-in fuel consumption is added to total diesel fuel consumption.

Allocating Harvesting Cost to Feedstock Cost

To estimate the harvest cost of feedstock, in addition to the on-to-truck cost for residues and move-in cost for residues, a portion of the stump-to-truck cost for primary products was allocated to chip trees. The allocations include a portion of the costs for small trees, including chip trees and small log trees, whose volume is smaller than 80 ft^3 (2.27 m^3) and a portion of the costs for all trees including chip trees, small log trees, and large log trees. For the forest operations dealing with the trees smaller than 80 ft^3 (2.27 m^3), the ratio of chip tree green weight to small tree (green) weight was used as the portion allocated to chip trees $[\mathrm{B}.29]$, and for those dealing with all trees, the ratio of chip tree (green) weight to all tree (green) weight was used $[\mathrm{B}.30]$. Forest operations performed in each harvesting system in the FRCS model are presented in Table 6. The green weight of trees used in calculating the cost allocated to chip trees has a different composition in the WT systems and the log length systems. In the WT systems both stem/bole and crown/residue biomass are harvested and delivered to the landing, and the green weight of trees is the sum of the green weight of boles and the green weight of residues; in the log length systems trees are cut into logs onsite and only logs/bole are delivered to the landing thus the green weight of trees is only the green weight of boles.

$$\mathrm{Cost}_{\mathrm{CT}} = \mathrm{Cost}_{\mathrm{ST}} \times \frac{\mathrm{Weight}_{\mathrm{CT}}}{\mathrm{Weight}_{\mathrm{ST}}} \qquad [\mathrm{B}.29]$$

where

$\mathrm{Cost}_{\mathrm{CT}}$ is the harvest cost ($/ac) allocated to chip trees

$\mathrm{Cost}_{\mathrm{ST}}$ is the cost ($/ac) of harvesting small trees

$\mathrm{Weight}_{\mathrm{CT}}$ is the yield of chip trees (green tons/ac)

$\mathrm{Weight}_{\mathrm{ST}}$ is the yield of small trees (green tons/ac)

For biomass salvage, the cost of acquiring feedstock is the cost of acquiring total biomass because all forms of biomass including stem and crown are utilized as the feedstock for the conversion facility.

$$\mathrm{Cost}_{\mathrm{CT}} = \mathrm{Cost}_{\mathrm{AT}} \times \frac{\mathrm{Weight}_{\mathrm{CT}}}{\mathrm{Weight}_{\mathrm{AT}}} \qquad [\mathrm{B}.30]$$

where,

$\mathrm{Cost}_{\mathrm{CT}}$ is the harvest cost ($/ac) allocated to chip trees

$\mathrm{Cost}_{\mathrm{AT}}$ is the cost ($/ac) of harvesting all trees

$\mathrm{Weight}_{\mathrm{CT}}$ is the yield of chip trees (green tons/ac)

$\mathrm{Weight}_{\mathrm{AT}}$ is the yield of all trees (green tons/ac)

To estimate the move-in cost for feedstock, in addition to the move-in cost for residues, the move-in cost of a chipper was allocated to feedstock. A chipper is required when chip trees are meant to be harvested or the option of whether to collect and chip residues is selected, in other words, it is required only for acquiring feedstock. For the ground-based CTL system, if residues are meant to be collected, an additional two pieces of equipment, including a bundler and a forwarder, are required solely for collecting and delivering residues. In summary, all harvesting systems require the move-in of a chipper when chip trees are meant to be harvested or the option of whether to collect and chip residues is selected; the ground-based CTL system would require the move-in of an additional two equipment - a bundler and a forwarder - when the option of whether to collect and chip residues is selected.

Allocating Fuel Consumption to Feedstock Cost

The estimation of the fuel consumed for acquiring feedstock follows the same approach used in the estimation of the cost of acquiring feedstock. The manual-felling related operations in Table 6 consume gasoline, helicopter-yarding related operations consume jet fuel, and the other operations consume diesel fuel. Fuel consumption for harvesting all trees can be calculated by summing over the fuel of the same category consumed for carrying out the relevant operations of the selected harvesting system, and a portion of the fuel consumption can be allocated to the acquisition of feedstock $[\mathrm{B}.31][\mathrm{B}.32]$ following the approach for allocating harvesting cost.

$$\mathrm{Fuel}_{\mathrm{CT}} = \mathrm{Fuel}_{\mathrm{ST}} \times \frac{\mathrm{Weight}_{\mathrm{CT}}}{\mathrm{Weight}_{\mathrm{ST}}} \qquad [\mathrm{B}.31]$$

where

$\mathrm{Fuel}_{\mathrm{CT}}$ is the fuel consumption (gals/ac) allocated to chip trees

$\mathrm{Fuel}_{\mathrm{ST}}$ is the fuel consumption (gals/ac) for harvesting small trees

$\mathrm{Weight}_{\mathrm{CT}}$ is the yield of chip trees (green tons/ac)

$\mathrm{Weight}_{\mathrm{ST}}$ is the yield of small trees (green tons/ac)

$$\mathrm{Fuel}_{\mathrm{CT}} = \mathrm{Fuel}_{\mathrm{AT}} \times \frac{\mathrm{Weight}_{\mathrm{CT}}}{\mathrm{Weight}_{\mathrm{AT}}} \qquad [\mathrm{B}.32]$$

where

$\mathrm{Fuel}_{\mathrm{CT}}$ is the fuel consumption (gals/ac) allocated to chip trees

$\mathrm{Fuel}_{\mathrm{AT}}$ is the fuel consumption (gals/ac) for harvesting all trees

$\mathrm{Weight}_{\mathrm{CT}}$ is the yield of chip trees (green tons/ac)

$\mathrm{Weight}_{\mathrm{AT}}$ is the yield of all trees (green tons/ac)

Similar to the allocation of move-in cost, the move-in fuel consumption considers the move-in of a chipper for all harvesting systems and the additional two pieces of equipment for the ground-based CTL system, which is determined using Equation $[\mathrm{B}.28]$ where $\mathrm{TruckLoads}$ is 0 if no chip trees or residues are to be harvested; $\mathrm{TruckLoads}$ is 1 for all harvesting systems representing one piece of equipment – a chipper – either chip trees or residues are to be harvested; $\mathrm{TruckLoads}$ is 3 for the ground-based CTL system representing a chipper and the additional two pieces of equipment - a bundler and a forwarder - if residues are to be harvested, i.e., the option of whether to including the cost of collecting and chipping residues is selected.

ENERGY RESEARCH AND DEVELOPMENT DIVISION

Appendix C: Biopower Facility Modeling: Technoeconomic Assessment

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APPENDIX C:
Biopower Facility Modeling: Technoeconomic Assessment

Table C-1: Inputs of the TEA Modeling Framework for Direct Combustion

Input	Default	Description
Capital Cost ($)	70,000,000	
Electrical and Fuel (base year)		
Net Plant Capacity (kW)	25,000	Size of plant based on net power output to grid
Capacity Factor (%)	85	Annual fraction that rated capacity is available from plant
Net Station Efficiency (%)	20	Ratio of net energy output from plant to fuel energy input to plant
Fuel Heating Value (kJ/kg)	18,608	Higher heating value (heat of combustion) of fuel
Fuel Ash Concentration (%)	5	Fraction of ash in fuel, percent dry basis
Expenses (base year)		
Fuel Cost ($/t)	22	Cost of fuel in $/dry metric ton
Labor Cost ($/y)	2,000,000	Cost of labor to operate facility
Maintenance Cost ($/y)	1,500,000	Cost of maintaining the plant
Insurance/Property Tax ($/y)	1,400,000	Cost of insurance for the plant plus any property or other local taxes
Utilities ($/y)	200,000	Purchased utilities including power, gas, water, waste disposal
Ash Disposal ($/y)	100,000	Cost of ash disposal from plant, use negative value when ash is sold at value
Management/Administration ($/y)	200,000	Cost for administrative personnel and other administration
		All other expenses for operating the plant, for example
Other Operating Expenses ($/y)	400,000	natural gas not included in utilities, chemicals, or additives

Input	Default	Description
Income other than energy		
Capacity Payment ($/kW-y)	166	Payment made from power purchaser if plant can guarantee capacity (depends on contract)
Interest Rate on Debt Reserve (%/y)	5	Interest income earned on reserve account if financing institution requires security deposit
Escalation/Inflation		
General Inflation (%/y)	2.1	Overall inflation rate used to adjust current dollar result to constant dollars
Escalation--Fuel (%/y)	2.1	Rate at which fuel cost escalates over time
Escalation for Production Tax Credit	2.1	Specified index for production tax credit
Escalation--Other (%/y)	2.1	Rate at which other expenses escalate over time
Financing		
Debt ratio (%)	75	Fraction of financing covered by debt borrowing
Interest Rate on Debt (%/y)	5	Interest rate applied to debt portion of investment
Economic Life (y)	20	Life of Loan
Cost of equity (%/y)	15	Rate of return on equity portion of investment
Debt Reserve ($)	4,212,736	Funds placed in reserve account as security deposit
Taxes		
Federal Tax Rate (%)	34	
State Tax Rate (%)	9.6	

Source: California Biomass Collaborative, UC Davis

Table C-2: Additional Inputs for the Combined Heat and Power TEA Model

Input	Default	Description
Heat (base year)		
Aggregate fraction of heat recovered (%)	60	Fraction of total heat production available for sale
Aggregate sales price for heat ($/kWh)	0.0207	Heat sales price

Input	Default	Description
Escalation/Inflation		
Escalation--Heat sales (%/y)	2.1	Escalation rate applied to heat sales

Source: California Biomass Collaborative, UC Davis

Table C-3: Inputs for Gasification TEA Model in Addition to Those included in the Combined Heat and Power TEA Model

Input	Default
Electrical and Fuel (base year)	
HHV Efficiency of Gasification System--Biomass to Clean Gas (%)	65
Net HHV Efficiency of Power Generation incl. Dual Fuel (%)	23
Dual Fuel: Fraction of Input Energy (%)	20
Expenses (base year)	
Dual Fuel Cost ($/L)	0.3
Waste Treatment/Disposal ($/y) for char/ash	2000
Income other than energy	
Sales Price for Char/Ash ($/t)	0
Escalation/Inflation	
Escalation--Dual Fuel (%/y)	2.1
Escalation--Char/Ash sales (%/y)	2.1
Clean Gas Composition (% by volume, dry)	
CO	20
H_2	12
Hydrocarbons (as CH_4)	5
CO_2	12
O_2	0

Table C-4: Variables of Annual Cash Flow In the TEA Models

Direct Combustion	Combined-Heat and Power	Gasification
Equity Recovery	Equity Recovery	Equity Recovery
Equity Interest	Equity Interest	Equity Interest
Equity Principal Paid	Equity Principal Paid	Equity Principal Paid
Equity Principal Remaining	Equity Principal Remaining	Equity Principal Remaining
Debt Recovery	Debt Recovery	Debt Recovery
Debt Interest	Debt Interest	Debt Interest
Debt Principal Paid	Debt Principal Paid	Debt Principal Paid
Debt Principal Remaining	Debt Principal Remaining	Debt Principal Remaining

Direct Combustion	Combined-Heat and Power	Gasification
Fuel Cost Non-fuel Expenses Debt Reserve Depreciation Income--Capacity Interest on Debt Reserve Taxes w/o credit Tax Credit Taxes Energy Revenue Required	Fuel Cost Non-fuel Expenses Debt Reserve Depreciation Income--Capacity Income--Heat Interest on Debt Reserve Taxes w/o credit Tax Credit Taxes Energy Revenue Required	Fuel Cost Dual Fuel Cost Non-fuel Expenses Debt Reserve Depreciation Income--Capacity Income--Heat Income--Char/Ash Interest on Debt Reserve Taxes w/o credit Tax Credit Taxes Energy Revenue Required

$$\text{Total Energy Revenue} = \sum_{k=1}^{n} \text{Energy Revenue}_i \times (1 + \text{Cost of Money})^{-i} \qquad [C1]$$

where

Total Energy Revenue is the total present worth of energy revenue at year 0.

Energy Revenue_i is the energy revenue (\$/y) required for the k^{th} year

Cost of Money is the rate of return (decimal) on the equity portion of investment

n is the economic life of the facility (y)

$$\text{Current CRF} = \frac{i(1+i)^n}{(1+i)^n - 1} \qquad [C2]$$

where Current CRF is the capital recovery factor and i is the interest rate per year

$$\text{Current LCOE} = \frac{\text{Total Energy Revenue} \times \text{Current CRF}}{\text{Annual Generation}} \qquad [C3]$$

where

Current LCOE is the levelized cost of electricity in current dollars (\$/kWh)

Annual Generation is the annual generation of electricity (kWh)

$$\text{Constant LCOE} = \frac{\text{Total Energy Revenue} \times \text{Constant CRF}}{\text{Annual Generation}} \qquad [C4]$$

where

Constant LCOE is the levelized cost of electricity in constant dollars ($/kWh)

Constant CRF is the capital recovery factor exclusive of inflation with the real interest rate adjusted as

$$i' = \frac{1 + i}{1 + f} - 1 \qquad [C5]$$

where i' is the real interest rate per year and f is the inflation rate per year

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Appendix D: Environmental Impact Assessment: Partial LCA Methodology

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APPENDIX D: Environmental Impact Assessment: Partial LCA Methodology

The life cycle emissions of woody biomass to electricity are a function of the fuel required to harvest and chip forest resources, transport them using a truck tractor and trailer to a biopower facility, and convert the feedstock to electricity, modeled per equation [0.52]. The fuel use, such as diesel, gasoline, and jet fuel, is subject to the harvesting system used; for example, jet fuel is only used in the helicopter yarding systems, and the value of jet fuel consumption is zero when the other harvesting systems are used; gasoline consumption only exists in some harvesting systems that require manual felling of trees where chainsaws are used. The fuel consumption is modeled in FRCS and the allocation methods for forest residues were described in Appendix B under the "FRCS Fuel Consumption Modeling" section.

$$\begin{aligned}\mathrm{LCI} = {} & \mathrm{Diesel\ Consumption} \times \mathrm{LCI}_{\mathrm{diesel}} + \mathrm{Gasoline\ Consumption} \times \mathrm{LCI}_{\mathrm{gasoline}} \\ & + \mathrm{JetFuel\ Consumption} \times \mathrm{LCI}_{\mathrm{jetfuel}} \\ & + \mathrm{Transport\ Distance} \times \mathrm{LCI}_{\mathrm{transportation}} + \mathrm{LCI}_{\mathrm{electricity}}\end{aligned} \qquad [\mathrm{D1}]$$

Emissions associated with the construction of a biomass energy facility are accounted at the beginning of the project, and those from the manufacturing of harvesting equipment are accounted at the beginning of the project and at replacement intervals within the overall project lifetime (Table D-1). Tractor trailers used to transport feedstock are assumed to have an economic life of 5 years with a purchase price of $100,000 in 2002 dollars. Six replacements of a tractor trailer are assumed on a five-year interval. One tractor trailer dedicated to transporting equipment is assumed to be used over the lifetime of a facility due to the relatively low mileage of the overall move-in distance. A chipper and the tractor trailers in all the harvesting systems, as well as a bundler and a forwarder in the ground CTL system, are dedicated to feedstock harvest and transport, so the emissions from their manufacturing are accounted for. A portion of the emissions from the manufacturing of the other harvesting equipment is allocated to feedstock according to the forest operation carried out by the equipment. Similar to the allocation method detailed in Appendix B under the "Allocating Fuel Consumption to Feedstock" section, the weight ratios of chip trees to small trees and chip trees to all trees are used as the partitioning factors. The weight ratio of chip trees to small trees is used to partition the emissions from the manufacturing of the equipment used for the small-tree harvesting operations, while the weight ratio of chip trees to all trees is used to partition the emissions from the manufacturing of the equipment used for the all-tree harvesting operations. For example, in the ground-based mechanized WT system, a feller buncher is used to harvest small trees, and the weight ratio of chip trees to small trees is multiplied by the emissions from the manufacturing of the feller buncher to calculate the emissions allocated to feedstock, while a skidder is used to transport all trees from the harvest unit to the landing site, and the emissions allocated to feedstock are calculated by multiplying the weight ratio of chip trees to all trees by the emissions from the manufacturing of the skidder. The weight ratios of the combinations of forest treatments and harvesting systems are predetermined by directly querying from the database (Table D-2, Table D-3). For convenience, forest treatments and harvesting systems are represented by letter-number combinations (Table 13). The weight ratio of any combination with T2, T4, and T6 is zero because no chip trees are harvested in these forest treatments. Partitioning by weight ratio is not relevant to some combinations as noted in the table. No weight ratio is derived for the biomass salvage treatment (T10) because all trees harvested are considered feedstock, and all the emissions are therefore attributed to feedstock.

Table D-1: Harvesting equipment costs assumptions and use life obtained from the FRCS model

Equipment	Chainsaw	FBuncher	Harvester	Skidder	Forwarder	Yarder	Processor	Loader	Chipper	Bundler
Equipment life (year)	1	4	4	4	4	10	5	5	5	5
Purchase price as of Dec 2002 ($)	700	256,667	400,000	170,000	275,000	245,000	350,000	220,000	250,000	450,000

Table D-2: Weight ratio of chip trees for small trees

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
T1	0.31	0.31	-	0.30	-	0.31	-	0.30	-	0.30
T2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
T3	0.65	0.65	-	0.62	-	0.56	-	0.53	-	0.62
T4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
T5	0.82	0.82	-	0.78	-	0.83	-	0.79	-	0.78
T6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
T7	0.41	0.41	-	0.39	-	0.41	-	0.39	-	0.39
T8	0.06	0.06	-	0.06	-	0.06	-	0.06	-	0.06
T9	0.11	0.11	-	0.10	-	0.11	-	0.10	-	0.10

Table D-3: Weight ratio of chip trees for all trees

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
T1	0.17	0.17	0.16	-	0.17	0.17	0.15	-	0.16	-
T2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
T3	0.58	0.58	0.55	-	0.49	0.49	0.46	-	0.54	-
T4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
T5	0.60	0.60	0.53	-	0.64	0.64	0.57	-	0.54	-

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
T6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
T7	0.22	0.22	0.20	-	0.21	0.21	0.19	-	0.19	-
T8	0.03	0.03	0.02	-	0.03	0.03	0.02	-	0.02	-
T9	0.05	0.05	0.04	-	0.05	0.05	0.04	-	0.04	-

Because no data considering different scales of facilities and different types of harvesting equipment were identified, EIO-LCA (Carnegie Mellon University Green Design Institute, 2008) was used to estimate the emissions from facility construction and various equipment manufacturing based on financial information as described below. The LCA model accounting for the emissions from facility construction and equipment manufacturing is presented below:

$$\begin{aligned}\mathrm{LCI} = {} & \mathrm{Diesel\ Consumption} \times \mathrm{LCI}_{\mathrm{diesel}} + \mathrm{Gasoline\ Comsumption} \times \mathrm{LCI}_{\mathrm{gasoline}} \\ & + \mathrm{JetFuel\ Consumption} \times \mathrm{LCI}_{\mathrm{jetfuel}} \\ & + \mathrm{Transport\ Distance} \times \mathrm{LCI}_{\mathrm{transportation}} + \mathrm{LCI}_{\mathrm{electricity}} \\ & + \mathrm{Facility\ Capital\ Cost} \times \mathrm{LCI}_{\mathrm{construction}} \\ & + \mathrm{Equipment\ Purchase\ Price} \times \mathrm{LCI}_{\mathrm{manufacturing}}\end{aligned} \qquad [\mathrm{D2}]$$

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Appendix E: FRREDSS User Guide

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APPENDIX E:
FRREDSS User Guide

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