Title
Integrated Economic and Environmental Modeling of Forest Biomass-to-Electricity in California

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Publication Date
2022

Peer reviewed|Thesis/dissertation

Integrated Economic and Environmental Modeling of
Forest Biomass-to-Electricity in California

By

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THESIS

Submitted in partial satisfaction of the requirements for the degree of

MASTER OF SCIENCE

in

Biological Systems Engineering

in the

OFFICE OF GRADUATE STUDIES

of the

UNIVERSITY OF CALIFORNIA

DAVIS

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2022

Abstract

Forests are a major natural resource of the state of California, where over a third of the land is forested, and provide a wide range of environmental, economic, and social benefits. Over the past decade, unprecedented drought and insect outbreaks have resulted in large-scale tree mortality that greatly affects the functionality of the forest ecosystem and amplifies the fire hazard. Forest thinning and management is considered imperative to improve forest health and resilience. Forest resources including dead and dying trees as well as the residues produced from forest thinning and timber harvesting operations can be utilized to generate electricity to meet the increasing demand for renewable energy and mitigate the risk of wildfires. However, efforts to construct new electricity generation capacity in the state at any scale over the last several decades have faced both economic and environmental challenges. As needs for alternative management approaches have become clear in the wake of extensive drought, intensive wildfire and other stresses on the forest ecosystem, opportunities have emerged for new bioenergy projects. These projects need to be effectively planned and potential economic and environmental performance carefully evaluated. Toward this purpose, a framework model for lifecycle and technoeconomic assessment was developed to quantify environmental and economic impacts of generating electricity using forest resources, with associated web services developed for a robust web-based application that allows potential users to quickly estimate the economic and environmental performance of a potential biopower facility at specified locations. While not intended to replace detailed project engineering, siting and permitting evaluations needed for any actual project implementation, the model can provide preliminary assessments to inform decisions and highlight information needs relating to further project development.

Case studies were conducted to assess the model performance and examine the ability to effectively predict costs and benefits for use of forest resources in California. For all the combinations of forest treatments and harvesting systems, levelized cost of energy (LCOE) ranges from $135 to $575 per MWh electricity generation in the case study modeling a 25 MWe facility using a conventional boiler-steam cycle, and ranges from $183 to $588 per MWh electricity generation in the case study modeling a 3 MWe gasification facility. Optimization based on a minimum feedstock cost objective function further lowers the LCOE and can be effectively realized at lower computational intensity than needed for complete evaluation over the full resource dataset by using a partial search employing an expansion factor method developed for this purpose.

Substantial environmental benefits were achieved from utilizing forest resources to generate electricity as compared to open pile burning under the assumption that the biomass will be burned in open piles in the absence of bioenergy uses, and from the displacement of grid electricity given the current mix of nonrenewable and renewable sources. Two baseline scenarios were considered in the case studies, in which for both clearcut was selected as the forest treatment and the ground-based mechanized whole-tree system as the harvesting system, along with the associated technical, economic, and financial assumptions. The potential emissions reductions from utilizing the forest biomass for electricity generation are significant. The emissions of GHG, CO, NO_x, $PM_{2.5}$, and VOC for a 25 MWe facility using a conventional boiler-steam cycle, a 25 MWe combined heat and power facility, and a 3 MWe gasification facility achieved reductions of between 21 and 99%, 44 and 99%, and 51 and 99%, respectively. Net GHG emissions for the three modeled conversion technologies in the baseline scenarios are negative compared to open burning at -440, -926, and -1084 kg per MWh electricity generation, indicating significant opportunities for resource management with improved overall environmental performance.

Acknowledgments

I would like to thank Professor Bryan Jenkins for his invaluable supervision and continuous support during my graduate studies. His immense knowledge and rigorous approach towards research have encouraged me constantly. Not only did his insightful feedback and constructive comments help me improve my analytical and technical writing skills but his consistent understanding and encouragement allowed me to complete this research. It was a pleasure working with him and a great honor being his student. He will always be my role model.

I am also deeply grateful to Professor Bruce Hartsough for his help in interpreting and adapting the FRCS model. This work could not have been done without his advice. I would also like to thank Professor Alissa Kendall for her constructive feedback in life cycle assessment methods. My gratitude extends to the California Energy Commission for providing funding for this research.

Finally, I want to thank my parents for their unconditional love, and my wife, Hong Guo, for her unfailing love and support.

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Nomenclature

FRCS	Fuel Reduction Cost Simulator
LCA	Life cycle assessment
TEA	Technoeconomic assessment
WT	Whole-tree
CTL	Cut-to-length
CT	Chip trees
SLT	Small log trees
LLT	Large log trees
ALT	All log trees
AT	All trees
TPA	Number of live trees per acre
SNG	Number of snags per acre
BMCWN	Crown biomass of live trees (BDT/acre)
DBMCN	Crown biomass of snags (BDT/acre)
BMSTM	Stem biomass of live trees (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)
CCF	Hundred cubic feet
O&M	Operation and Maintenance

1 Introduction

Forests are an important component of natural ecosystems and provide a wide range of environmental, economic, and social benefits. Forests play a critical role in helping to mitigate climate change by removing carbon dioxide from the atmosphere and storing it for long periods of time. Between 2001 and 2019, the world's forests constituted an annual net carbon sink of 7.6 billion metric tons (Harris et al., 2021), which is 30% more than the net carbon emissions of the United States (US) in 2019, and 21% of global emissions during the same period. Forests enhance soil infiltration and improve groundwater recharge, disperse water through water and energy cycles, and moderate floods (Ellison et al., 2017). Forests provide raw materials for commercial uses such as home construction, furniture, and board products, and contribute to rural economies. Forests are habitats for a variety of plants and animals and are outdoor recreation for humans. Recreational activities in U.S. national forests and grasslands sustain about 154,000 jobs and contribute over $12 billion to the U.S. economy (U.S. Forest Service, 2020).

Forests are a major natural resource of the state of California (CA), where over a third of the land is forested. The forest industry constitutes an important sector of the state economy. In 2016, approximately 57,890 workers were employed in the forest industry in California, earning a total of $3.64 billion, and about $1.5 billion in sales were generated for primary forest products (Marcille et al., 2020). However, unprecedented drought and insect outbreaks have resulted in large-scale tree mortality that greatly affects the functionality of the forest ecosystem and amplifies the fire hazard. Frequent and intense wildfires not only cost lives and destroy property, infrastructure, and services but release large amounts of greenhouse gases and air pollutants into the atmosphere. In the past decade, tree mortality has increased drastically due to drought, bark beetle outbreaks, and wildfires. Over 147 million dead trees across 9.7 million acres of land in California were reported from 2010 to 2018 (California Department of Forestry and Fire Protection, 2019). Climate change is considered 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 (California Department of Forestry and Fire Protection, 2021a). Increased forest fires are attributed to global warming, as are significant impacts on ecosystems due to increased area burned and fire intensity and severity (Flannigan et al., 2000). According to the statistics published by the California Department of Forestry and Fire Protection, there has been a sharp rise in fire suppression expenditures over the past decade (Figure 1.1).

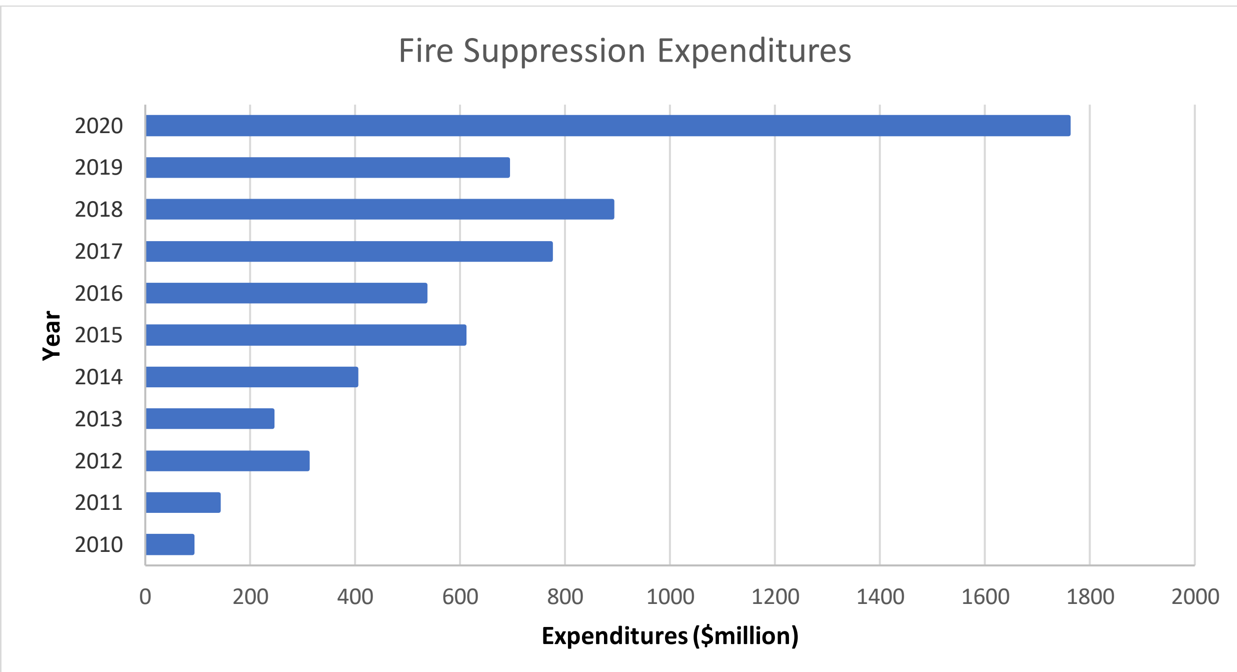

Figure 1.1 Fire suppression expenditures from 2010 to 2020 (California Department of Forestry and Fire Protection, 2021b).

Forest thinning and management is considered imperative to improve forest health and resilience. Historic forest suppression practices that aimed to eliminate fires accumulate a massive amount of fuel on the ground and result in overly dense forests. Fuel in the form of small trees, shrubs and grasses accumulated on the forest floor constitute a hazard that facilitates the spread of wildfire into the forest canopy or crown leading to more destructive fires. Low-intensity fires carried out periodically to remove fuel accumulated on the forest floor can be beneficial to forest health. Such practices mitigate fire risks by restricting fire spread and transport via ground fuel and small trees (so-called ladder fuels) into the crown or canopy. Prescribed burning of ground fuels may not, however, sufficiently reduce fuel load and density. Forest thinning is a means of restoring forest health and resilience by the planned removal of small trees or defective trees in overcrowded forests. It reduces the competition among trees for nutrients, water and sunlight and allows better growth of large trees. Due to the large number of dead and dying trees, their removal can also help reduce susceptibility to wildfires ("Thinning | OregonForests," 2022).

Trees harvested via forest thinning and management, based on commercial value, can be divided into merchantable and unmerchantable components. Merchantable trees are processed into logs that are transported to pulpmills 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 harvested for feedstock. Pile burning is currently the preferred forest residue disposal method on many forest sites. Research has shown that slash pile burning can be harmful to soil chemistry and water quality (Johnson et al., 2011). Also, the burning process releases criteria pollutants, air toxins, and greenhouse gases. Additionally, open burning forest residues wastes the resource value of the biomass; according to the 2016 Billion-ton Report by the U.S. Department of Energy, the quantities of forest resources, primarily logging residues and whole-tree biomass, in the U.S. ranged potentially from 21 to 116 million dry tons in 2017 (Langholtz et al., 2016). One way to utilize these residues is as feedstock to generate electricity in biomass power plants. Forest biomass has long been used as the primary fuel to generate heat. Since the 19th century fossil fuel has been used as the primary energy source for thermal power generation by virtue of its high heating value and low acquisition cost. Environmental issues from consuming fossil fuel including climate change and sustainability have attracted more and more attention, and countries are shifting energy sources from fossil fuel to renewable energy sources such as solar, wind, and biomass. In contrast to solar and wind-based power that suffer from intermittency, forest biomass is flexible and can be used to balance fluctuations in power supply and demand (Xu et al., 2021). Forest biomass can be used to generate heat and power through combustion. It can also be converted to liquid or gaseous fuel through other thermochemical and biochemical processes. Forest biomass-based power has been widely implemented in California. In 2020, wood and wood derived fuels produced over 3 Terawatt-hours (TWh) of electricity (U.S. Energy Information Administration, 2021a), accounting for roughly 1.6% of in-state electric power generation. However, efforts to construct new biomass-fueled electricity generation capacity at any scale over the last several decades in the state have been hampered by increasing capital costs without similar increases in revenue from energy sales. Moreover, despite that forest biomass as energy resources are mostly carbon neutral in the process of energy conversion and regrowth, the processes of harvesting, processing, and transporting at present create emissions from fossil fuels. Similarly, conventional biopower projects utilizing forest residues typically need extensive emission controls that add to cost to satisfy federal, state and local permitting regulations and community demands while potential environmental and social benefits such as wildfire risk reduction and overall forest ecosystem health remain largely external to the cost determination in the absence of specific incentives or subsidies and quantified net environmental accounting.

To help address these issues, a framework model for lifecycle and technoeconomic assessment was developed to quantify the environmental and economic impacts of generating electricity using forest resources, with associated web services developed for a robust web-based application that allows potential users to quickly estimate the economic and environmental performance of a potential biopower facility at specified locations.

2 Literature Review

The potential for utilizing forest biomass for energy production from economic and environmental perspectives has been extensively studied. Esteban and Carrasco (2011) assessed agricultural and forest biomass resources available for energy use and associated acquisition cost in 11 European Union (EU) countries and investigated possible locations for the erection of biomass hydrogen plants. Mangoyana (2011) assessed the potential of forest thinning-based energy systems that involve two thinning operations: two-machine and harwarder (combined harvester and forwarder). The two-machine system uses one machine for cutting trees and the other for forwarding trees, while the harwarder system uses one machine for cutting and forwarding trees. The results show positive energy balances and reduced carbon emissions compared to fossil fuels in forest thinning-based energy systems, and also indicate that the two-machine system is more efficient from economic and environmental perspectives. Murphy et al. (2014) performed a life cycle assessment on forest biomass supply chains in Ireland and discovered transport as the most energy and GHG emissions-intensive process. Anttila et al. (2015) carried out a case study in northern China to assess the feasibility of using residual forest biomass for energy from the perspectives of biomass availability, supply chains, and supply costs. The results suggest increasing thinning intensity, mechanizing the hauling of trees, and building roads in inaccessible areas in order to lower supply costs and achieve economic viability. Springsteen et al. (2015) conducted a case study for utilizing forest wastes yielded from hazardous fuels reduction and timber operations for electricity production in the Sierra Nevada. The study reported that converting forest residues into energy has air quality benefits, with a 98~99% reduction in particulate matter with 2.5 μm or less in diameter ($PM_{2.5}$), carbon monoxide (CO), non-methane volatile organic compounds (NMOC), methane (CH_4), and 20% reduction in NO_x and GHG emissions. It also calculated that energy used in transporting and processing only takes 2.5% of biomass heating value. Zhang et al. (2016) conducted an assessment of cost, energy use, and GHG emissions for forest biomass harvesting operations. The authors developed a harvesting cost model and performed an economic assessment and life cycle assessment in the state of Michigan, US. The results indicate that productivity is the major factor that impacts harvesting cost, followed by machinery purchase price, yearly scheduled hours and expected utilizations; productivity and fuel use are the main factors impacting energy consumption and GHG emissions. Schnorf et al. (2021) examined costs, energy requirements, and CO_2 emissions associated with biomass transport in the main supply chains identified in Switzerland and found that cost is the main barrier to biomass transport rather than energy and CO_2 emissions.

Previous research has revealed net environmental benefits from using forest biomass to substitute fossil fuels for energy production. Greenhouse gas (GHG) and climate impacts of bioenergy production using forest residues were investigated in Finland (Repo et al., 2012). Compared with coal and natural gas, bioenergy production from forest residues had lower GHG emissions and climate impacts over the longer term. Zhang et al. (2015) analyzed life cycle energy consumption and GHG emissions of forest residues harvest and transport for biofuel production in Michigan and found that biofuel production from forest biomass resulted in a 62% reduction in GHG emissions compared with petroleum-based fossil fuel production. Gustavsson et al. (2015) analyzed the climate impacts of bioenergy systems and fossil-based energy systems and found that compared to fossil-based energy systems where coal, oil, or natural gas are used for energy and forest residues are left onsite to decompose, bioenergy systems reduce longer-term climate impacts measured as atmospheric cumulative radiative forcing. Beagle and Belmont (2019) investigated life cycle GHG emissions of biomass utilization for electricity generation in the EU and the US, concluding that biomass-derived electricity produces up to 76% lower GHG emissions than coal-fired electricity. Xu et al. (2021) studied the life cycle GHG emissions of biomass utilization for electricity in different regions of the US and concluded an 86%-93% reduction of GHG emissions from forest biomass-derived electricity compared to the emissions of the average grid electricity in the US.

However, the studies discussed above do not always fully assess the economic and environmental performance across the lifetime of a biomass energy facility. Most analyses have been focused on the economics of the feedstock acquisition stage, i.e., forest operations or transport, but rarely the full life cycle of feedstock from harvesting, transport, to energy conversion. Moreover, they do not take into consideration the availability of economically feasible resources. Most comparative studies make upfront assumptions about the amount of available feedstock or transport distance and compare costs and GHG emissions from the utilization of feedstock for energy production with those from generating the same amount of energy using conventional fossil fuels. Such analysis ignores spatial and temporal dimensions involved in acquiring biomass feedstock. For a bioenergy facility operating for many years, available biomass resource is distributed differently from year to year, and the corresponding topological attributes of harvest sites and transportation routes between the harvest sites to the facility are different, which directly affects the economic and environmental factors associated with feedstock harvest and transport. Spatial analysis with respect to resource distribution and availability, and actual transportation routes are necessary to help evaluate the economic and environmental performance of a bioenergy facility over its lifetime. Furthermore, unsuccessful deployment of forest biomass-based bioenergy projects in the past due to lack of revenue as well as opposition from local communities urges new bioenergy projects to be effectively planned and potential economic and environmental performance carefully evaluated.

Efforts have been made in the development of decision support systems for bioenergy production incorporating spatial analysis. Frombo et al. (2009) introduced a GIS-based Environmental Decision Support System (EDSS) to determine optimal logistics that minimize costs for energy production from woody biomass, accounting for environmental impacts. Esteban and Carrasco (2011) created a GIS-based tool that can be used to estimate the amount of available biomass resources and acquisition costs. Zambelli et al. (2012) developed a decision support system to assess forest biomass availability for energy production. The system considers morphology of the terrain, capability of harvesting techniques, and road accessibility and can be used to estimate the amount of available biomass yielded from forest management. Paredes-Sánchez et al. (2016) developed a GIS-based decision-making framework that can help select the biomass logistic center by assessing the feasibility of solid biofuel production based on mass, energy, and cost of available biomass. Merz et al. (2018) developed a decision support application for siting hybrid poplar-based biorefineries. The application uses information from a crop growth model, farm budget application, parcel service, crop service, soil and weather services, and transportation routing service specifically developed to assess available resources and determine net revenue for biofuel production based on user-specified conditions. Yet little research considering spatial and temporal complexity has been done to incorporate spatial analysis, economic and environmental assessment across the lifetime of a potential bioenergy facility and allow the specifications of fine details such as forest prescription, harvesting system, conversion technology, economic, technical and financial parameters that would provide insights of the economic and environmental impacts of a potential bioenergy facility.

3 Methodology

3.1 Integrated Economic and Life Cycle Emissions Model

To expand the availability of more detailed decision support for forest-based renewable energy systems, a more comprehensive integrated model application was developed for open access. The application is structured to integrate the Fuel Reduction Cost Simulator (FRCS) (Fight et al., 2006), transportation, transmission, technoeconomic assessment (TEA), and life cycle assessment (LCA) models yielding information on the cost of energy and potential environmental impacts (Figure 3.1**Error! Reference source not found.**).

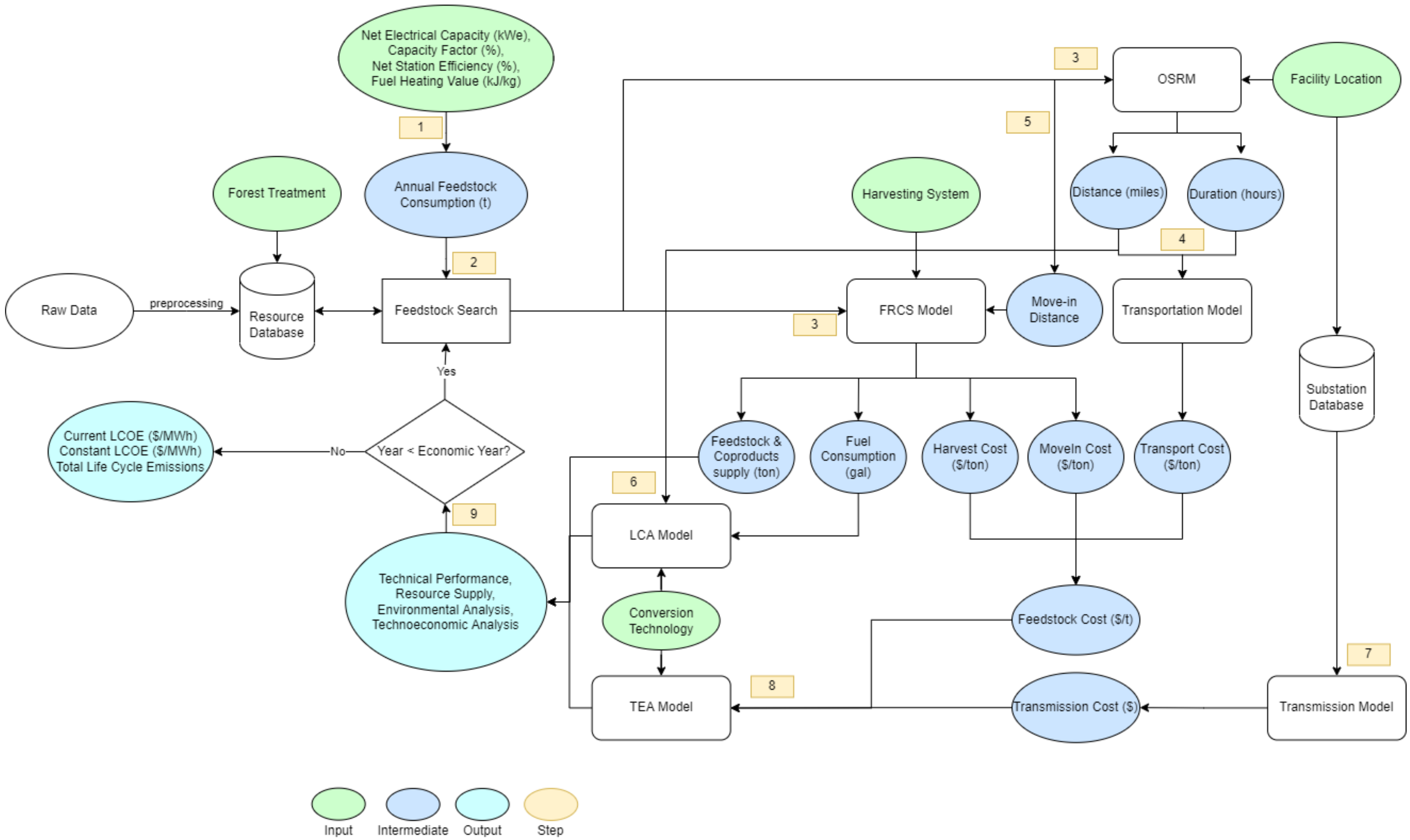

Figure 3.1 Integrated structure of the forest resource and renewable energy decision support system application.

The workflow from user input to the model output is described below:

1. Based on the user inputs including net electrical capacity, capacity factor, net station efficiency, and fuel heating value, the annual feedstock demands of the power station or other conversion facility are estimated.

2. Spatial analysis is conducted to identify feedstock supply sufficient to meet the annual demands through selection of a set of predefined clusters providing information on forest resources necessary for the subsequent economic and environmental analyses. This resource search routine is designed to optimize cost by using a minimum total feedstock delivered cost objective function.

3. For each cluster, the interpreted FRCS model (Fight et al., 2006) is used to estimate harvest cost, equipment fuel consumption, and feedstock and coproduct supply. Cluster and conversion facility site location coordinates are used with the Open Source Routing Machine (OSRM) (Luxen and Vetter, 2011) to determine supply routing to the facility and the transportation distance and travel time.

4. Transportation cost is estimated from the transportation distance, travel time, and related equipment and labor cost factors.

5. OSRM is used to determine the shortest route to transport equipment from conversion facility site, through all the clusters, and eventually back to the facility site. This route information is then used in FRCS to develop a move-in cost associated with all clusters that adds to the total delivered cost.

6. Estimated resource supply and conversion facility criteria pollutant and greenhouse gas emissions over the full supply chain are estimated in developing a lifecycle inventory (LCI) and assessment (LCA), yielding potential impact per unit output (kg MWh^{-1} among others). These are computed on both total and net emissions.

7. Based on the facility location, the nearest electricity distribution or transmission grid is located and the distance to the facility used to estimate additional transmission or distribution costs. Facility interconnection costs for grid applications are included in the facility costs.

8. Feedstock delivered costs are combined with transmission and distribution costs and facility capital and operating costs in a comprehensive technoeconomic analysis (TEA) yielding annual cash flows and revenue requirements.

9. The above procedure is repeated for each year over the full economic life of the project to estimate the overall levelized cost of energy (LCOE) in both current and inflation-adjusted amounts along with total lifecycle emissions.

10. Results of the analysis are provided in graphical and comprehensive spreadsheet formats.

3.2 Forest Resource Dataset

Spatial resource data in pixel format with 30 by 30 m resolution was provided by the U.S. Forest Service using the F^3 modeling framework (Huang et al., 2018). The dataset is comprised of nine variable categories containing information on the number and the volume of trees, the amount of stem and crown biomass, and basal area (Table 3.1) for six size classes (Table 3.2). Variable categories include the number of live trees and snags/dead trees, the amount of stem biomass and crown biomass of live trees and snags, the volume of live trees and snags, and the basal area of live trees. Size classes as defined by F^3 delineate trees by diameters. For example, the size class 2 includes trees between 1 and 5 inches diameter at breast height (DBH) as noted in Table 3.2. Combining variable category TPA with size class 2, written as TPA_2, represents the number of live trees per acre (TPA, original units) with diameters greater than or equal to 1-inch DBH and smaller than 5-inch DBH. Combining the 9 variable categories and the 6 size classes, the dataset has in total 54 variables.

Table 3.1 F^3 variable categories

Variable Category	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 3.2. Size classes

Size Class	Diameter (inches)
2	$1 \leq DBH < 5$
7	$5 \leq DBH < 10$
15	$10 \leq DBH < 20$
25	$20 \leq DBH < 30$
35	$30 \leq DBH < 40$
40	$DBH \geq 40$

In order to facilitate computations and create harvest units with a reasonable size, pixel-level data were aggregated into 360 by 360 m clusters with a standard 12x12 pixel configuration although this varies to some extent in proximity to feature boundaries (e.g., lake, rivers) and other terrain characteristics. This standard configuration yields a projected 12.96 ha (32.02 acres) area per cluster. The F^3 variables in the pixel data were similarly aggregated to cluster-level with the same units by summing over the product of each variable multiplied by pixel area for all the pixels in the cluster and then dividing by the sum of pixel area for all the pixels in the cluster.

3.3 Tree Categories

According to FRCS, trees are categorized into three types: chip trees, small log trees, and large log trees. Chip trees are the trees to be chipped for board products or fuel, small log trees are trees with less than 80 ft^3 (2.27 m^3) volume that can be mechanically felled and processed into logs, and large log trees are trees with 80 ft^3 (2.27 m^3) or more volume that are felled manually with chainsaws. Both chip trees and small log trees have volumes less than 80 ft^3 (2.27 m^3) and they together are categorized as small trees. Small log trees and large log trees together are categorized as log trees.

3.4 Forest Treatments

For the sake of forest establishment, growth, composition, health, and quality, activities that change current stand structure and composition of a stand require silvicultural prescriptions that document a planned series of treatments to be prepared before implementation (U.S. Forest Service, 2021). Ten forest treatments, developed by Tubbesing (2020), include clearcut, commercial thin, commercial thin with chip tree removal, timber salvage, timber salvage with chip tree removal, selection, selection with chip tree removal, 10% group selection, 20% group selection, and biomass salvage with chip tree removal, of which land types and trees to be removed may vary from one to another. Land type refers to the type of land on which a treatment is performed, including private and public (principally U.S. Forest Service (FS)) lands. The specification of each treatment is summarized (Table 3.3) and discussed below in terms of land types and tree categories.

Table 3.3 Specifications of the ten forest treatments

Treatment #	Treatment name	Land Type	Log Trees Live	Log Trees Dead	Chip Trees Both Live and Dead
1	Clearcut	Private	100%	100%	1-5" DBH - 60% 5-10" DBH - 90%
		FS			
2	Commercial Thin	Private	calculated %		
		FS			
3	Commercial Thin CT	Private	calculated %		1-5" DBH - 50% 5-10" DBH - 80%
		FS			1-5" DBH - 85% 5-10" DBH - 90%
4	Timber Salvage	Private		100%	
		FS		100%	
5	Timber Salvage CT	Private		100%	1-5" DBH - 60% 5-10" DBH - 90%
		FS		100%	1-5" DBH - 85% 5-10" DBH - 90%
6	Selection	Private	calculated %		
		FS			
7	Selection CT	Private	calculated %		1-5" DBH - 50% 5-10" DBH - 80%
		FS			
10	Biomass Salvage CT	Private		100%	1-5" DBH - 60% 5-10" DBH - 90%
		FS		100%	1-5" DBH - 85% 5-10" DBH - 90%

* FS refers to U.S. Forest Service; CT = chip tree removal.

1. **Clearcut** harvests all log trees on private land, and 60% of the chip trees with 1-5’’ DBH and 90% of the chip trees with 5-10’’ DBH on private land.

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 site 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 $\mathrm{Residual_{BA}}$, according to the California Forest Practice Rules (CFPR) (California Department of Forestry and Fire Protection, 2020), based on site class and principal forest type of the cluster (Table 3.4).

Table 3.4 Basal area that should remain for commercial thin (source: CFPR)

Site Class	Forest Type	$\mathrm{Residual_{BA}}$ (ft^2/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

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

$$\mathrm{Initial_{BA}} = \mathrm{BA_{15}} + \mathrm{BA_{25}} + \mathrm{BA_{35}} + \mathrm{BA_{40}} \qquad [3.1]$$

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

$$\mathrm{BA_{remove}} = \mathrm{Initial_{BA}} - \mathrm{Residual_{BA}} \qquad [3.2]$$

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

If $\mathrm{BA_{remove}} \leq \mathrm{BA_{15}}$,

$$P_{15} = \frac{BA_{remove}}{BA_{15}}, P_{25} = P_{35} = P_{40} = 0 \quad [3.3]$$

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

If $BA_{15} < BA_{remove} \leq BA_{15} + BA_{25}, P_{15} = 1,$

$$P_{25} = \frac{BA_{remove} - BA_{15}}{BA_{25}}, P_{35} = P_{40} = 0 \quad [3.4]$$

If $BA_{15} + BA_{25} < BA_{remove}$ and Land Type is Private,

$$P_{15} = P_{25} = 1, P_{35} = P_{40} = 0 \quad [3.5]$$

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

$$P_{15} = P_{25} = 1, P_{35} = \frac{BA_{remove} - BA_{15} - BA_{25}}{BA_{35}}, P_{40} = 0 \quad [3.6]$$

If $BA_{15} + BA_{25} + BA_{35} < BA_{remove}$ and Land Type is Private,

$$P_{15} = P_{25} = P_{35} = 1, P_{35} = \frac{BA_{remove} - BA_{15} - BA_{25} - BA_{35}}{BA_{40}} \quad [3.7]$$

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% of the chip trees with 1-5'' DBH and 80% of the chip trees with 5-10'' DBH are harvested; on FS land 85% of the chip trees with 1-5'' DBH and 90% of the chip trees with 5-10'' DBH are harvested.

4. **Timber salvage** harvests all dead log trees on both private and FS 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% of the chip trees with 1-5’’ DBH and 90% of the chip trees with 5-10’’ DBH are harvested; On FS land, 85% of the chip trees with 1-5’’ DBH and 90% of the chip trees with 5-10’’ DBH are harvested.

6. **Selection** harvests only live log trees 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 site class.

The percentages to be removed of different size class of trees can be determined in a similar way to that for commercial thin while the determination of $Residual_{BA}$ is based on Table 3.5.

Table 3.5 Basal area that should remain for selection (source: CFPR)

Site Class	$Residual_{BA}$ (ft^2/ac)
1	100
2	75
3	75
4	50
5	50

7. **Selection with chip tree removal** is the same as **selection** but with the additional removal of chip trees on private land. 50% of the chip trees with 1-5’’ DBH and 80% of the chip trees with 5-10’’ DBH are harvested.

8. **10% group selection** applies **clearcut** to 10% of the area of a harvest unit and **selection** to the rest of the area**.**

9. **20% group selection** applies **clearcut** to 20% of the area of a harvest unit and **selection** to the rest of the area**.**

10. **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.

3.5 Economic Modeling

3.5.1 Adaptation of the Fuel Reduction Cost Simulator

FRCS was developed for the U.S. Forest Service and is a Microsoft Excel™,[1] spreadsheet application used to estimate the costs of harvesting trees from stump to truck based on machine costs and production equations derived from existing studies (Fight et al., 2006). The original FRCS model uses cost data that can be traced back to the year 2000. The cost data, including wages, equipment costs, and diesel fuel price, were updated to December 2007, and three new variants of FRCS, categorized by regions as west, north, and south, were developed with newly added production equations to estimate harvesting cost in the west, north, and south of the U.S., respectively (Dykstra et al., 2009). This research focuses on the state of California; hence the FRCS west variant is used, which is applicable to the following states: Alaska, Oregon, Washington, Arizona, California, Hawaii, Nevada, and New Mexico. The cost data for California in FRCS were updated and the model capability was enhanced through this work. Fuel consumption for harvesting trees is modeled based on the machine information and production rates embedded in FRCS. An allocation method was developed and implemented in the FRCS model 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

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

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. Furthermore, 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.

3.5.1.1 Harvesting Systems

The FRCS harvesting systems are divided into two categories: whole-tree (WT) systems and log length systems. In WT 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 applied to the areas accessible by road and where slopes are smaller than 40%. Cable-yarding and helicopter yard systems are applied to areas inaccessible by road or with slopes greater than 40%. The specifications of the ten harvesting systems in FRCS are as below:

- **Ground-based mechanized WT system (Ground Mech WT)**: At the stump, small trees are felled and bunched by feller bunchers. Large log trees are felled, limbed, and bucked into logs with chainsaws. The bunches from 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. Log tree tops and limbs and chip trees are chipped and loaded onto chip vans.

- **Ground-based manual-felling WT 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. Log tree tops and limbs and chip trees are chipped and loaded onto chip vans.

- **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 and blown into chip vans.

- **Ground-based CTL system (Ground CTL)**: At the stump, trees are felled, limbed and bucked into logs by a harvester. Logs are transported to the landing by forwarders. At the landing, logs from log trees are loaded onto trucks, and logs from chip trees are chipped and blown into chip vans.

- **Cable-yarding manual-felling WT 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 tree tops and limbs and chip trees are chipped and loaded onto chip vans.

- **Cable-yarding manual-felling WT/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 and loaded onto chip vans.

- **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 and blown into chip vans.

- **Cable-yarding CTL 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 and blown into chip vans.

- **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 and blown into chip vans.

- **Helicopter-yarding CTL 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 and blown into chip vans.

Table 3.6. Forest operations in FRCS

	Ground-Based				Cable				Helicopter	
	Mech WT	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 >80cf	✓		✓			✓				
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 <=80 cf								✓		✓
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		✓								

* cf = cubic feet.

3.5.1.2 Feedstock Composition

Feedstock is comprised of wood chips processed from chip trees, and tops and limbs of small log trees, which is different from residues as defined in FRCS that include only tops and limbs of trees, i.e., 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. A separate operation would be required to retrieve any residues. Logs from log trees are usually considered high-value material to be processed into lumber. Feedstock recovered from different FRCS harvesting systems has different compositions (Table 3.7). The stem biomass of chip trees is always fully recovered because both WT and log length systems harvest chip tree boles/stems; WT systems are designated 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, essentially stem biomass, are delivered to the landing. In contrast, 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 WT systems, a portion of tops and limbs are assumed to be left onsite in FRCS, and 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 CTL system additional harvesting equipment including a bundler and a forwarder can be brought to the harvest site and used to collect and deliver the biomass to the landing. Compared to WT systems, a smaller fraction of crown biomass is recovered in the ground-based CTL system. Typically cable and helicopter-based log length systems are applied where the terrain is steep and the equipment such as bundlers and forwarders cannot be easily brought in, hence no crown biomass is recovered in these systems. The amount of feedstock is computed by the adapted FRCS model.

Table 3.7 Feedstock composition

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.

Trees smaller than 10-inch DBH are chip trees and those with 10-inch DBH or greater are log trees. The tree structure is divided into two components: crown and stem. Typically, the feedstock for biopower facilities includes both the crown and stem of chip trees and only the crowns of log trees. Whole chip trees and log tree crowns are considered feedstock. Stems of log trees are considered sawlogs. 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 taken into account and FRCS sets percentages, subject to the type of harvesting system, for how much biomass is actually harvested.

3.5.1.3 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 3.8 summarizes the latest published cost data.

Table 3.8 Cost data

	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% 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 [3.8] 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.

$$\mathrm{PurchasePrice}_{\mathrm{current}} = \mathrm{PurchasePrice}_{2002} * \frac{\mathrm{PPI}_{\mathrm{current}}}{\mathrm{PPI}_{2002}} \qquad [3.8]$$

where

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

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

$PPI_{current}$ is the current PPI

PPI_{2002} is the PPI of year 2002

3.5.1.4 Inputs

The original FRCS requires the specifications of a series of parameters/inputs in order to run simulations and generate logging costs, including system type, cut type, location, yard/skid/forward slope distance, percent slope, elevation, whether or not to include loading costs, whether or not include move-in costs, area treated, one-way move-in distance, whether or not to include the costs of collecting and chipping residues, tree characteristics including green wood density, residue fraction, and hardwood fraction of chip trees, small log trees, and large log trees, and the number of trees per acre and the average volume per tree with respect to chip trees, small log trees, and large log trees.

- **System type** is selected from the ten harvesting systems including four ground-based systems, four cable-yarding systems, and two helicopter systems.

- **Cut type** is selected from two types: clearcut and partial cut. Cut type is always partial cut if forest treatment is not clearcut.

- **Location** is selected from the states in the contiguous United States. Since the FRCS west variant is used, the options are limited to those within the west region, including Alaska, Oregon, Washington, Arizona, California, Hawaii, Nevada, and New Mexico.

- **Yard/Skid/Forward slope distance** (ft) is the distance that trees or logs are moved from the stump to be delivered to the landing. Subject to the selected harvesting system, trees or logs can be yarded, skidded, or forwarded to the landing.

- **Percent slope** is the slope (%) of the harvest unit.

- **Elevation** (ft) only needs to be specified for helicopter systems.

- **Move-in costs** are the costs of moving harvesting equipment to a harvest unit.

- **Area treated** and **one-way move-in distance** are only required when the option of **whether to include move-in costs** is selected. Area treated (acres) is the area of the harvest unit and one-way move-in distance (miles) is the one-way distance of moving harvesting equipment to the harvest unit.

- The option of **whether to include the costs of collecting and chipping residues** is only applicable for the WT systems and ground-based CTL system because in the WT systems whole trees are delivered to the landing, and tree tops and limbs, referred to as residues in FRCS, are recovered. In the ground-based CTL system additional equipment, including a bundler and a forwarder, is required to collect residues onsite and forward them to the landing. In the other systems, however, trees are felled, limbed, and bucked onsite, and only logs are delivered to the landing. Cable-yarding and helicopter yarding systems are usually applied when the terrain is greater than 40% and inaccessible to bundlers and forwarders. Enabling this option also requires a chipper being moved to the landing.

- **Wood density** (pounds per cubic foot) is the ratio of tree green weight to green volume.

- **Residue fraction** (FRCS definition) is the ratio of the green weight of tree tops and limbs to the green weight of the tree bole.

- **Hardwood fraction** is the ratio of the green volume of hardwood to the total green volume of trees in the harvest unit.

Nine additional inputs were added to the FRCS model, including moisture content, residue recovery fraction for WT systems, residue recovery fraction for CTL systems, wages of fallers, wages of other workers, benefits and overhead, diesel fuel price, current producer price index (PPI), and an option of whether or not the harvesting is biomass salvage.

- **Moisture content** is the moisture content of biomass on a wet basis (% w.b.)
- **Residue recovery fraction for WT systems** is the green weight fraction of residues recovered in WT systems
- **Residue recovery fraction for CTL systems** is the green weight fraction of residues recovered in CTL systems
- **Wages of fallers** are the hourly wages of fallers/buckers
- **Wages of other workers** are the hourly wages of other logging workers
- **Benefits and overhead** for workers is the ratio (**%)** of benefits and overhead to wages
- **Diesel fuel price** is the current wholesale price ($/gallon) of low-sulfur diesel fuel in the California
- **Current producer price index** is the latest published value of the U.S. producer price index (PPI)
- **The option of whether or not the harvesting is biomass salvage** allows users to indicate if all trees will be utilized as feedstock for the conversion facility.

In the original FRCS implementation, moisture content, residue recovery fraction for WT systems, and residue recovery fraction for CTL were assumed to be 50%, 80%, and 50%, respectively, but these critical parameters could heavily affect the harvest cost and the amount of residues recovered, and predetermining the values of these parameters could lead to inaccurate results. Establishing them as inputs allows users to provide better information, if available, based on local conditions. Default values, however, remain the same as the original.

Current cost data in the model (Table 3.8) are applicable to California. To use FRCS in other states of the western region, the corresponding cost data are required in order to update the cost information in FRCS. Annual updates are necessary for the spreadsheet implementation of FRCS and only FRCS developers are authorized to modify the hard-coded cost numbers in the FRCS codebase. Additionally, labor and fuel costs are statewide averages. To enhance the flexibility of FRCS for user input, new input entries were created for these parameters 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 that is assumed to be chipped at the landing. The modeling is detailed in Section 3.5.1.11.

3.5.1.5 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 [3.10]-[3.30] below. Because the data do not contain the volumes of individual trees, size class by diameter is used to categorize CT, SLT, and LLT. Trees with $1 \le DBH < 10$ 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 [3.9] from the FRCS model as derived from a study by Drews et al. (2001).

$$\mathrm{TreeVol} = \mathrm{DBH}^2 \times 0.216 - 3.675 \qquad [3.9]$$

$$\mathrm{BoleWeight}_{\mathrm{CT}} = \frac{2000 \times \sum_{\mathrm{i}}^{2,7}(\mathrm{BMSTM}_{\mathrm{i}} + \mathrm{DBMSM}_{\mathrm{i}})}{1 - \mathrm{MoistureContent}} \qquad [3.10]$$

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

$$\mathrm{BoleWeight}_{\mathrm{SLT}} = \frac{2000 \times (\mathrm{BMSTM}_{15} + \mathrm{DBMSM}_{15})}{1 - \mathrm{MoistureContent}} \qquad [3.11]$$

$$\mathrm{BoleWeight}_{\mathrm{LLT}} = \frac{2000 \times \sum_{\mathrm{i}}^{25,35,40}(\mathrm{BMSTM}_{\mathrm{i}} + \mathrm{DBMSM}_{\mathrm{i}})}{1 - \mathrm{MoistureContent}} \qquad [3.12]$$

$$\mathrm{ResidueWeight}_{\mathrm{CT}} = \frac{2000 \times \sum_{\mathrm{i}}^{2,7}(\mathrm{BMCWN}_{\mathrm{i}} + \mathrm{DBMCN}_{\mathrm{i}})}{1 - \mathrm{MoistureContent}} \qquad [3.13]$$

$$\mathrm{ResidueWeight}_{\mathrm{SLT}} = \frac{2000 \times (\mathrm{BMCWN}_{15} + \mathrm{DBMCN}_{15})}{1 - \mathrm{MoistureContent}} \qquad [3.14]$$

$$\mathrm{ResidueWeight}_{\mathrm{LLT}} = \frac{2000 \times \sum_{\mathrm{i}}^{25,35,40}(\mathrm{BMCWN}_{\mathrm{i}} + \mathrm{DBMCN}_{\mathrm{i}})}{1 - \mathrm{MoistureContent}} \qquad [3.15]$$

$$\mathrm{ResidueFraction}_{\mathrm{CT}} = \frac{\mathrm{ResidueWeight}_{\mathrm{CT}}}{\mathrm{BoleWeight}_{\mathrm{CT}}} \qquad [3.16]$$

$$\mathrm{ResidueFraction}_{\mathrm{SLT}} = \frac{\mathrm{ResidueWeight}_{\mathrm{SLT}}}{\mathrm{BoleWeight}_{\mathrm{SLT}}} \qquad [3.17]$$

$$\mathrm{ResidueFraction}_{\mathrm{LLT}} = \frac{\mathrm{ResidueWeight}_{\mathrm{LLT}}}{\mathrm{BoleWeight}_{\mathrm{LLT}}} \qquad [3.18]$$

$$\mathrm{Volume}_{\mathrm{CT}} = \sum_{\mathrm{i}}^{2,7} \mathrm{VOL}_{\mathrm{i}} + \mathrm{VMSG}_{\mathrm{i}} \qquad [3.19]$$

$$\mathrm{Volume}_{\mathrm{SLT}} = \mathrm{VOL}_{15} + \mathrm{VMSG}_{15} \qquad [3.20]$$

$$\mathrm{Volume}_{\mathrm{LLT}} = \sum_{\mathrm{i}}^{25,35,40} (\mathrm{VOL}_{\mathrm{i}} + \mathrm{VMSG}_{\mathrm{i}}) \qquad [3.21]$$

$$\mathrm{WoodDensity}_{\mathrm{CT}} = \frac{\mathrm{BoleWeight}_{\mathrm{CT}}}{\mathrm{Volume}_{\mathrm{CT}}} \qquad [3.22]$$

$$\mathrm{WoodDensity}_{\mathrm{SLT}} = \frac{\mathrm{BoleWeight}_{\mathrm{SLT}}}{\mathrm{Volume}_{\mathrm{SLT}}} \qquad [3.23]$$

$$\mathrm{WoodDensity}_{\mathrm{LLT}} = \frac{\mathrm{BoleWeight}_{\mathrm{LLT}}}{\mathrm{Volume}_{\mathrm{LLT}}} \qquad [3.24]$$

$$\mathrm{Removals}_{\mathrm{CT}} = \sum_{\mathrm{i}}^{2,7} \mathrm{TPA}_{\mathrm{i}} + \mathrm{SNG}_{\mathrm{i}} \qquad [3.25]$$

$$\mathrm{Removals}_{\mathrm{SLT}} = \mathrm{TPA}_{15} + \mathrm{SNG}_{15} \qquad [3.26]$$

$$\mathrm{Removals}_{\mathrm{LLT}} = \sum_{\mathrm{i}}^{25,35,40} \mathrm{TPA}_{\mathrm{i}} + \mathrm{SNG}_{\mathrm{i}} \qquad [3.27]$$

$$\mathrm{TreeVol}_{\mathrm{CT}} = \frac{\mathrm{Volume}_{\mathrm{CT}}}{\mathrm{Removals}_{\mathrm{CT}}} \qquad [3.28]$$

$$\mathrm{TreeVol}_{\mathrm{SLT}} = \frac{\mathrm{Volume}_{\mathrm{SLT}}}{\mathrm{Removals}_{\mathrm{SLT}}} \qquad [3.29]$$

$$\mathrm{TreeVol}_{\mathrm{LLT}} = \frac{\mathrm{Volume}_{\mathrm{LLT}}}{\mathrm{Removals}_{\mathrm{LLT}}} \qquad [3.30]$$

As an approximation, the slope of a cluster is calculated by dividing the elevation difference between the center of biomass [3.31] 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:

$$\overline{\mathrm{lat}} = \frac{\sum W_i \mathrm{lat}_i}{\sum W_i}, \qquad \overline{\mathrm{lng}} = \frac{\sum W_i \mathrm{long}_i}{\sum W_i} \qquad [3.31]$$

where

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

$\overline{\mathrm{lng}}$ 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:

$$\overline{d_l} = \frac{\sum W_i l_i \tau_i}{\sum W_i} \qquad [3.32]$$

where

$\overline{d_l}$ 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)

3.5.1.6 Outputs

In addition to the outputs of the original FRCS (harvesting cost in dollars per hundred cubic feet (CCF), dollars per green ton of trees, and dollars per acre of harvest unit, the adapted FRCS also computes biomass yield and fuel consumptions for diesel, gasoline, and helicopter fuel (Table 3.9). The outputs of the adapted FRCS are comprised of two components: total biomass and feedstock, and each component consists of yield, harvesting cost in dollars per hundred cubic feet of trees, dollars per green tons of biomass, and dollars per acre of harvest unit (cluster), diesel fuel consumption in gallons per hundred cubic feet of wood and gallons per acre of harvest unit, gasoline fuel consumption in gallons per hundred cubic feet of wood and gallons per acre of harvest unit, and jet fuel consumption in gallons per hundred cubic feet of wood and gallons per acre of harvest unit.

The yield of total biomass and feedstock is computed by FRCS. The modeling of fuel consumption is detailed in Section 3.5.1.7. The allocation of harvesting cost and fuel consumption to feedstock is detailed in Section 3.5.1.8.

Table 3.9 FRCS Outputs

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

* GT = green tons. CCF = hundred cubic feet.

3.5.1.7 Fuel Consumption Modeling

All manual-felling related operations in Table 3.6 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 [3.33]. Fuel consumption per CCF is then computed [3.34].

$$\mathrm{FuelConsumptionPMH} = \mathrm{Horsepower} * \ \mathrm{FuelConsumptionHpPMH} \qquad [3.33]$$

where

$\mathrm{FuelConsumptionPMH}$ is fuel consumption rate in gallons per machine hour

$\mathrm{FuelConsumptionHpPMH}$ is fuel consumption rate in gallons per horsepower per machine hour

$$\mathrm{FuelConsumptionCCF} = \frac{\mathrm{FuelConsumptionPMH}}{\mathrm{CostPMH}} \times \mathrm{CostCCF} \qquad [3.34]$$

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 (Šumarija Vareš 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 3.10 (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 3.10. Fuel consumption rates of the helicopters modeled in FRCS

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 [3.35]. 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 3.11 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 truck loads 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.

$$\mathrm{FuelConsumption}_{\mathrm{move-in}} = \frac{\mathrm{MoveInDist} \times (\mathrm{NumTrips} \times \mathrm{TruckLoads})}{\mathrm{FuelEconomy}} \qquad [3.35]$$

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.

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

Table 3.11 Truck loads and equipment used in the 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 3.6). Move-in fuel consumption is added to total diesel fuel consumption.

3.5.1.8 Allocation of Harvesting Cost and Fuel Consumption to Feedstock

FRCS was customized 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. This project considers chip trees plus residues as defined by FRCS as feedstock.

3.5.1.8.1 Components

There are four components involved in the estimation of total harvest cost: (1) stump-to-truck cost for primary products; (2) move-in cost for primary products; (3) on-to-truck cost for residues; and (4) move-in cost for residues. Residues in the various components refer to tops and limbs from log trees to be consistent with the names of the variables in the original FRCS.

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 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 refer 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 CTL system where a bundler is required to be transported to the harvest site for collecting residues, and a forwarder is required for transporting residues. For feedstock, a chipper is also required and is included separately in move-in costs for that option, see below.

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

3.5.1.8.2 Allocating Harvest Cost to Feedstock

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 [3.36], and for those dealing with all trees, the ratio of chip tree (green) weight to all tree (green) weight was used [3.37]. Forest operations performed in each harvesting system in the FRCS model are presented in Table 3.6. 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.

$$\mathrm{Cost_{CT}} = \mathrm{Cost_{ST}} \times \frac{\mathrm{Weight_{CT}}}{\mathrm{Weight_{ST}}} \qquad [3.36]$$

where

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

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

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

$\mathrm{Weight_{ST}}$ 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.

$$\mathrm{Cost_{CT}} = \mathrm{Cost_{AT}} \times \frac{\mathrm{Weight_{CT}}}{\mathrm{Weight_{AT}}} \qquad [3.37]$$

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.

3.5.1.8.3 Allocating Fuel Consumption to Feedstock

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 3.6 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 [3.38][3.39] following the approach for allocating harvesting cost.

$$\mathrm{Fuel_{CT}} = \mathrm{Fuel_{ST}} \times \frac{\mathrm{Weight_{CT}}}{\mathrm{Weight_{ST}}} \qquad [3.38]$$

where

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

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

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

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

$$\mathrm{Fuel_{CT}} = \mathrm{Fuel_{AT}} \times \frac{\mathrm{Weight_{CT}}}{\mathrm{Weight_{AT}}} \qquad [3.39]$$

where

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

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

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

$\mathrm{Weight_{AT}}$ 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 [3.35] 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; 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.

3.5.1.9 Limits

The original FRCS sets limits on tree volumes. By definition chip trees and small log trees are smaller than 80 ft^3 (2.27 m^3), and large log trees are greater than or equal to 80 ft^3 (2.27 m^3). Also, FRCS sets 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). The inputs that exceed the tree volume maximums will trigger input validation errors and halt FRCS from computing results. After reviewing the tree volume maximums for the ten harvesting systems, they were revised as follows (Table 3.12):

For the three CTL systems, since no forest operations in these systems involve harvesting large log trees, constraining the volume of large log trees is irrelevant and limits the capability of FRCS. When user input of large log trees has an average volume greater than 100 ft^3 (2.83 m^3) (the maximum volume of large log trees allowed in the original FRCS), FRCS should run simulations for the CTL systems regardless, but the original FRCS generates an error indicating the inputs were invalid in such cases and stops running. Therefore, the tree volume maximum limits for large log trees in the CTL systems were removed.

For the two manual WT systems, the maximum volume of large log trees was changed from 500 ft^3 (14.16 m^3) to 250 ft^3 (7.08 m^3) to match the physical maximum of the ground-based mechanized WT system. Additionally, 250 ft^3 (7.08 m^3) was the maximum in the first version of FRCS published in 2006.

For the four manual log-length systems, no limits were set on small or large log trees, but limits were instead assigned on all log trees and all trees. For consistency with other systems, the limits on small and large log trees were set to 80 and 250 ft^3 (2.27 to 7.08 m^3), respectively, the limits on all log trees and all trees for the four manual log-length systems and the three manual WT systems were removed as they are unnecessary when the volumes of chip trees, small log trees, and large log trees are constrained. For example, if the maximum volume of small log trees is 80 ft^3 (2.27 m^3) and that of large log trees is 250 ft^3 (7.08 m^3), the volume of all log trees, which is the average volume of small log trees and large log trees, must be below 250 ft^3 (7.08 m^3), thus the limit of 250 ft^3 (7.08 m^3) on the volume of all log trees is redundant.

FRCS also places constraints on slope and yarding distance. The ground-based systems and the CTL systems cannot be performed on harvest units with a slope greater than 40%. The cable-yarding systems cannot be performed on harvest units with a yarding distance greater than 1300 feet (396.24 m). The helicopter-yarding systems cannot be performed on harvest units with a yarding distance greater than 10,000 feet (3048 m).

Table 3.12. Updated tree volume maximums.

Limits		Ground-Based				Cable				Helicopter	
		Mech WT	CTL	Manual WT	Manual Log	Manual WT/Log	Manual WT	Manual Log	CTL	Manual WT	CTL
TreeVol Maximums, ft3:	CT	80	80	80	80	80	80	80	80	80	80
	SLT	80	80	80	80	80	80	80	80	80	80
	LLT	250	~~100~~	250	250	250	250	250	~~100~~	250	~~100~~
	ALT	~~250~~		~~500~~	~~250~~	~~250~~	~~500~~	~~250~~		~~250~~	
	AT	~~250~~		~~500~~	~~250~~	~~250~~	~~500~~	~~250~~		~~250~~	
Maximum Slope, %		40	40	40	40	100	100	100	40	100	40
Maximum Yarding Dist, ft						1300	1300	1300	1300	10000	10000

* CT = chip trees; SLT = small log trees; LLT =large log trees; ALT = all log trees; AT = all trees.

3.5.1.10 Harvesting Trees beyond Limits

FRCS can simulate harvesting large log trees with up to 250 ft^3 (7.08 m^3) 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 ft^3 (7.08 m^3), in the absence of better information the harvest cost per hundred cubic feet of trees greater than 250 ft^3 (7.08 m^3) volume is assumed equal to that of trees with 250 ft^3 (7.08 m^3) volume. Costs per green ton of trees and per acre of harvest unit can be calculated by dividing the total costs by yield in green tons and by area of harvest unit in acres. The same approach is applied to fuel consumption modeling when harvesting trees greater than 250 ft^3 (7.08 m^3) volume.

3.5.1.11 Biomass Salvage Option

In the original FRCS model, only chip trees and log tree tops and limbs are assumed chipped, and the log tree stems are always considered merchantable components. However, in the scenarios where log trees are of insufficient quality to be made into high-value materials, or in certain regions where most trees are considered biomass feedstock for conversion facilities, all types of trees including log trees need to be chipped. An additional biomass salvage input is added which is used to determine if all trees are meant to be chipped. If so, all trees including log trees are chipped.

FRCS computes the unit cost of chipping chip trees on a per hundred cubic feet basis subject to the harvesting system used. The cost of chipping chip trees is calculated based on various tree characteristics such as volume, wood density, load weight, and moisture content, and the total costs of chipping chip trees are calculated by multiplying the unit cost by the total volume of chip trees. To estimate the cost of chipping all trees, the unit cost is multiplied by the total volume of all trees [3.40], which assumes that the chipping cost per unit volume of chip trees also applies to log trees. Since the chipping cost per unit volume of trees is expected to decrease as the volume per tree increases, the cost of chipping all trees determined in this way is expected to be greater than the actual cost, so the estimate is conservative. If biomass salvage is selected, i.e., all trees are meant to be chipped, the cost of processing and loading log trees to trucks at the landing needs to be excluded because all log trees are chipped and blown into trucks directly from a chipper. In this case, FRCS feedstock harvest costs are set equal to the total costs because all trees are considered biomass.

$$\mathrm{CostChip}_{\mathrm{AT}} = \mathrm{UnitCostChip}_{\mathrm{CT}} * \mathrm{Volume}_{\mathrm{AT}} \qquad [3.40]$$

where

$\mathrm{CostChip}_{\mathrm{AT}}$ is the cost of chipping all trees

$\mathrm{UnitCostChip}_{\mathrm{CT}}$ is the cost of chipping chip trees ($/CCF)

$\mathrm{Volume}_{\mathrm{AT}}$ is the volume of all trees (CCF)

3.5.1.12 Software

FRCS was created in Microsoft Excel™ and contains 30 spreadsheets, and the original FRCS application is no longer supported on the Macintosh operating system and available only 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 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 named **@ucdavis/frcs** (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 Section 3.5.1.4.

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 which incorporates the FRCS npm package and computes harvest costs based on user-specified inputs such as harvesting system, cut type, tree characteristics, etc. The FRCS web application is currently hosted at https://frcs.ucdavis.edu/.

3.5.2 Transportation Model

Feedstock is collected, chipped at the landing, loaded onto trucks, and assumed directly transported to a conversion facility. To estimate the cost of transporting biomass to the facility, a transportation model from a previously developed decision support web application for siting hybrid poplar-based biorefineries was adopted (Merz et al., 2018). The model estimates the transportation cost by summing over the estimated labor, fuel, lubricating oil, and truck ownership costs [3.41]-[3.45].

$$\text{Labor Cost} = \text{Labor Wage} \times (1 + \text{Benefits Overhead}) \times \text{Transport Duration} \qquad [3.41]$$

where

Labor Cost is the labor cost for transporting biomass to a biopower facility ($/trip)

Labor Wage is the hourly wage of tractor-trailer truck drivers ($/h)

Benefits Overhead is the benefits and overhead rate for the truck labor (driver) (%)

Transport Duration is the time for transporting biomass to a biopower facility (h)

$$\text{Fuel Cost} = \frac{\text{Fuel Price} \times \text{Transport Distance}}{\text{Fuel Economy}} \qquad [3.42]$$

where

Fuel Cost is the fuel cost for transporting biomass to a biopower facility ($)

Fuel Price is the diesel fuel price ($/gallon)

Transport Distance is the distance for transporting biomass to a biopower facility (miles)

Fuel Economy is the average miles a truck travels per gallon of fuel consumed (mpg).

$$\text{Oil Cost} = \text{Unit Oil Cost} \times \text{Transport Distance} \qquad [3.43]$$

where

Oil Cost is the oil cost for transporting biomass to a biopower facility, in dollars

Unit Oil Cost is the average cost of oil in dollars per mile

$$\text{Truck Ownership Cost} = \text{Hourly Truck Ownership Cost} * \text{Transport Duration} \qquad [3.44]$$

where $\text{Hourly Truck Ownership Cost}$ is the hourly truck ownership cost ($/h) (assumed to be $13.10/h by default).

$$\text{Transport Cost} = \text{Labor Cost} + \text{Fuel Cost} + \text{Oil Cost} + \text{Truck Ownership Cost} \qquad [3.45]$$

where Transport Cost is the total cost for transporting biomass to a biopower facility ($)

The hourly mean wage for tractor-trailer truck drivers in California is $24.71 (BLS, 2020). The average oil cost is assumed to be $0.35/mile. Fuel economy is 6 mpg which is the same as that in the FRCS model. Default values of the oil cost and the benefits and overhead for truck drivers remain the same as the original and are $0.35/mile and 67%, respectively.

Table 3.13 Default input values for the transportation model.

Input	Unit	Value
Hourly wage for truck drivers	$/h	24.71
Benefits and overhead	%	67
Oil cost	$/mile	0.35
Fuel economy	miles/gallon	6

Transport distance and duration between a harvest unit and a biopower facility are obtained from OSRM, which is an open source router that can efficiently compute the shortest path between two coordinates using the data from the OpenStreetMap project (Luxen and Vetter, 2011) that creates and distributes an open-source geographic database. Due to the complex nature of OpenStreetMap data, simple tag mappings are not supported by OSRM; instead scripts named OSRM profiles can be incorporated to generate the desired route as well as transport distance and duration between two coordinates by defining in advance the routing behavior and rules. An OSRM profile specifies the routing properties such as vehicle category, vehicle size and weight, the speed on different types of roads, among other attributes. It also associates a penalty to 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).

When feedstock is transported to the conversion facility, the truck self-unloads the feedstock at the designated area. Assuming the whole unloading process takes 15 minutes, the labor cost is calculated using Equation [3.41] and the ownership cost is calculated using Equation [3.45], where Transport Duration is 0.25 h. The fuel consumption rate for unloading is assumed to be 2 gallons per hour, so the total fuel usage during the unloading is 0.5 gallons. These assumptions may be adjusted in the model.

3.5.3 Technoeconomic Model

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

The three conversion technologies share the same 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 detailed inputs, default values, and descriptions from the energy cost calculator for direct combustion are presented in Table 3.14. The asset depreciation is based on the U.S. federal Modified Accelerated Cost Recovery System (MACRS). According to Internal Revenue Code, a production tax credit was available at $0.013 per kWh electricity generated using open-loop biomass including forest resources, but beginning 2022 the tax credit is no longer appliable. The equivalent of one year of debt repayment is assumed required to secure loans (debt) in addition to equity financing and is placed into a savings account, known as debt reserve, in the event of unanticipated facility outage that would reduce income necessary for loan repayment until repairs can be affected.

While the same modeling framework is used for the three technologies, additional inputs are required for the other two technologies due to technological differences. For combined heat and power technology, heat is recovered for other industrial processes in addition to electricity generation. Additional inputs of the modeling of combined heat and power are presented in Table 3.15. For the gasification technology, biomass is first converted to syngas, and the syngas is combusted to generate electricity. Additional inputs for gasification modeling are presented in Table 3.16.

Based on the inputs, annual cash flows of the three technologies are derived (Table 3.17) including the energy revenue required. Summing the present worth of the annual energy revenues required for the economic life of the facility yields the total present worth of energy revenue [3.46] from which the current dollar levelized cost of electricity is determined from the capital recovery factor and in these cases the electrical energy generation [3.47][3.48]. For comparison purposes, a constant dollar levelized cost of electricity is similarly calculated using an inflation-adjusted capital recovery factor [3.49][3.50].

Table 3.14 Inputs of TEA modeling framework for direct combustion (source: CBC, values provided as example)

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 ($/y)	200,000	Cost for administrative personnel and other administration
Other Operating Expenses ($/y)	400,000	All other expenses for operating the plant, for example natural gas not included in utilities, chemicals, or additives
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	

Table 3.15 Additional inputs for combined heat and power modeling (source: CBC).

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

Table 3.16 Inputs for gasification modeling in addition to those of combined heat and power (source: CBC).

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 3.17 Variables of annual cash flows (source: CBC).

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

$$\text{Total Energy Revenue} = \sum_{k=1}^{n} \text{Energy Revenue}_{i} \times (1 + \text{Cost of Money})^{-i} \qquad [3.46]$$

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)

$$\text{Current CRF} = \frac{i(1+i)^n}{(1+i)^n - 1} \qquad [3.47]$$

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

$$\text{Current LCOE} = \frac{\text{Total Energy Revenue} \times \text{Current CRF}}{\text{Annual Generation}} \qquad [3.48]$$

where

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

Annual Generation is the annual generation of electricity (kWh)

$$\text{Constant LCOE} = \frac{\text{Total Energy Revenue} \times \text{Constant CRF}}{\text{Annual Generation}} \qquad [3.49]$$

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

$$i' = \frac{1+i}{1+f} - 1 \qquad [3.50]$$

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

3.5.3.1 Software

Similar to FRCS, to integrate the TEA, the model analysis was converted to a npm package named @ucdavis/tea (https://www.npmjs.com/package/@ucdavis/tea).

3.5.4 Transmission Model

To connect a new biopower facility to the utility electricity grid, new transmission lines generally need to be installed. The installation cost of new transmission lines or transmission cost is derived from the transmission model that was developed by Black & Veatch for the Western Electricity Coordinating Council (Mason et al., 2012). The transmission model takes as inputs the voltage class, line characteristics, new construction or re-conductor, terrain type, and location, and computes the capital cost of installing new transmission lines. The Length category has three options: < 3 miles, 3-10 miles, >10 miles. 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 needs to be specified: Forested, Scrubbed/Flat, Wetland, Farmland, Desert/Barren Land, Urban, Rolling Hills (2-8% Slope), and Mountain (>8% 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 3.18).

Table 3.18 Default input values of the transmission model.

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

To determine the transmission cost, The transmission model multiplies baseline transmission cost by various multipliers adjusted for specific design considerations[3.51] (Mason et al., 2012), where both baseline transmission cost and multipliers were identified in the original model and the baseline cost was adjusted to 2021 dollars using CPI.

$$\begin{aligned} &\text{Total Transmission Line Cost} \\ &\quad = \text{Base Transmission Cost} \times \text{Conductor Multiplier} \\ &\quad \times \text{Structure Multiplier} \times \text{Reconductor Multiplier} \\ &\quad \times \text{Terrain Multiplier} + \text{Right of Way Cost} \end{aligned} \quad [3.51]$$

3.6 Life Cycle Assessment

LCA is a technique for assessing the environmental impacts of a product, process, or service throughout its life cycle, from raw material acquisition and processing through manufacturing, distribution and use, to recycling or disposal (EPA, 2008). LCA can 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 is released, and thus provide for more informed decisions. LCA consists of four phases: goal and scope, inventory, impact assessment, and interpretation (EPA, 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 life cycle. Inventory quantifies the inputs and outputs throughout the life cycle, such as diesel consumption, coal combustion, carbon dioxide emissions, and particulate matter releases. Impact assessment evaluates the potential environmental impacts by characterizing the inventory into specific categories, such as global warming potential, acidification, and eutrophication. Interpretation serves to conclude the overall environmental performance of the study, identify processes of concern, inform policymakers, investors, or local communities, and recommend what could be improved in the future by analyzing the results of the inventory and impact assessment.

The two main methods are process-based and economic input-output LCA (EIO-LCA). Process-based LCA focuses on the material and energy flows of every life cycle stage of the targeted product or process, while EIO-LCA uses the association of energy and environmental information with aggregated industry sectors to infer the potential energy use and environmental emissions associated to an economic value. In general, process-based LCA is preferred as it analyzes every life cycle stage and presents details of material and energy flows, but it is time-consuming and information intensive in order to collect the relevant data. EIO-LCA is easier to use as the economic and environmental information is aggregated into the industry sectors, but the results are averaged across the products of a sector. EIO-LCA is often used to assist process-based LCA where data may be lacking for some life cycle stages and the combination of the two LCA methods is referred to as hybrid LCA.

3.6.1 Goal and Scope Definition

The goal of this research is to estimate the emissions of greenhouse gases including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), and the 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 life cycle of generating electricity utilizing woody biomass as feedstock. Carbon intensity, in kilograms CO_2 equivalent per MWh of electricity generation, is modeled based on the emissions of CO_2, CH_4, N_2O, CO, and VOC. Also, environmental impacts such as global warming potential (GWP) are determined.

The scope of this research is to develop a life cycle emission model for the generation of electricity utilizing forest resources acquired through forest management and prescriptions. The system boundary is from forest resources at harvesting sites (stump) to the plant gate for electricity generated at a biopower facility as shown in Figure 3.3. The three main phases of the life cycle include feedstock acquisition at harvesting sites, feedstock transportation from harvesting sites to a biopower facility, and feedstock conversion at the facility. Also, the construction of a new facility and the manufacturing of harvesting equipment are included. The electricity transmission and distribution and the end-of-life of facility and harvesting equipment, which could be either disposed of or recycled, are not included in the scope of this research.

The audience is intended to include power project developers, policymakers, and local communities in California among other users of the decision support system. Power project developers can conduct preliminary studies using the model developed from this research and assess the feasibility of potential facility sites. Policymakers can leverage the model to simulate environmental burdens from incentivizing the construction of new biopower facilities. Local communities can benefit from a transparent evaluation of the environmental performance of local facilities.

The functional unit is 1 MWh electricity generated.

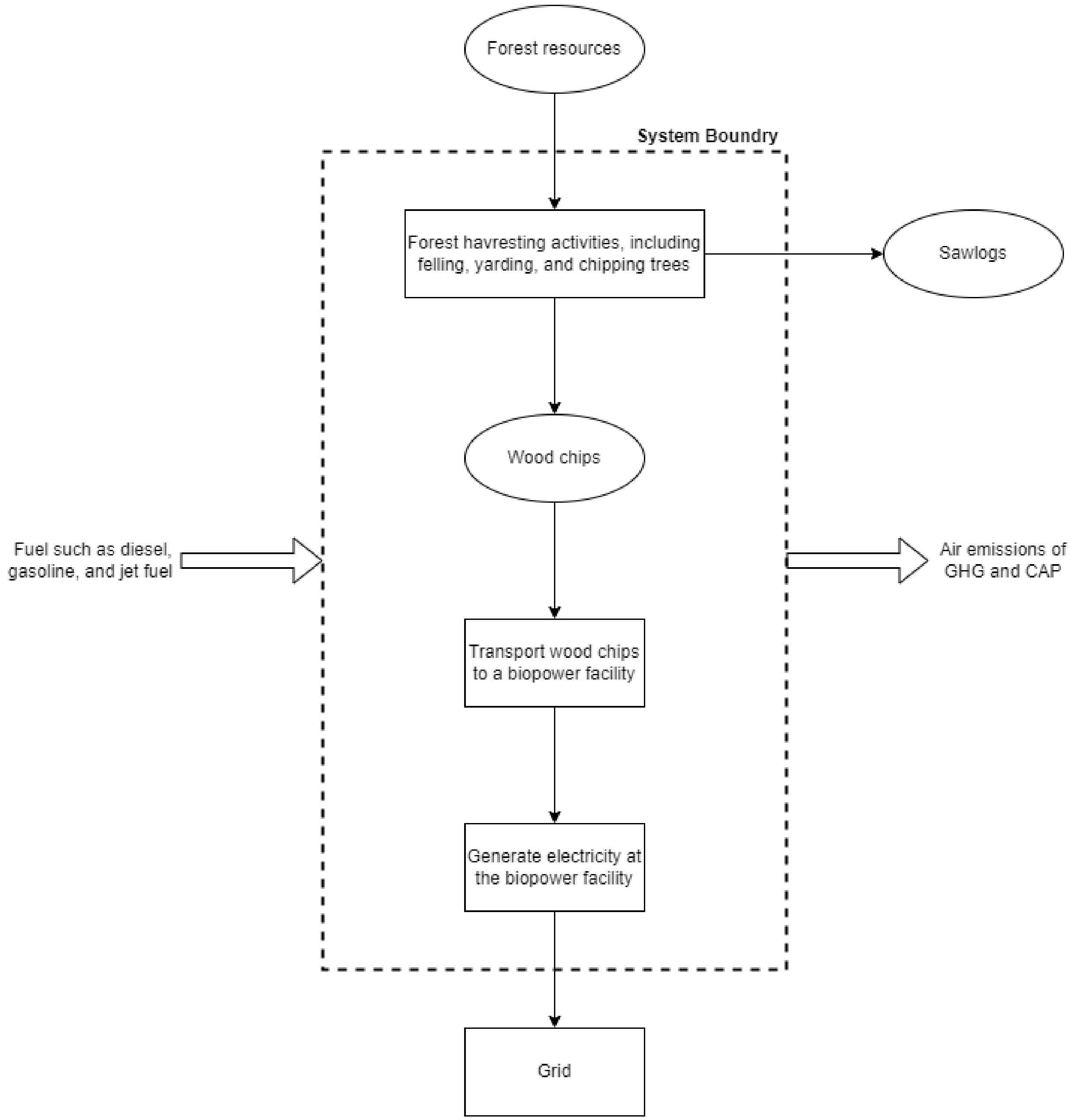

Figure 3.3 System Boundary

3.6.2 LCA Methods

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 [3.52]. 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 Section 3.5.1.7.

$$\begin{aligned}\mathrm{LCI} = {} & \text{Diesel Consumption} \times \mathrm{LCI}_{\mathrm{diesel}} + \text{Gasoline Consumption} \times \mathrm{LCI}_{\mathrm{gasoline}} \\ & + \text{JetFuel Consumption} \times \mathrm{LCI}_{\mathrm{jetfuel}} \\ & + \text{Transport Distance} \times \mathrm{LCI}_{\mathrm{transportation}} + \mathrm{LCI}_{\mathrm{electricity}}\end{aligned} \qquad [3.52]$$

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 3.19). 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 Section 3.5.1.8.3, 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, 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 3.21, Table 3.22). For convenience, forest treatments and harvesting systems are represented by letter-number combinations (

Table *3.20*). 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 3.19 Harvesting equipment price assumptions and use life obtained from FRCS.

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 3.20 Representations of forest treatments and harvesting systems.

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

Table 3.21 Weight ratio of chip trees to 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 3.22 Weight ratio of chip trees to 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	-
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:

$$\begin{aligned} \mathrm{LCI} = {} & \text{Diesel Consumption} \times \mathrm{LCI_{diesel}} + \text{Gasoline Comsumption} \times \mathrm{LCI_{gasoline}} \\ & + \text{JetFuel Consumption} \times \mathrm{LCI_{jetfuel}} \\ & + \text{Transport Distance} \times \mathrm{LCI_{transportation}} + \mathrm{LCI_{electricity}} \\ & + \text{Facility Capital Cost} \times \mathrm{LCI_{construction}} \\ & + \text{Equipment Purchase Price} \times \mathrm{LCI_{manufacturing}} \end{aligned} \qquad [3.53]$$

3.6.3 Life Cycle Inventory

LCI data include emission factors of GHG and CAP. Table 3.24 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 3.25. 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 (CA) reformulated gasoline (E10), and conventional jet fuel. The LCIs of fuel consumption were compiled as follows. LCI data for CAP and CO_2 emissions of diesel and gasoline were derived from the EMFAC emissions inventory developed by the California Air Resources Board (2021b), where the emission factors of VOC were assumed to be the same as those of reactive organic gas (ROG) (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 agricultural equipment. The LCI data for jet fuel except $PM_{2.5}$ were derived from the emissions of freight aircraft in GREET (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 GREET, were converted from the well-to-wheel emission rates of low-sulfur fueled heavy duty trucks, categorized as HD Truck: Combination Short-Haul CIDI – LS Diesel in GREET.

The LCI data for the integrated gasification combined cycle (IGCC) conversion facilities were obtained from the California-specific version of GREET (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 the combined heat and power (CHP) conversion technology were derived from the Emissions & Generation Resource Integrated Database (eGRID) (U.S. Environmental Protection Agency, 2019). The power plants located in California and categorized as non-CHP and using the primary fuel of wood or wood waste solids (WDS) 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 CARB Facility Search Engine (California Air Resources Board, 2021c) that 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 electric allocation factor in eGrid, and further, the emission factors were calculated as the average weighted by the annual net generation of the selected plants. The emission factors of VOC were assumed to be the same as those of ROG.

The LCI data of facility construction and equipment manufacturing were from the widely used EIO-LCA web model developed by 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 all the way to purchase of the product. With respect to industry and sector (Table 3.23), 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 was resolved to 2002 dollars using the CPI. The equipment purchase prices from FRCS were already in 2002 dollars so no conversion was needed.

Table 3.23 Selection of the EIO-LCA model, industry and sector.

Category	Facility construction	Equipment manufacturing
EIO-LCA Model	US 2002 (428 sectors) Purchaser	US 2002 (428 sectors) Purchaser
Sector group	Construction	Machinery and Engines
Detailed sector	Other nonresidential structures	Construction machinery manufacturing

Table 3.24 LCI for feedstock acquisition, transport 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

* Levels of precisions were reduced to three decimal places for convenience. Full precisions are used in the model.

Table 3.25 Data types and sources

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

3.6.4 Impact Assessment

To evaluate potential environmental impacts of a process, elementary flows obtained in LCI are typically classified into various impact categories and further characterized using characterization factors (Nieuwlaar, 2004). Due to the open-source nature of this project and limited publicly available data, the elementary flows obtained in the LCI are air emissions of GHG and CAP. Due to the limitations in LCI data and the tracked flows, the only impact category included is Global Warming, which is quantified by multiplying the elementary flows by the corresponding characterization factors (Table 3.26) from the IPCC Fifth Assessment Report (AR5).

Table 3.26 Characterization factors for global warming potential (IPCC, 2014).

GHG	GWP Factor
CO_2	1
CH_4	30
N_2O	265

3.6.5 Software

Similar to the FRCS and TEA models, to integrate the LCA model into the decision support system and other web applications, it was converted to the npm package @ucdavis/lca (https://www.npmjs.com/package/@ucdavis/lca).

4 Application

Case studies were conducted to assess the model performance as a decision support tool that can help examine the potential economic and environmental impacts associated with new biomass energy facilities. Full statewide data, as well as time-series data, are not yet available, and the F^3 dataset was limited to the Sierra Nevada region with a reference year of 2016. Thus, the case studies used the same dataset across the lifetime of a project, assumed no forest growth in future years, and did not account for more recent wildfires that have significantly reduced resource inventories in certain areas.

4.1 Case Study: 25 MW Capacity

A 25 MW biopower facility with an economic life of 20 years using a conventional boiler-steam cycle was modeled. A facility site located in the Sierra Nevada foothills was selected at a position near the location of an existing similarly sized power station using wood fuel as feedstock although no direct relation to this existing facility should be assumed or inferred. The capital cost was assumed to be $100 million with a capacity factor of 80%. The annual operation and maintenance (O&M) cost was assumed to be $334 per kWe. No production tax credit applies. Other than facility location, capital cost, capacity factor, and annual O&M cost, the default model technical, financial and economic information were used, including the ones for the FRCS model (Table 3.8), the transportation model (Table 3.13), and the TEA model (Table 3.14). The labor wages, fuel price, and PPI were escalated by the default inflation rate of 2.1% over the lifetime of the project. The annual feedstock demand of the facility is 169,475 bone dry metric tons (BDMT) to realize an annual electric generation of 175,200 MWh. The nearest substation is in close proximity at 231 meters from the facility, which yields a transmission infrastructure cost of $636,058.

Table 4.1 Facility assumptions

Latitude	37.87439642
Longitude	-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

4.1.1 LCOE and GHG emissions

As described earlier, both forest treatments and harvesting systems have ten options each yielding 100 combinations. To determine the combination of forest treatments and harvesting systems to yield the lowest cost or least environmental impact, an assessment of all combinations was conducted and the LCOE and GHG emissions associated with every combination were obtained (Figure 4.1). Commercial thin (T2), Timber Salvage (T4), and Selection (T6) treatments can only be combined with Ground-based Mech WT (S1), Ground-based Manual WT (S2), Ground-based CTL (S4), and Cable Manual CTL (S6) systems because these three treatments do not harvest chip trees and the harvesting systems other than S1, S2, S4, and S6 do not harvest crown biomass from log trees; in essence, no available feedstock would be harvested in such combinations. Additionally, no results for this case study were derived for any combinations with T4 and the combination of T6 and S4 because of the limited amount of biomass available within the region from timber salvage (Table 4.2, Table 4.3). This is not a general result, however, and the option may have value for smaller facilities.

Table 4.2 Amount of available feedstock (millions of bone-dry metric tons) 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	0.0	3.8	0.0	5.0	0.0	0.0	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	0.8	0.0	0.8	0.0	0.0	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	0.0	2.8	0.0	3.7	0.0	0.0	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

Table 4.3 Resource sufficiency from combinations of forest treatments and harvesting systems.*

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
T1	S	S	S	S	S	S	S	S	S	S
T2	S	S	I	S	I	S	I	I	I	I
T3	S	S	S	S	S	S	S	S	S	S
T4	I	I	I	I	I	I	I	I	I	I
T5	S	S	S	S	S	S	S	S	S	S
T6	S	S	I	I	I	S	I	I	I	I
T7	S	S	S	S	S	S	S	S	S	S
T8	S	S	I	S	I	S	I	I	I	I
T9	S	S	I	S	I	S	I	I	I	I
T10	S	S	S	S	S	S	S	S	S	S

* S = Sufficient and I = Insufficient, relative to total resource demand.

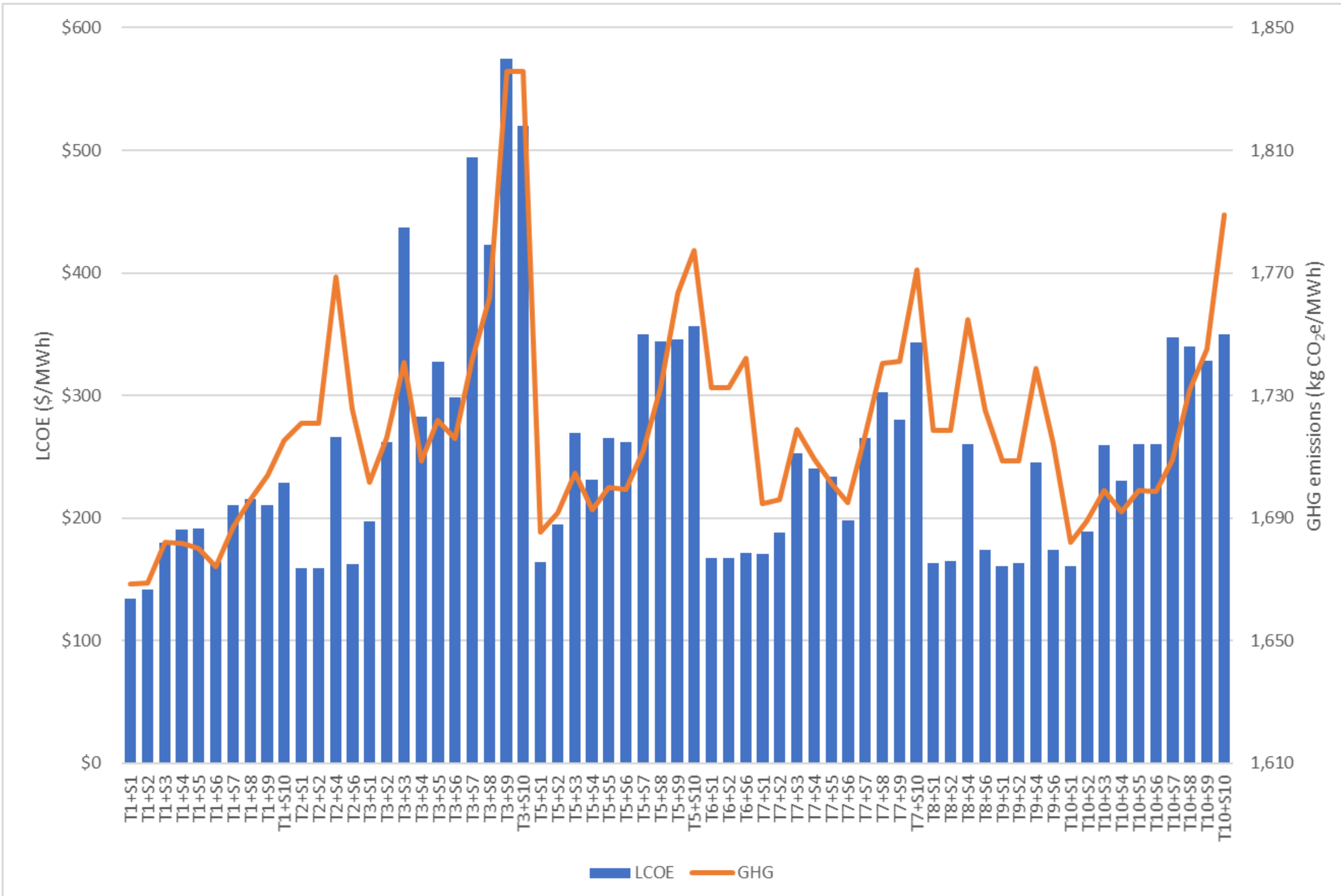

Figure 4.1 LCOE and GHG emissions from different combinations of forest treatments and harvesting systems.

LCOE ranges from $135 to $575 per MWh electricity generation and GHG emissions range from 1668 to 1836 kg CO_2 equivalent per MWh electricity generation. The combination of clearcut (T1) and ground-based mechanized WT system (S1) resulted in the lowest LCOE and GHG emissions.

The combination of T1 and S1 was regarded as the baseline scenario of this study. 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 of $0.02 per BDMT feedstock. The baseline harvests from clusters extending from the facility site, i.e., the clusters closer to the facility are assumed to be harvested first, and transport cost is monotonically growing over the lifetime of the project (Figure 4.2) as the harvesting strategy leads to an increasing transport distance. In contrast, harvest cost, which on average accounts for 73% of the feedstock cost, is not monotonically increasing across the lifetime of the facility. The move-in cost associated with feedstock is essentially negligible on a per BDMT acquired feedstock basis because it only accounts for the move-in of a chipper in the ground mechanized WT 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.

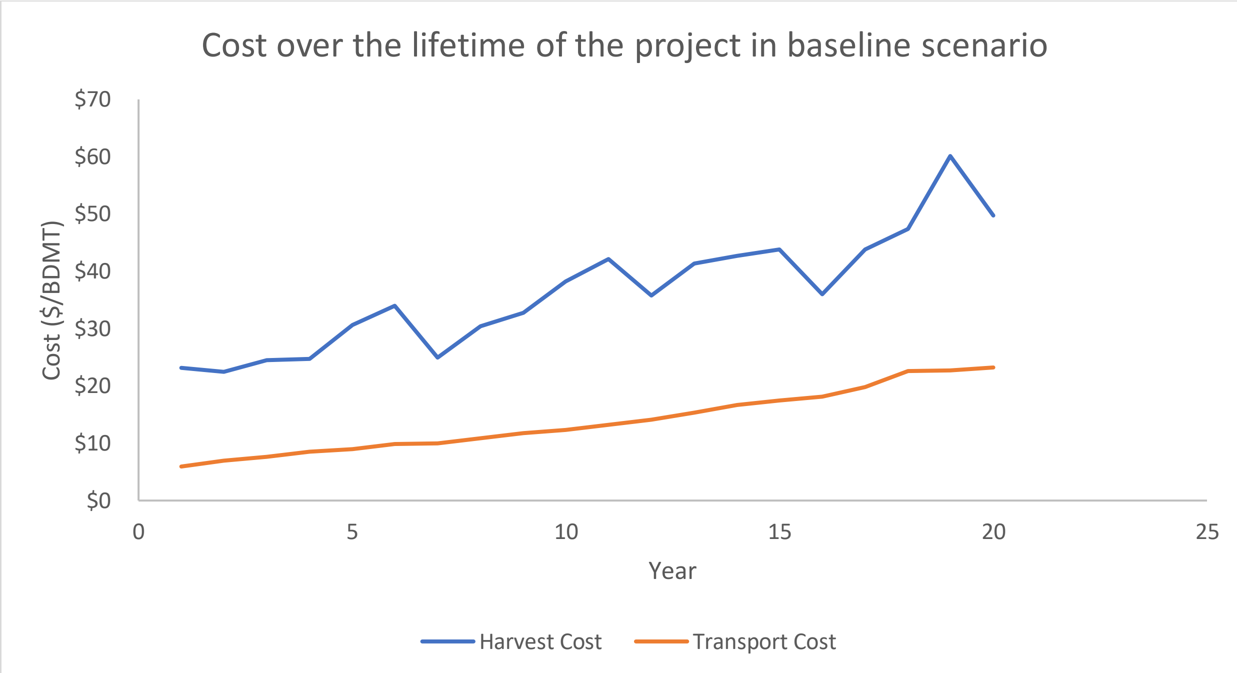

Figure 4.2 Cost across the economic life of the project, baseline scenario.

4.1.2 Environmental Benefits

Under an assumption that in the absence of bioenergy uses, the biomass will be burned in open piles as a business-as-usual scenario, the baseline scenario realizes major 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). As Springsteen 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 the 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 the forest biomass for electricity production are significant. GHG, CO, NO_x, $PM_{2.5}$, and VOC emissions decline between 21 and 99% (Table 4.4). The net GHG emissions calculated by subtracting the emissions from open pile burning and electricity displacement are negative at -440 kg per MWh electricity generation. 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 released 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 4.4 Baseline air emissions reductions from forest biomass electricity generation.

	Air Emissions (kg/MWh electricity generated)				
Scenario	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

A CHP facility with the same technical parameters could realize greater emission reductions in NO_x, $PM_{2.5}$, VOC, CO_2, and CH_4 but a bit smaller in CO than the baseline scenario using the conventional boiler-steam cycle. The net GHG emissions are again negative at -926 kg per MWh electricity generation. The TEA model for the conventional boiler-steam cycle and CHP technologies are essentially the same except that CHP modeling involves an additional income from heat sales. Without heat sales, or if the aggregate sales price for heat is 0, the projected LCOE using CHP would be the same as that in the baseline, i.e., \$135 per MWh electricity generation. The default heat price of \$0.0207/kWh can bring the LCOE down to \$79 per MWh electricity generation.

Table 4.5 Air emissions reductions from forest biomass electricity generated using CHP.

	Air Emissions (kg/MWh electricity generated)				
Scenario	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	0.62	0.07	0.06	1.78	1183
Emission reductions	2.62	6.23	4.78	59.24	926
Overall reduction (%)	81	99	99	97	44

4.1.3 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 in which each parameter in turn was varied over a range of ±50 percent from the baseline in 10 percent increments (Table 4.1). Capacity factor is important to the annual electrical energy generation, thereby partially determining 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.

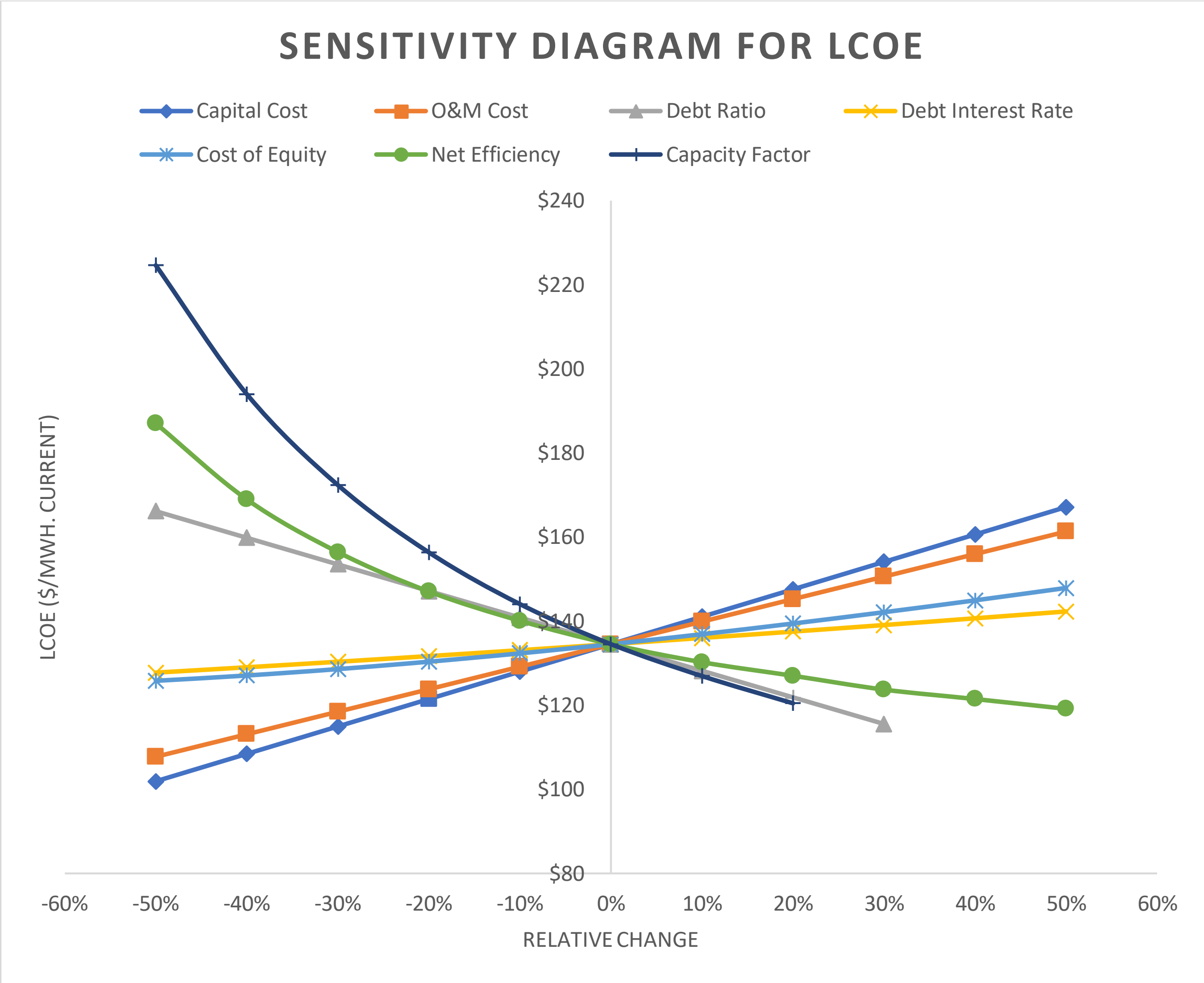

Figure 4.3 Sensitivity Diagram for LCOE

Within ±20% of baseline, capacity factor has the largest impact on LCOE among the eight parameters, followed by capital cost, debt ratio, net efficiency, O&M cost, cost of equity, and debt interest rate (Figure 4.3). More significant declines in net efficiency, however, generate substantial increases in LCOE, second only to those for continued declines in capacity factor. The relative change driven by the change of capacity factor and net efficiency is non-linear while that driven by the change of the others appear to be linear, and capacity factor and net efficiency have a greater relative change from the negative deviation (poorer technical performance of the facility) than from the positive deviation. The lower the capacity factor, the lower the annual electric generation as well as annual feedstock demand. Naturally, annual feedstock acquisition cost decreases as capacity factor decreases, however, the decrease of feedstock cost is insufficient in offsetting the increase of the cost attributed on a unit output basis (per kWh) for electricity generation, resulting in an increase in LCOE. Capacity factor is also assumed to be limited to 100%, thus the restriction on reductions in LCOE with improvements in operations affecting this factor. The change of net efficiency does not affect the annual electric generation (capacity held constant) but does affect annual feedstock demand needed to meet that capacity. A smaller efficiency corresponds to a greater annual feedstock demand, and a higher annual feedstock acquisition cost, therefore LCOE increases as net efficiency decreases. The impact from the debt ratio benefits from the low interest rate and the relatively high cost of equity. A low debt ratio corresponds to a high equity ratio and because of the high cost of equity relative to the interest rate on the debt, it incurs a high annual energy revenue requirement, and thus the high LCOE. Conversely, a high debt ratio corresponds to a low equity ratio, and thereby a lower annual energy revenue requirement.

The impacts of net efficiency and feedstock moisture content on GHG emissions were small within the range of deviations for the baseline scenario. Although the feedstock demand is in part determined by the net efficiency of a facility, the change of the GHG emissions on a per MWh electricity generation basis only ranges from -0.8 to 2.8%. As for moisture content, since the amount of dry biomass from a cluster is unchanged and the model at this time assumes no relationship between the moisture content of biomass and the net efficiency of a facility, adjusting moisture content will not affect the clusters to be harvested. Moisture content affects the GHG emissions from the feedstock transportation stage because the maximum payload of a truck transporting wet biomass is constant and the number of trips for transporting feedstock changes with the moisture content of the feedstock (trucks are weight limited). For the baseline scenario, the average feedstock transport distance is only 6.6 km per MWh electricity generation, and changing moisture content of the biomass has little impact (a relative change from -0.4% to 1.2%) on the overall GHG emissions under these assumptions although combustion outcomes are related to feedstock moisture and more detailed analyses may alter these results. Using the same emission factors per unit electricity generation in the LCA model regardless of the conversion efficiency may not accurately reflect the actual operations of a conversion facility, and the relationship between feedstock moisture content and conversion efficiency requires information or modeling beyond what is included here.

Table 4.6 Direct GHG emissions from sensitivity analysis

Inputs	Deviation (%)	Value (%)	GHG emissions (kg CO_2e/MWh)	Relative Change (%)
Net Efficiency	50	30	1,655	-0.8
	-50	10	1,715	2.8
Moisture Content	50	75	1,688	1.2
	-50	25	1,662	-0.4

4.1.4 Optimization

The cluster selection algorithm to fulfill annual feedstock requirement uses a circular search centered at the facility location, or a predefined center of resource if the facility is located outside the feedstock acquisition area. The search is implemented by increasing the radius in 1 km increments until the harvestable clusters within the radius can supply the annual feedstock demand. The harvest and transport costs per unit feedstock associated with each of the harvestable clusters 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 move-in cost per unit feedstock is generally quite small in comparison to other costs for the assumptions used and does not affect the final selection outcomes. The clusters are then sorted by feedstock cost and selected until the selected ones can supply the annual feedstock demand. With each succeeding year, the selection radius increases as clusters are assumed to be harvested only once within project lifetimes. Differences in biomass yields, however, mean that some clusters located at a greater distance from the facility may have lower harvest cost sufficient to reduce total delivered cost even with greater transportation distance and cost. 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 search. 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, and then sorting the clusters by feedstock cost to supply the annual feedstock demands at lowest cost, albeit increasing year to year. The LCOE from full optimization is $131.88 and direct GHG emissions are 1668.49 kg CO_2 equivalent per MWh electricity generation. As expected, feedstock cost is monotonically increasing over the economic life of the project (Figure 4.4). On a relative cost basis, the average feedstock harvest cost per BDMT (14.4%) in the optimized scenario declines slightly more than the average transport cost increases (13.8%), 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 by $3.30 or 7% overall including the accompanying increase in move-in cost (Table 4.7). The feedstock distribution in the optimized scenario

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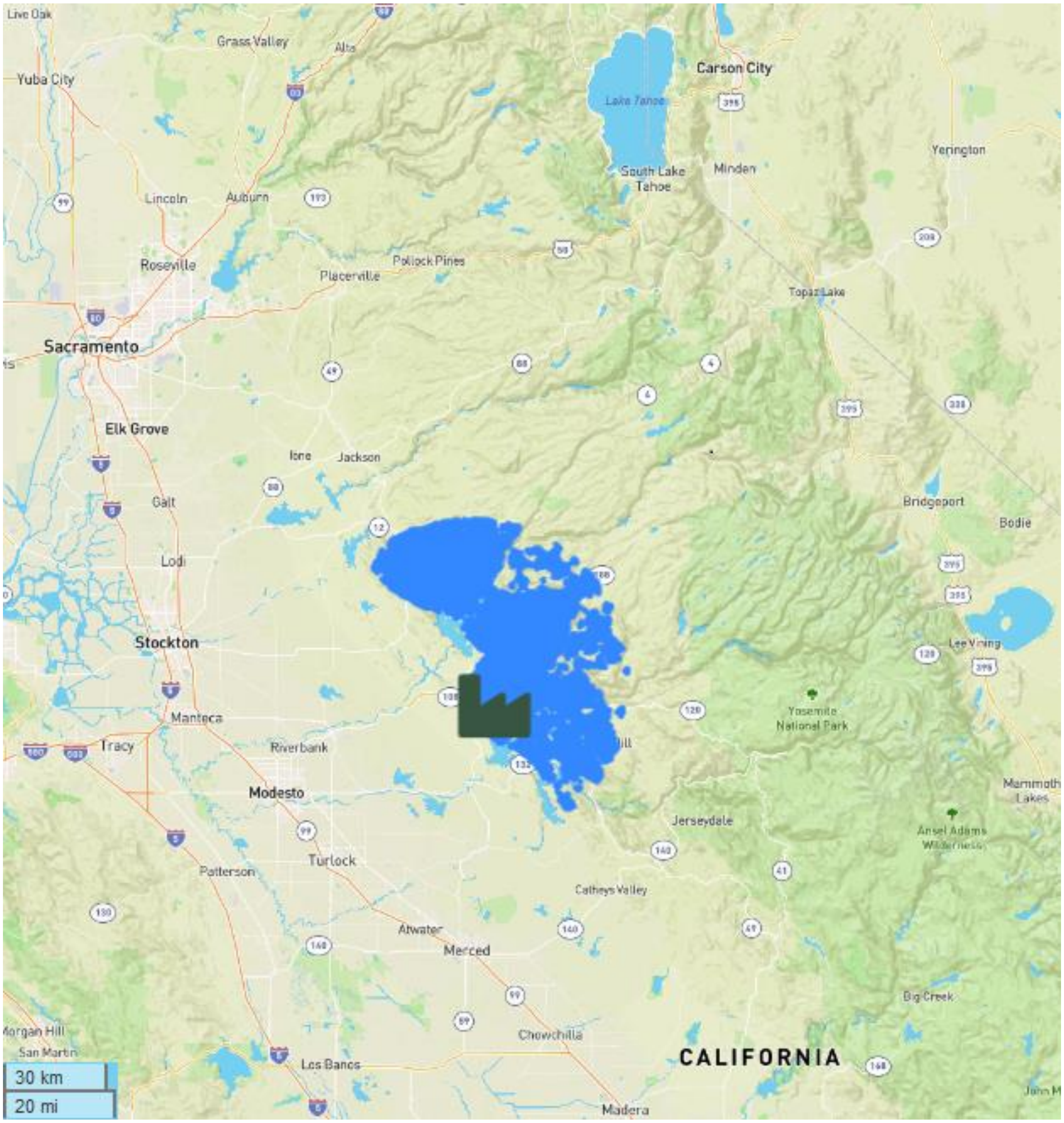

Figure *4.5*) is sparser than that in the baseline

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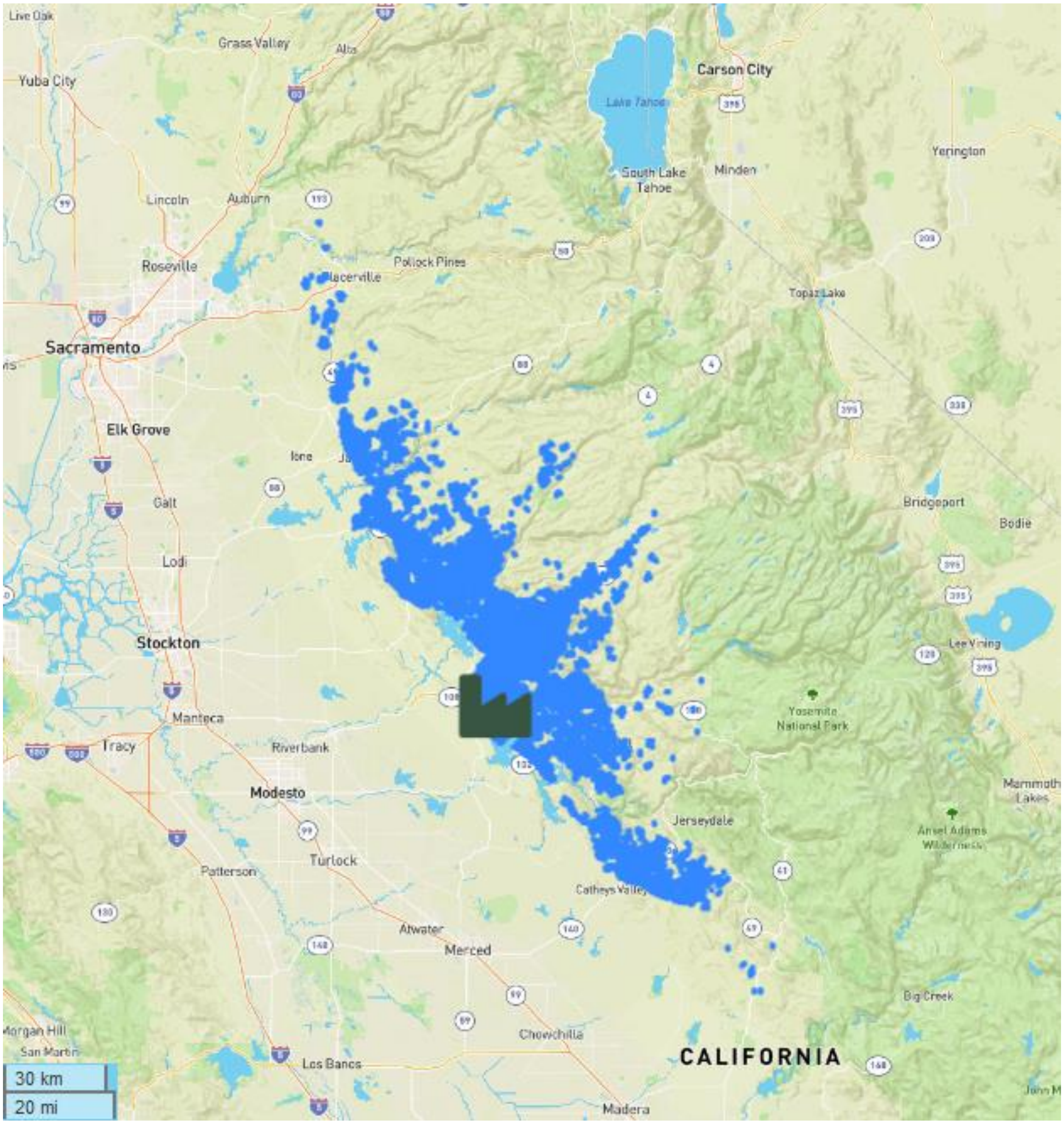

Figure *4.6*). Move-in cost is more than doubled in the optimized scenario compared to the baseline due to the sparse distribution of feedstock although it is a small contribution with little impact on overall feedstock cost. The average feedstock delivered cost was reduced from $50.25/BDMT in the baseline to $46.95/BDMT through full optimization. The net GHG emissions from the economic optimization (-440.13 CO_2e/BDMT) are, however, slightly less negative than those from the baseline (-440.25 kg CO_2e/BDMT) due to the added transportation.

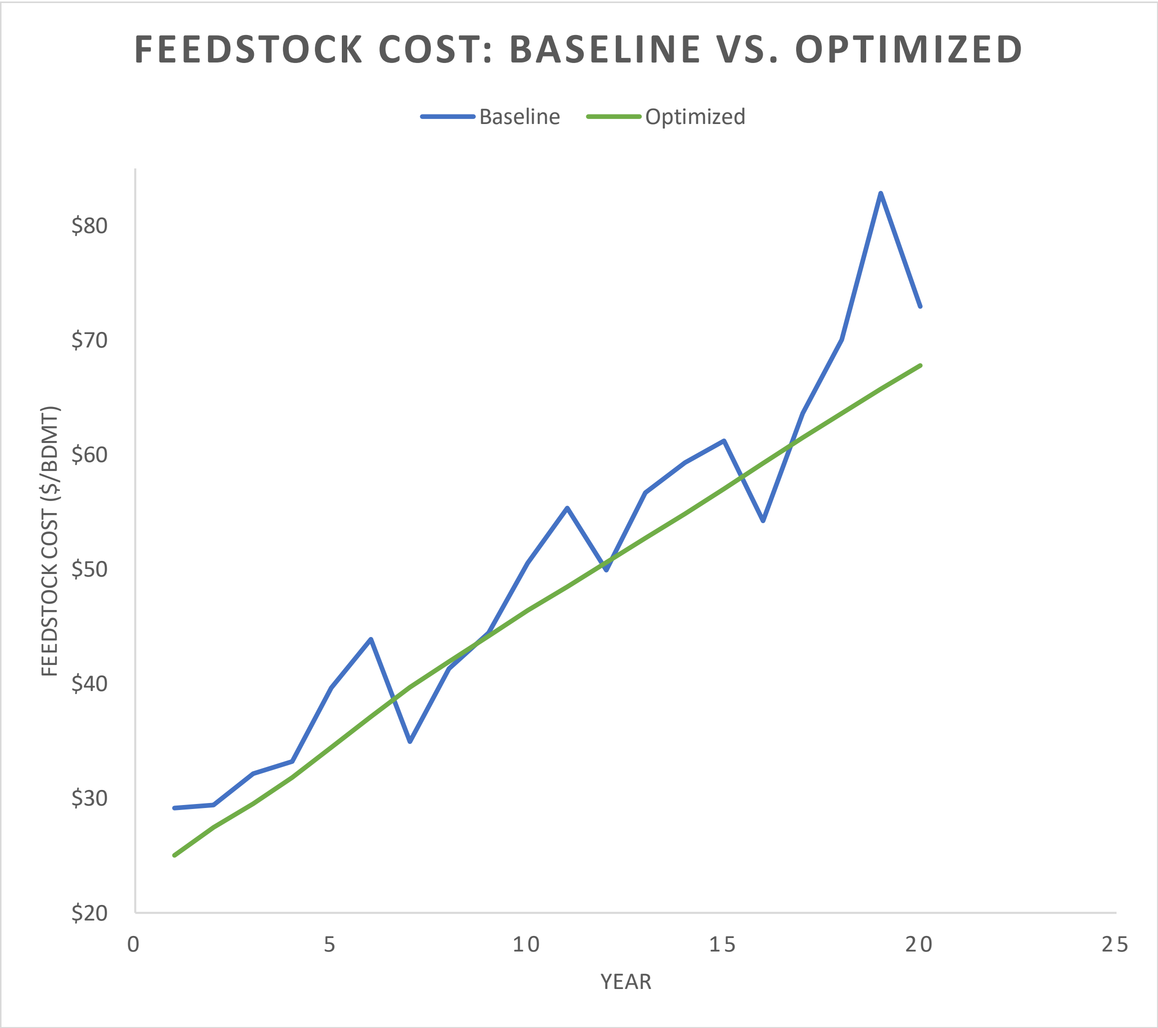

Figure 4.4 Feedstock cost comparison between baseline and optimized scenarios.

Table 4.7 Cost comparison: baseline vs. optimized scenarios.

Category	Baseline ($/BDMT)	Optimized ($/BDMT)	Change (%)
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

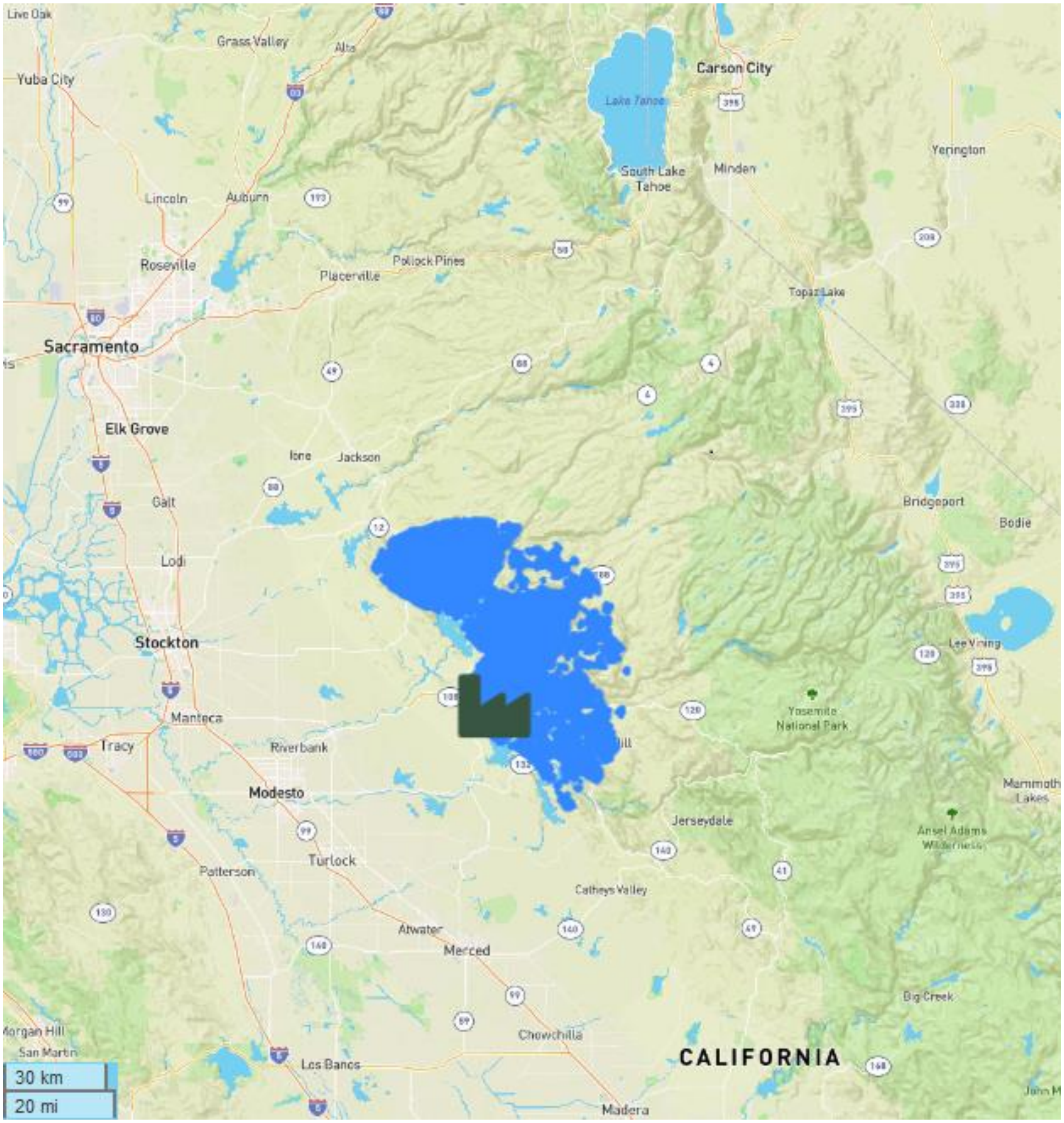

Figure 4.5 Feedstock distribution in the baseline scenario.

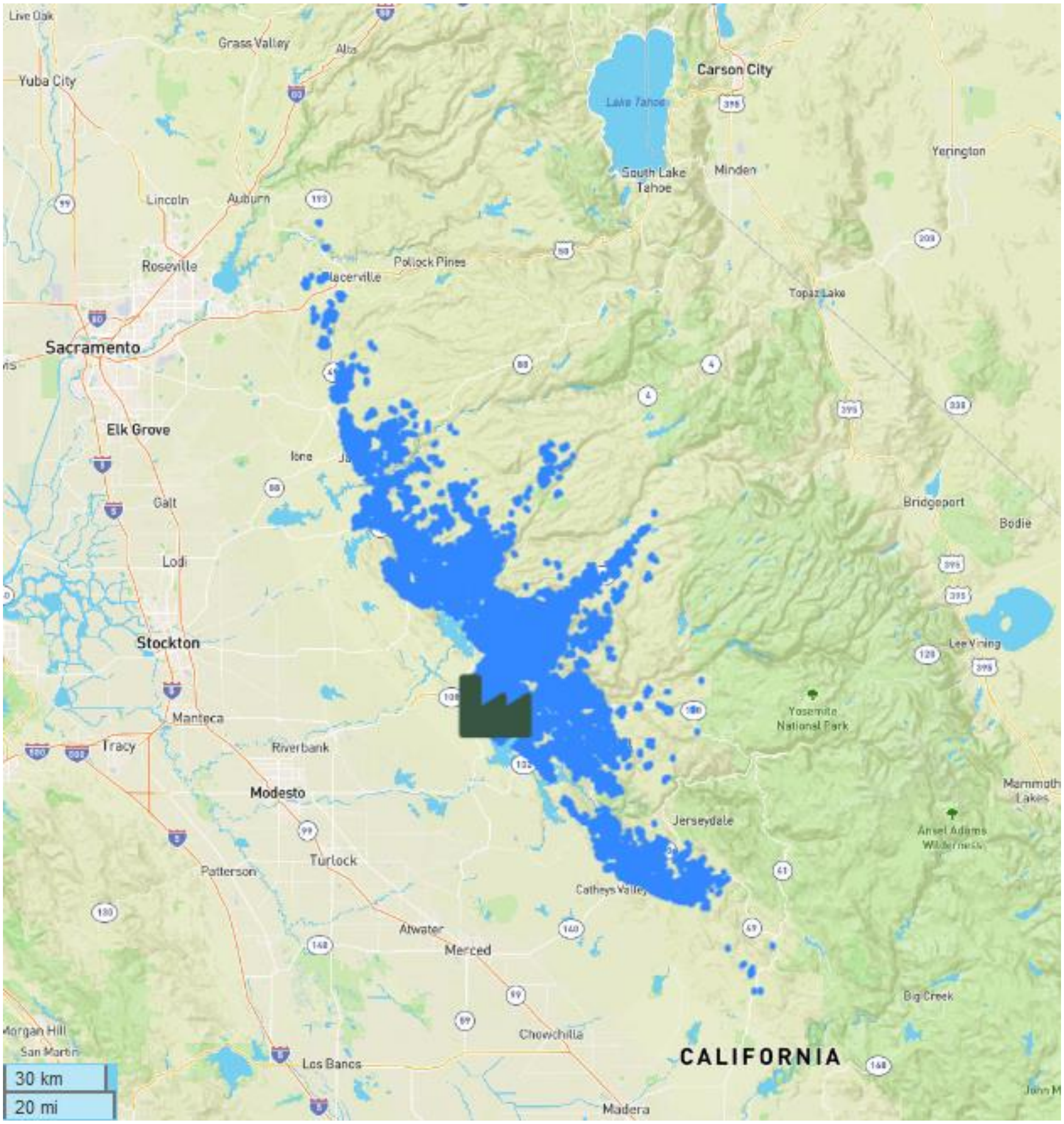

Figure 4.6 Feedstock distribution in the optimized scenario.

While the optimization generates the desired outcome, i.e., minimizing LCOE by minimizing feedstock cost, it is more computationally intensive and increases computer memory requirements and computational time. The API backend as hosted on the servers used here was unable to process the full Sierra Nevada supply region at once, and larger statewide datasets will require additional resources. An approach was therefore developed 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 so as to reduce the computational needs while approaching an optimal solution. This approach used an expansion factor defined as a multiplier of annual feedstock demand. A unity expansion factor searches only until the feedstock requirement in that year is satisfied and is subject to the problem 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 were carried out to compare the LCOE with that from a full optimization over all clusters (Figure 4.7). As the expansion factor increases, the LCOE gradually approaches the LCOE from the full optimization. The LCOE from an expansion factor of 30 is only 0.03% higher than the fully optimized LCOE while the LCOE in the baseline of this case study with unity expansion factor is 2% higher. The sensitivity in net GHG emissions (Figure 4.8), while fairly minor, reveals that when the expansion factor is small, a greater reduction in GHG emissions occurs with the feedstock harvest stage than the increase in GHG emissions with the feedstock transportation stage, and as the expansion factor increases, the feedstock transportation has more and more impact on GHG emissions.

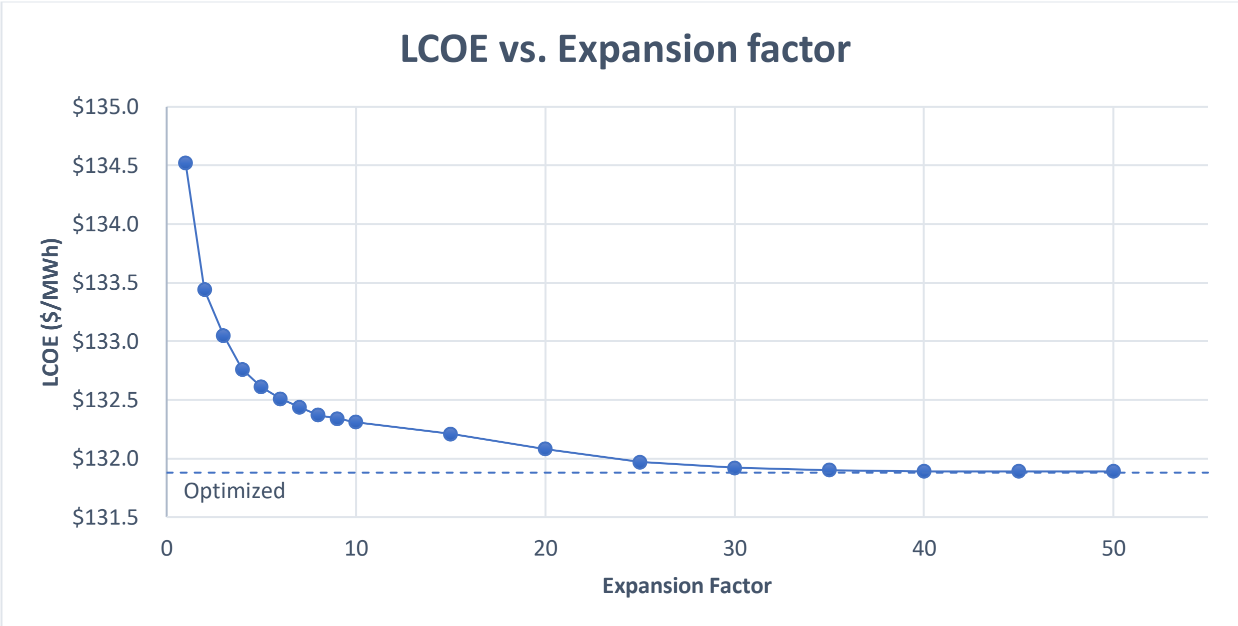

Figure 4.7 LCOE derived from various expansion factors.

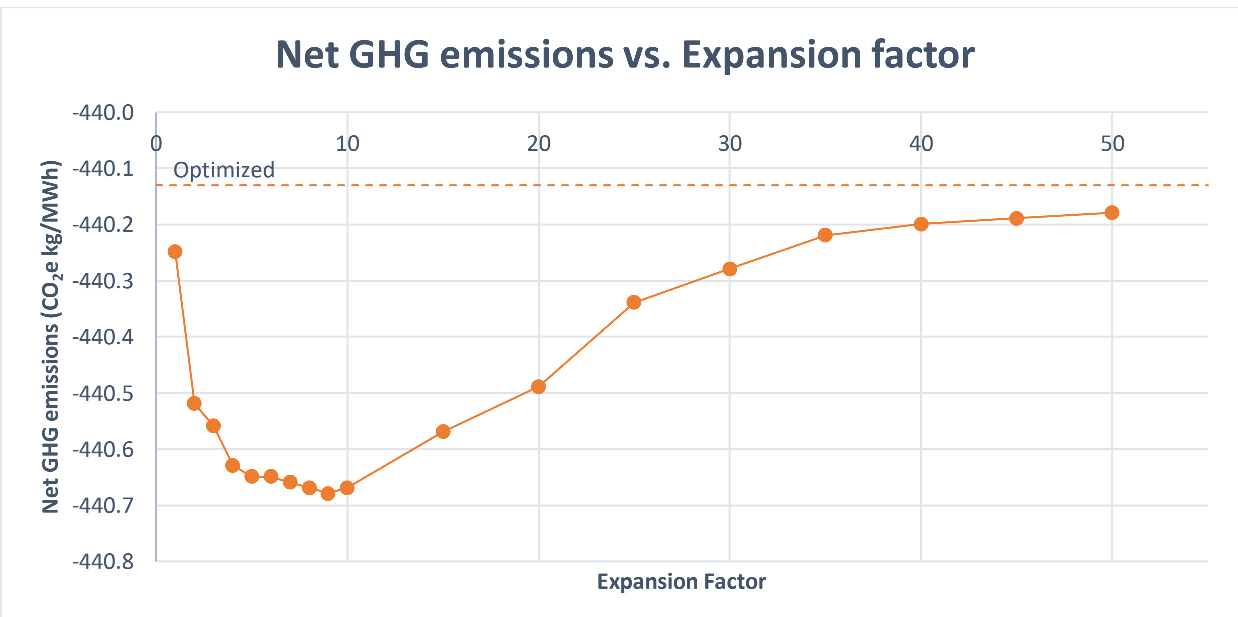

Figure 4.8 Net GHG emissions derived from various expansion factors.

As the expansion factor increases, feedstock cost per BDMT over the economic life of the facility eventually becomes lower, however it is also monotonically increasing over time approaching the condition of full optimization (Figure 4.9). Gains in this direction diminish with increasing expansion factor, however, so there is little benefit in applying expansions above about 30 to 50 although factors in this range can substantially reduce computational needs compared with searching the entire resource dataset.

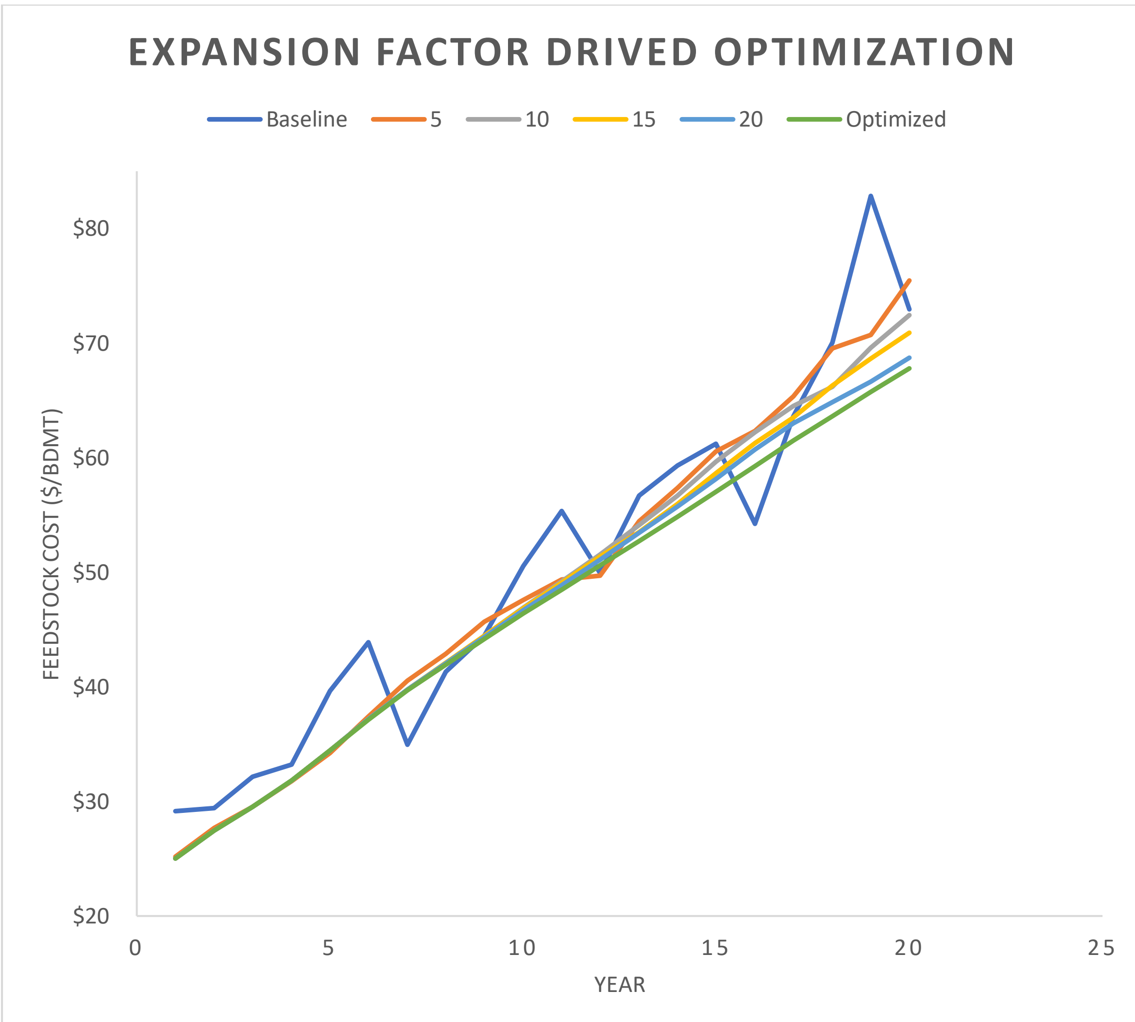

Figure 4.9 Feedstock cost across the facility lifetime derived by various expansion factors.

4.2 Case Study: 3 MW Capacity

The Bioenergy Market Adjusting Tariff (BioMAT) is a feed-in tariff program in support of bioenergy production by incentivizing renewable bioenergy projects through executing standard contracts (Rubio, 2012). Up to a statewide total of 250 MW electric capacity is allocated in the BioMAT program, including 110 MW for biogas from wastewater treatment, municipal organic waste diversion, food processing, and codigestion, 90 MW for dairy and other agricultural bioenergy, and 50 MW for bioenergy using byproducts of sustainable forest management. To date, four forest contracts have been executed at a price of $199.72/MWh and provide a total of 11 MW of capacity (California Public Utilities Commission, 2021).

Four BioMAT projects planned to provide 3 MW each using a gasifier were identified. Four gasification biopower facilities with an economic life of 20 years were modeled at the same locations as the planned projects (Table 4.8) although no direct relation to these facilities should be assumed or inferred. The capital cost was assumed to be $18 million, the annual O&M cost $437 per kWe, the capacity factor 80%, and the debt ratio 90% (Table 4.9). No production tax credit applies. Other than facility location, capital cost, annual O&M cost, capacity factor, and debt ratio, the default model technical, financial and economic information were used, including those for the FRCS model (Table 3.8), the transportation model (Table 3.13), and the TEA model (Table 3.14, Table 3.15, Table 3.16). The labor wages, fuel price, and PPI are escalated by the default inflation rate of 2.1% over the lifetime of the projects. The efficiency of a gasifier (Table 3.16) has two elements: one from converting feedstock to clean gas (65% by default) and the other from converting clean gas to electricity (23% by default), which yields an overall efficiency of 15% for converting feedstock to electricity. The efficiency from clean gas to electricity is referred to as net efficiency in this case study. The annual feedstock demand of the facility is 21,765 BDMT to realize an annual electric generation of 21,024 MWh.

Table 4.8 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

Table 4.9 Facility 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

4.2.1 LCOE and GHG emissions

The LCOE and GHG emissions associated with the four projects were obtained (Table 4.10) by selecting Ground Mech WT and clearcut as the harvesting system and the forest treatment. Project 4 has the lowest LCOE and GHG emissions and is regarded as the baseline of this case study. While the LCOE is dependent upon the feedstock cost as the technical, economic, and financial assumptions are the same across the four projects, the installation cost of new distribution or transmission lines, i.e., transmission cost, also constitutes a crucial part of the overall capital cost. Since the inputs to the transmission model except the distance from the facility to the nearest substation are the same across all projects, the distance to substation determines the relative magnitude of transmission cost (Table 4.11). The distance to substation for Project 1 is the largest among the four projects and the transmission cost accounts for 41% of the overall capital cost. In contrast, Project 4 has the smallest distance to substation and thus the smallest transmission cost that accounts for 12% of the overall capital cost. Alternatively, a new substation could be built near a facility, where the incurred cost may be lower than the installation cost of long transmission lines, although currently the model always seeks to install new transmission lines from a facility to the nearest substation and if onsite use of electricity beyond parasitic load is not intended, another load center must be available in proximity.

The LCOE for the baseline is \$186/MWh of electricity generated. 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 a move-in cost of \$0.05/BDMT feedstock. The move-in cost per unit feedstock is larger than that in the baseline of the first study, which is attributed 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% of that in the first study while the total move-in distance is 27%.

Table 4.10 LCOE and GHG emissions of the four projects.

Project	LCOE ($/MWh)	GHG emissions (kg CO_2e/MWh)
1	231	1034
2	190	1024
3	217	1032
4	186	1024

Table 4.11 Transmission cost of the four projects.

Project	Distance to substation (km)	Transmission cost ($)
1	5.78	12,698,886
2	1.42	3,896,653
3	3.26	8,959,228
4	0.92	2,531,433

To determine the best combination of forest treatments and harvesting systems to yield the lowest cost or least environmental impact, an assessment of all combinations was conducted and the LCOE and GHG emissions associated with every combination were obtained (Figure 4.10). As described in Section 4.1.1, no available feedstock would be harvested in the combinations of forest treatment T2, T4, or T6 and harvesting system S3, S5, S7, S8, S9, or S10 (Table 4.2, Table 4.12). No results were derived for any combination with T4 due to the limited resource associated with this alternative. When the treatment is T4, the amount of available biomass per cluster in average is smaller than when any other treatment is selected, leading to many more clusters required each year to fulfill the annual feedstock demand; the query size of that many clusters exceeds the current limits.

Table 4.12 Resource sufficiency from combinations of forest treatments and harvesting systems.*

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
T1	S	S	S	S	S	S	S	S	S	S
T2	S	S	I	S	I	S	I	I	I	I
T3	S	S	S	S	S	S	S	S	S	S
T4	S	S	I	S	I	S	I	I	I	I
T5	S	S	S	S	S	S	S	S	S	S
T6	S	S	I	S	I	S	I	I	I	I
T7	S	S	S	S	S	S	S	S	S	S
T8	S	S	S	S	S	S	S	S	S	S
T9	S	S	S	S	S	S	S	S	S	S
T10	S	S	S	S	S	S	S	S	S	S

* S = Sufficient and I = Insufficient, relative to total resource demand.

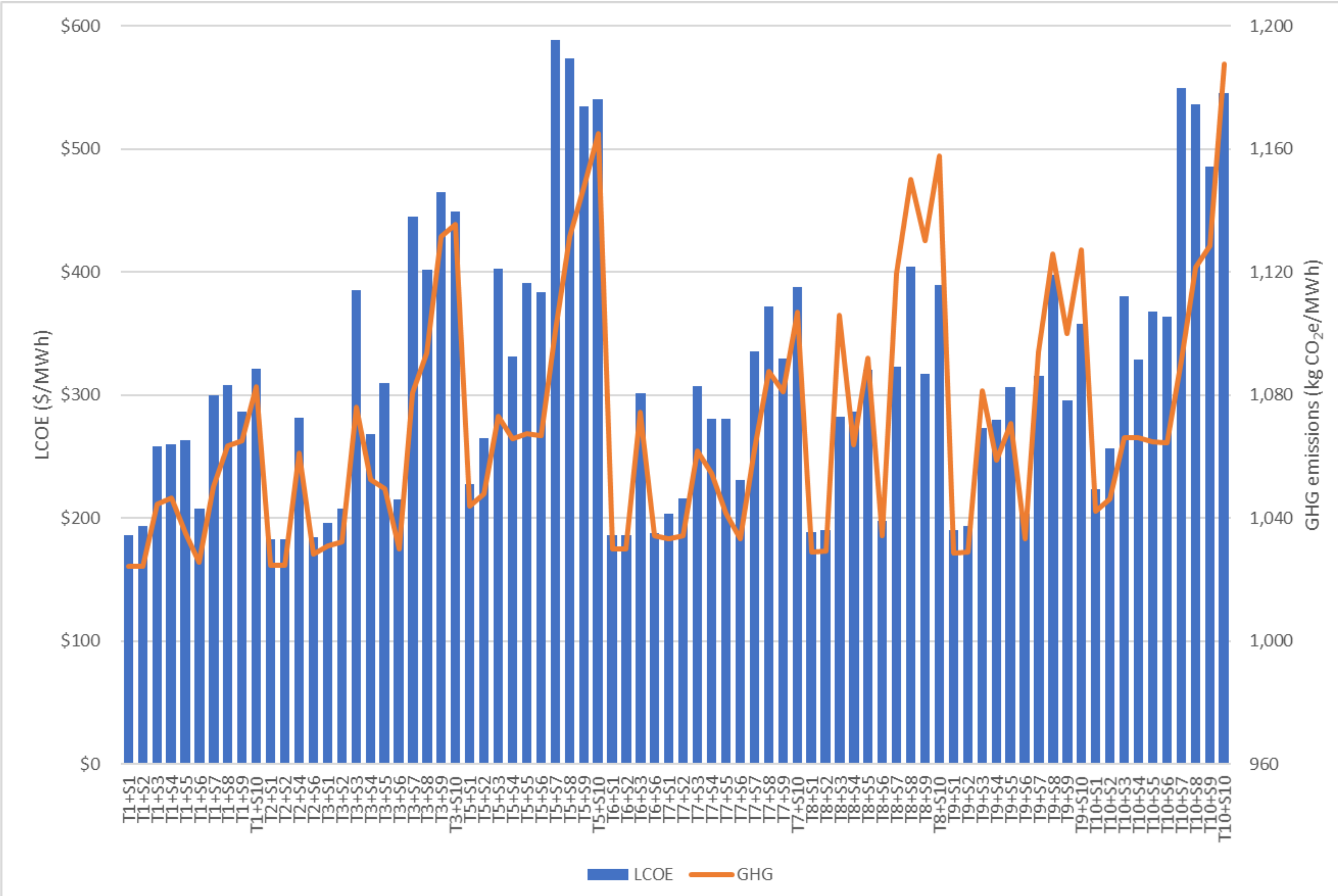

Figure 4.10 LCOE and GHG emissions resulted from different combinations of forest treatments and harvesting

The LCOE ranges from \$183 to \$588/MWh electricity generation and the GHG emissions range from 1024 to 1188 kg CO_2 equivalent/MWh electricity generation. The combination yielding the lowest LCOE among all the combinations is T2+S1, while that yielding the lowest GHG emissions is T1+S1. In comparison with the results from the first case study where the combination of T1 and S1 yielded the lowest LCOE (Table 4.13), the combination yielding the lowest LCOE in this study is from T2 while they both use the Ground Mech WT system. Such a difference is attributed to the availability of feedstock. T2, commercial thin, only harvests live log trees from private land, in which 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 study is 23% while that in the first study is 15%, which indicates that for the combination T2+S1, feedstock is more accessible in this study than in the first study. The findings highlight the necessity of a comprehensive assessment of all combinations of forest treatments and harvesting systems in order to determine those yielding the lowest LCOE and/or GHG emissions.

Table 4.13 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

4.2.2 Environmental Benefits

Under an assumption that in the absence of bioenergy uses, the biomass will be burned in open piles as a business-as-usual scenario, the baseline scenario realizes major environmental benefits in terms of GHG and CAP reductions. The emission factors from open pile burning and the electricity from grid were detailed in Section 4.1.2. The potential emissions reductions from utilizing the forest biomass for electricity generation are significant for GHG, CO, NO_x, $PM_{2.5}$, and VOC, and achieved reductions of between 51 and 99% (Table 4.14). The net GHG emissions are again negative at -1084 kg/MWh. Compared to 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 using gasification are lower due to the lower CO_2 emission factors for this conversion technology (Table 3.24).

Table 4.14 Baseline air emissions reductions from forest biomass electricity generation.

	Air Emissions (kg/MWh electricity generated)				
Scenario	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

4.2.3 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 in which each parameter in turn was varied over a range of ±50 percent from the baseline in 10 percent increments (Table 4.9). Capacity factor is important to the annual electrical energy generation, thereby partially determining 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.

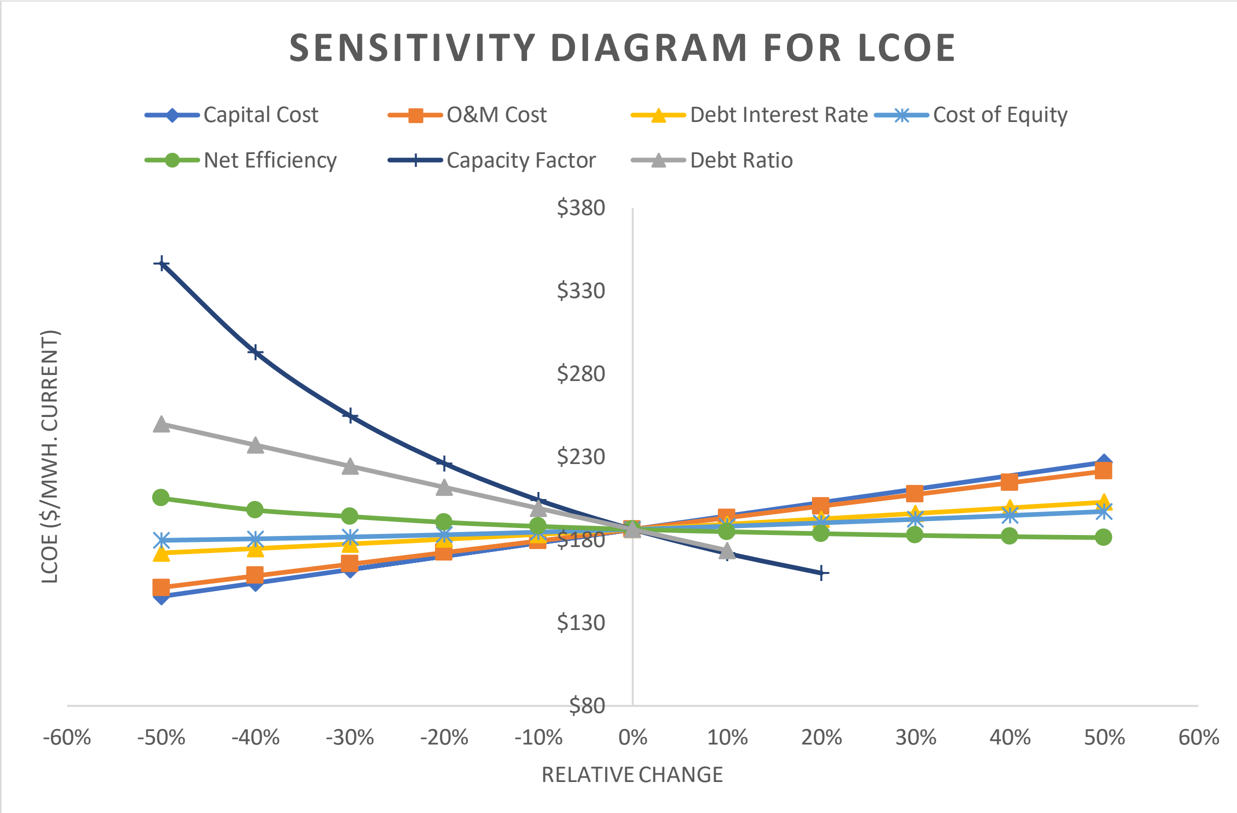

Figure 4.11 Sensitivity Diagram for LCOE.

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 4.11). The relative change driven by the change of capacity factor and net efficiency is non-linear while those by the change of the others appear to be linear (Figure 4.11). Similar to what is observed in Section 4.1.3, capacity factor, capital cost, debt ratio, O&M cost, and net efficiency are the largest five factors while the others are of less importance.

Similar to the results derived from the first case study, net efficiency and moisture content 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% and 1.7 to -0.6%, respectively.

Table 4.15 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

4.2.4 Optimization

The expansion-driven optimization based on minimum feedstock cost objective function achieved a minor impact on the LCOE and net GHG emissions (Table 4.16). The sensitivity of LCOE and net GHG emissions to the expansion factor at this site reflects 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 distribution at the expansion factor 1 and 50

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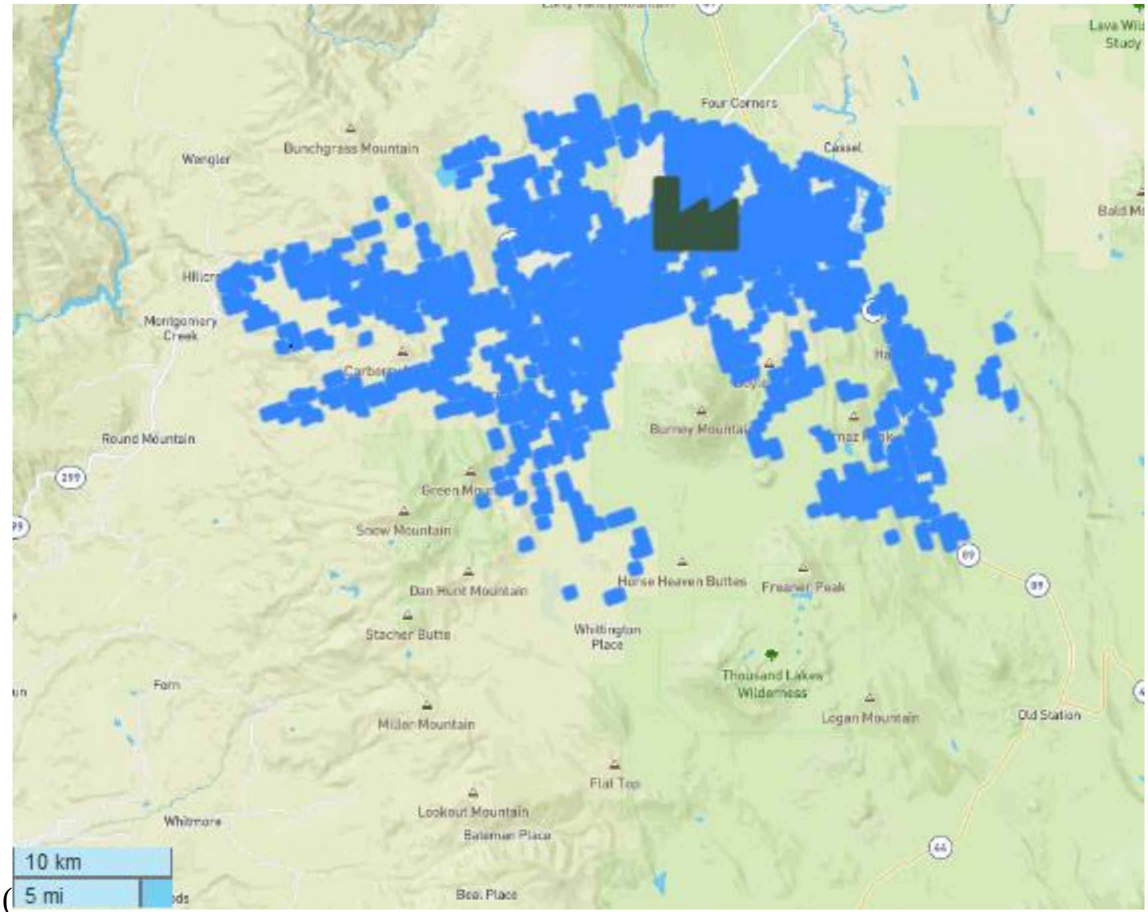

Figure *4.12*,

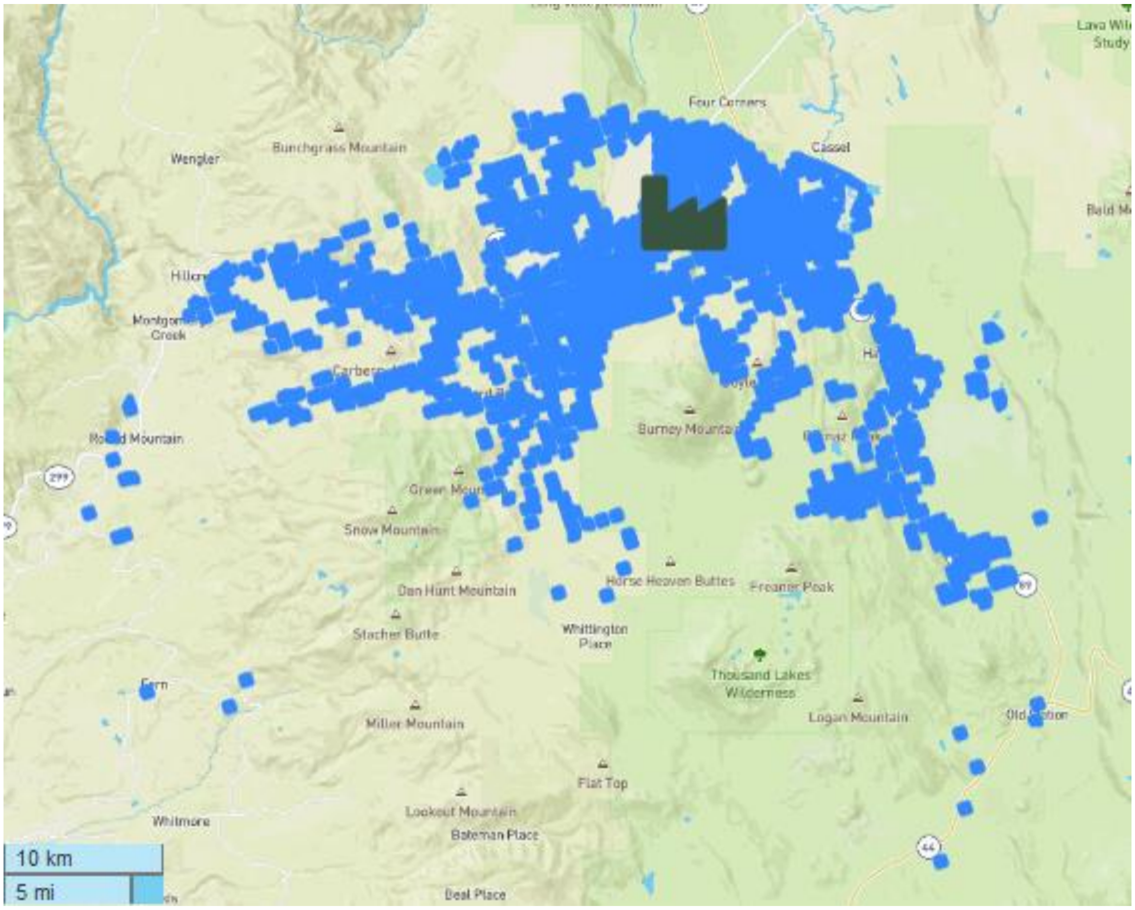

Figure *4.13*) indicates that a majority of the clusters with a low feedstock acquisition cost is close to the selected facility site.

Table 4.16 Expansion factor vs. LCOE and net 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

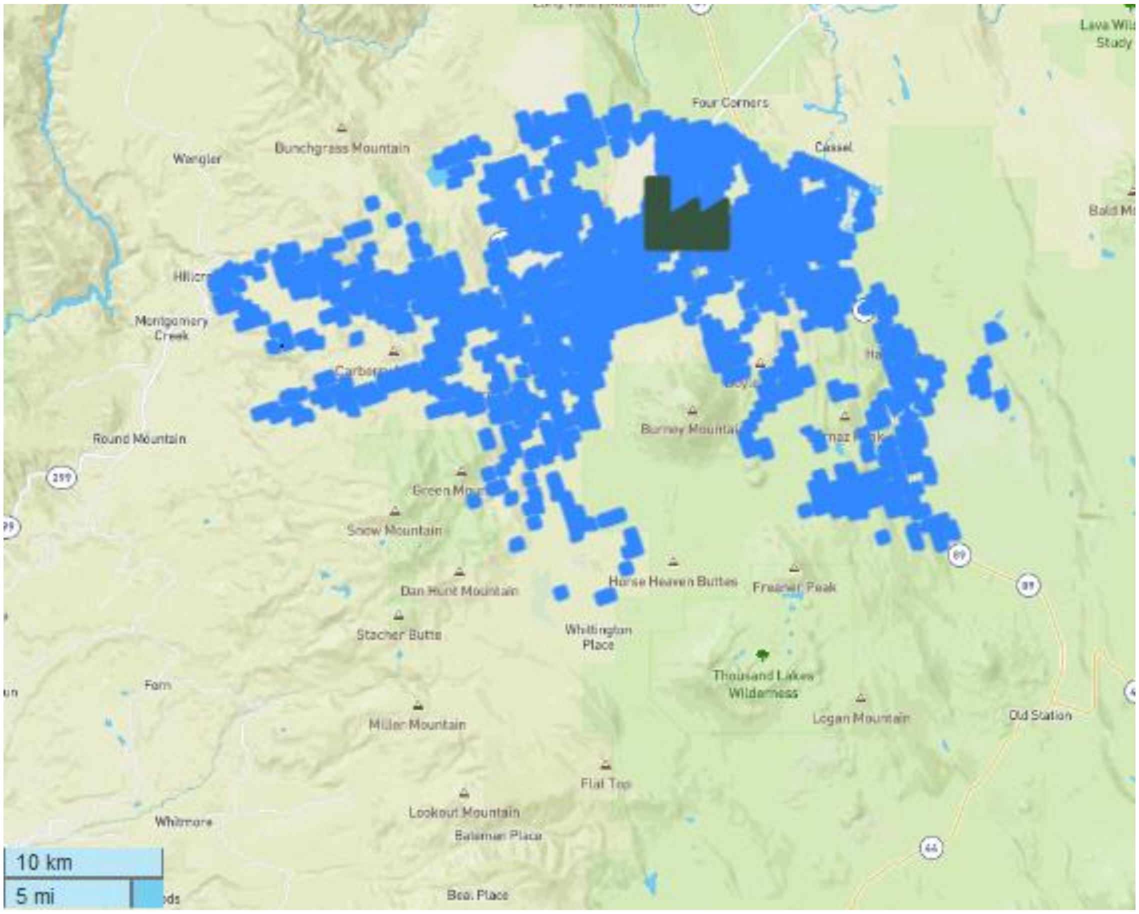

Figure 4.12 Feedstock distribution at the expansion factor of 1.

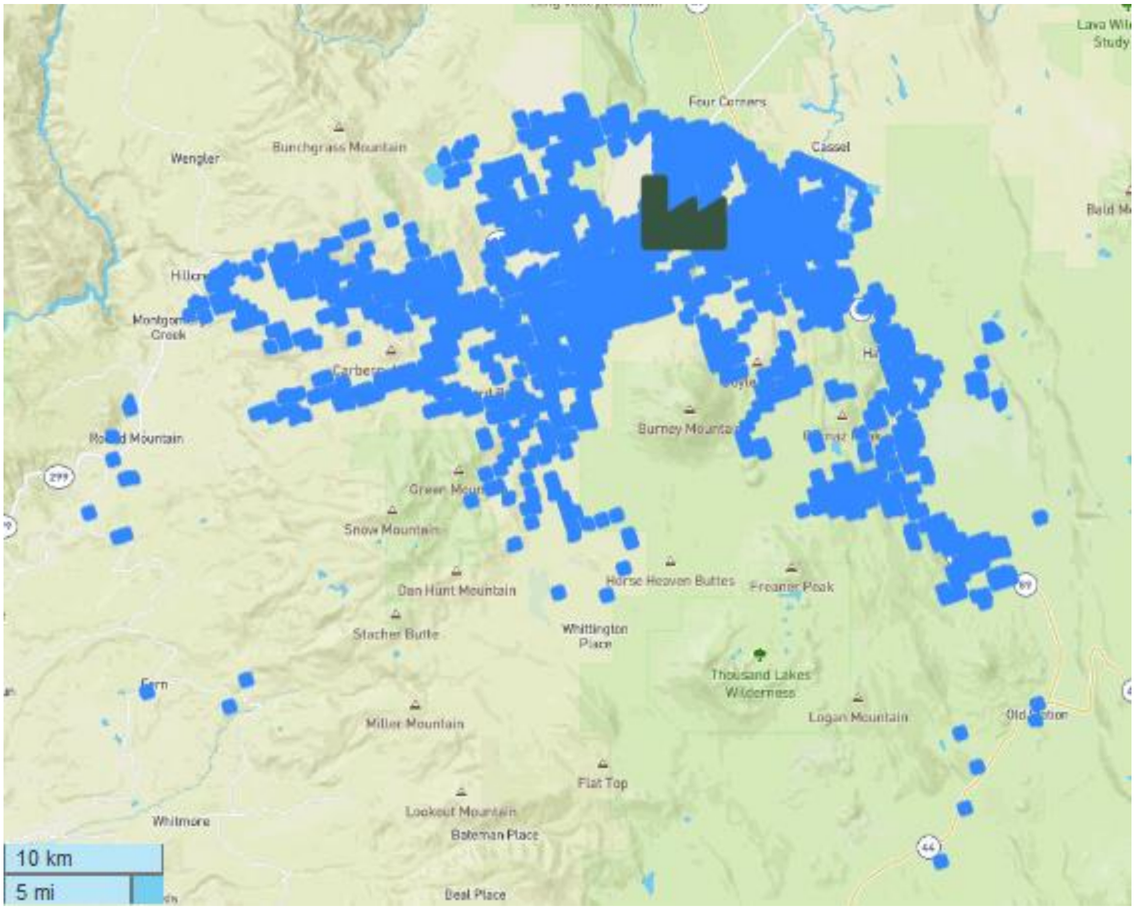

Figure 4.13 Feedstock distribution at the expansion factor of 50.

5 Conclusions

A comprehensive model was developed to quantify the environmental and economic impacts of generating electricity utilizing forest resources as feedstock by integrating a number of models yielding information on the cost of energy and potential environmental impacts. The model allows stakeholders to quickly evaluate the potential economic and environmental performance associated with establishing and operating a bioenergy facility at specific locations under a set of technical, economic, and financial decision factors. Two case studies were conducted to assess the model performance as a decision support tool that can help examine the potential economic and environmental impacts associated with new biomass energy facilities. The results from the case studies indicate that a comprehensive assessment is necessary to determine the combination of harvesting system and forest treatment within the terrain, stand, infrastructure and land distribution constraints of the supply region to yield the lowest cost or least environmental impact.

Substantial environmental benefits are apparent from utilizing forest resources to generate electricity as compared to an assumed business-as-usual scenario of open pile burning, and from the displacement of utility grid electricity given the current mix of nonrenewable as well as renewable sources. In terms of the results from the case studies, the 3 MWe gasification type conversion facility had lower net GHG emission per unit electricity generation than the 25 MWe conventional boiler and CHP systems, but partly due to its much smaller assumed size, it has the highest LCOE, a barrier for the commercialization. These results are preliminary, of course, in that gasification and many other types of technologies are still developmental, and well documented cost and environmental data are not necessarily available. Incentives from carbon reductions (e.g., carbon credits) by utilizing forest resources for energy production can lower the LCOE and improve the competitiveness of forest bioenergy production.

Capacity factor is the largest factors impacting LCOE, especially as it declines below baseline assumptions. Efforts should be made to maximize the operating time of a facility and the conversion efficiency while reducing capital and O&M costs, although advanced design to improve performance may typically result in higher capital costs. The full optimization by minimizing feedstock cost through searching the entire cluster database realized the lowest LCOE among all simulations but is computationally intensive. Alternatively, the method of employing an expansion factor with its larger but computationally feasible feedstock search, can be used for partial optimization and achieves a similar outcome as the full optimization.

While the model was developed for decision support in forest electricity generation with only three conversion technologies, it can be adapted to utilize other types of biomass feedstock such as agricultural residues, apply other conversion technologies, and for other forms of bioenergy such as biofuels. The npm packages developed for the FRCS, TEA, and LCA models are open-sourced and can be incorporated into other web applications.

6 Future Work

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 selections of harvesting systems and forest treatments. Furthermore, the selection could be automated by attempting all possible combinations for a cluster and identifying that yielding the lowest harvest cost or environmental impact.

The supply chain of the integrated model is onefold: feedstock is always chipped at the landing and then directly transported to a conversion facility, while feedstock chipping could occur at other intermediate locations, as could other phases such as feedstock storage and drying. Other supply chain designs can be explored and incorporated into the model.

The transportation model uses the transportation distance and travel time between two coordinates generated by OSRM to estimate the associated cost and emissions. Although OSRM generates the transportation information based on prescribed truck and route profiles, an economic and environmental model targeted on the specific road classes along the route could produce more accurate estimates. Other transport modes such as railway and waterway could also be modeled.

For power transmission, the algorithm always seeks the nearest substation and assumes new transmission lines are installed, which excludes the option of building a new substation or using existing transmission lines. Also, the default input values of the transmission model, such as voltage class, structure and conductor type, are used to estimate the installation cost for new transmission lines, and further research is needed as to determine the proper input values for the transmission model.

The TEA model is currently configured for three conversion technologies: conventional boiler-steam cycle, CHP, and gasifiers, and could be expanded for more advanced technologies that are still in the experimental phase, such as gasifiers integrated with fuel cells. The model can be customized to evaluate biofuels such as hydrogen and ethanol, or integrated biorefineries producing multiple products.

The LCA model uses the emission factors averaged from facilities of the same conversion technology in California. The emission factors, however, vary depending on the type of control devices installed and the conversion efficiency. The emissions from the construction of a facility and the manufacturing of harvesting equipment modeled with EIO-LCA are approximate at best, and detailed process-based LCA is recommended to model the material and energy flows from specific processes. Feedstock moisture can affect the facility conversion efficiency and thus the emissions from the facility. Nor are all forest resources of the same composition; differences in heating value 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 air emissions only and additional research should be done to quantify the emissions to water and soil. The impact from the end-of-life or decommissioning of a conversion facility and from land use and forest management should be assessed. To support better decision-making, a broad array of environmental impacts such as biodiversity, erosion/top soil loss, soil carbon changes, etc., in addition to GWP, should be considered.

The environmental benefits realized from utilizing forest resources to generate electricity are compared to a business-as-usual scenario of open pile burning. In practice, not all biomass would necessarily be burned in open piles if not used for bioenergy. A number of alternative fates can also be considered, for example, biomass could be left on the ground to decompose or burned in future wildfires resulting in different environmental burdens. 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 the 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.

7 References

Anttila, P., Vaario, L. M., Pulkkinen, P., Asikainen, A., Duan, J. (2015). Availability, supply technology and costs of residual forest biomass for energy – A case study in northern China. Biomass and Bioenergy, 83, 224–232. https://doi.org/10.1016/J.BIOMBIOE.2015.09.012

Argonne National Laboratory. (2021). Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model.

Bare, J. (2012). TRACI 2.1: User Manual. US Environmental Protection Agency.

Beagle, E., Belmont, E. (2019). Comparative life cycle assessment of biomass utilization for electricity generation in the European Union and the United States. Energy Policy, 128, 267–275. https://doi.org/10.1016/J.ENPOL.2019.01.006

California Air Resources Board. (2000). FACT SHEET #1: Development of Organic Emission Estimates For California's Emission Inventory and Air Quality Models. Retrieved from www.arb.ca.gov.

California Air Resources Board. (2019). CA-GREET3.0 Model.

California Air Resources Board. (2021a). Current California GHG Emission Inventory Data. Retrieved February 13, 2022, from https://ww2.arb.ca.gov/ghg-inventory-data

California Air Resources Board. (2021b). EMission FACtor (EMFAC). Retrieved June 22, 2021, from https://arb.ca.gov/emfac/

California Air Resources Board. (2021c). Facility Search Tool. Retrieved November 30, 2021, from https://ww2.arb.ca.gov/our-work/programs/ab-2588-air-toxics-hot-spots/facility-search-tool

California Air Resources Board. (2022). Stationary Source Emissions. Retrieved January 17, 2022, from https://ww2.arb.ca.gov/applications/stationary-source-emissions

California Biomass Collaborative. (2013). Energy Cost Calculator. Retrieved December 17, 2021, from https://biomass.ucdavis.edu/tools/energy-cost-calculator/

California Department of Forestry and Fire Protection. (2019). Survey Finds 18 Million Trees Died in California in 2018. Retrieved from https://www.fire.ca.gov/media/5120/2018-catreemortalitynumbersjointrelease_020519.pdf

California Department of Forestry and Fire Protection. (2020). CALIFORNIA FOREST PRACTICE RULES 2020. Retrieved from www.fire.ca.gov

California Department of Forestry and Fire Protection. (2021a). 2021 Fire Season Outlook. Retrieved December 22, 2021, from https://www.fire.ca.gov/incidents/

California Department of Forestry and Fire Protection. (2021b). Emergency Fund Fire Suppression Expenditures. Retrieved January 31, 2022, from https://www.fire.ca.gov/

California Public Utilities Commission. (2021). 2021 CALIFORNIA RENEWABLES PORTFOLIO STANDARD Annual Report.

Carnegie Mellon University Green Design Institute. (2008). Economic Input-Output Life Cycle Assessment (EIO-LCA), US 1997 Industry Benchmark model [Internet], Available from:<http://www.eiolca.net> Accessed 13 January, 2022.

Climate Action Reserve. (2011). Biomass Waste for Energy Project Reporting Protocol. Retrieved from https://www.climateactionreserve.org/wp-content/uploads/2012/08/FPP-V3.3-Public-Comment-PCAPCD.pdf

Drews, E. S., Hartsough, B. R., Doyal, J. A., Kellogg, L. D. (2001). Harvester-Forwarder and Harvester-Yarder Systems for Fuel Reduction Treatments. International Journal of Forest

Engineering. Retrieved from https://journals.lib.unb.ca/index.php/IJFE/article/view/30039/1882525302

Dykstra, D., Hartsough, B., Stokes, B. (2009). Updating FRCS, the Fuel Reduction Cost Simulator, for National Biomass Assessments.

Ellison, D., Morris, C. E., Locatelli, B., Sheil, D., Cohen, J., Murdiyarso, D., Gutierrez, V., Noordwijk, M., Creed, I.F., Pokorny, J., Gaveau, D., Spracklen, D.V., Tobella, A., Ilstedt, U., Teuling, A.J., Gebrehiwot, S., Sands, D.C., Muys, B., Verbist, B., Springgay, E., Sugandi, Y., Sullivan, C. A. (2017). Trees, forests and water: Cool insights for a hot world. Global Environmental Change, 43, 51–61. https://doi.org/10.1016/J.GLOENVCHA.2017.01.002

EPA. (2008). Life Cycle Assessment: Principles and Practice. Vasa, (May).

Esteban, L. S., Carrasco, J. E. (2011). Biomass resources and costs: Assessment in different EU countries. Biomass and Bioenergy, 35(SUPPL. 1), S21–S30. https://doi.org/10.1016/J.BIOMBIOE.2011.03.045

Federal Highway Administration. (2017). Table VM-1 - Highway Statistics 2017 - Policy | Federal Highway Administration. Retrieved July 27, 2020, from https://www.fhwa.dot.gov/policyinformation/statistics/2017/vm1.cfm

Fight, R. D., Hartsough, B. R., Noordijk, P. (2006). Users Guide for FRCS: Fuel Reduction Cost Simulator Software. Gen. Tech. Rep. PNW-GTR-668. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 23 p.

Flannigan, M. D., Stocks, B. J., Wotton, B. M. (2000). Climate change and forest fires. Science of The Total Environment, 262(3), 221–229. https://doi.org/10.1016/S0048-9697(00)00524-6

Frombo, F., Minciardi, R., Robba, M., Rosso, F., Sacile, R. (2009). Planning woody biomass logistics for energy production: A strategic decision model. Biomass and Bioenergy, 33(3), 372–383. https://doi.org/10.1016/J.BIOMBIOE.2008.09.008

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

Harris, N. L., Gibbs, D. A., Baccini, A., Birdsey, R. A., de Bruin, S., Farina, M., Fatoyinbo, L., Hansen, M.C., Herold, M., Houghton, R.A., Potapov, P.V., Suarez, D., Roman-Cuesta, R.M., Saatchi, S.S., Slay, C.M., Turubanova, S.A., Tyukavina, A. (2021). Global maps of twenty-first century forest carbon fluxes. Nature Climate Change 2021 11:3, 11(3), 234–240. https://doi.org/10.1038/s41558-020-00976-6

Huang, S., Ramirez, C., McElhaney, M., Evans, K. (2018). F3: Simulating spatiotemporal forest change from field inventory, remote sensing, growth modeling, and management actions.

Forest Ecology and Management, 415–416, 26–37. https://doi.org/10.1016/j.foreco.2018.02.026

IPCC, 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

Johnson, B. G., Johnson, D. W., Miller, W. W., Carroll-Moore, E. M., Board, D. I. (2011). The effects of slash pile burning on soil and water macronutrients. Soil Science, 176(8), 413–425. https://doi.org/10.1097/SS.0B013E318223CFAD

Langholtz, M. H., Stokes, B. J., Eaton, L. M. (2016). 2016 Billion-ton report: Advancing domestic resources for a thriving bioeconomy, Volume 1: Economic availability of feedstock. OAK RIDGE NATIONAL LABORATORY, Oak Ridge,Tennessee, Managed by UT-Battelle, LLC for the U.S. DEPARTMENT OF ENERGY, 2016(Vol. 1), 1–411.

Luxen, D., Vetter, C. (2011). Real-time routing with OpenStreetMap data. GIS: Proceedings of the ACM International Symposium on Advances in Geographic Information Systems, 513–516. https://doi.org/10.1145/2093973.2094062

Mangoyana, R. B. (2011). Bioenergy from forest thinning: Carbon emissions, energy balances and cost analyses. Renewable Energy, 36(9), 2368–2373. https://doi.org/10.1016/J.RENENE.2011.01.026

Marcille, K. C., Morgan, T. A., Mciver, C. P., Christensen, G. A. (2020). California's forest products industry and timber harvest, 2016. Gen. Tech. Rep. PNW-GTR-994. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 58 p.

Mason, T., Curry, T., Wilson, D. (2012). CAPITAL COSTS FOR TRANSMISSION AND SUBSTATIONS Recommendations for WECC Transmission Expansion Planning Western Electricity Coordinating Council.

Merz, J., Bandaru, V., Hart, Q., Parker, N., Jenkins, B. M. (2018). Hybrid Poplar based Biorefinery Siting Web Application (HP-BiSWA): An online decision support application for siting hybrid poplar based biorefineries. Computers and Electronics in Agriculture, 155(October), 76–83. https://doi.org/10.1016/j.compag.2018.09.042

Murphy, F., Devlin, G., McDonnell, K. (2014). Forest biomass supply chains in Ireland: A life cycle assessment of GHG emissions and primary energy balances. Applied Energy, 116, 1–8. https://doi.org/10.1016/J.APENERGY.2013.11.041

Nieuwlaar, E. (2004). Life Cycle Assessment and Energy Systems. Encyclopedia of Energy, 647–654. https://doi.org/10.1016/B0-12-176480-X/00233-3

Project-OSRM/osrm-profiles-contrib. (2021). Retrieved December 15, 2021, from https://github.com/Project-OSRM/osrm-profiles-contrib/tree/master/5/21/truck-soft

Paredes-Sánchez, J. P., García-Elcoro, V. E., Rosillo-Calle, F., Xiberta-Bernat, J. (2016). Assessment of forest bioenergy potential in a coal-producing area in Asturias (Spain) and recommendations for setting up a Biomass Logistic Centre (BLC). Applied Energy, 171, 133–141. https://doi.org/10.1016/J.APENERGY.2016.03.009

Repo, A., Känkänen, R., Tuovinen, J. P., Antikainen, R., Tuomi, M., Vanhala, P., Liski, J. (2012). Forest bioenergy climate impact can be improved by allocating forest residue removal. GCB Bioenergy, 4(2), 202–212. https://doi.org/10.1111/J.1757-1707.2011.01124.X

Rubio. (2012). SB-1122 Energy: renewable bioenergy projects. Retrieved January 22, 2022, from https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201120120SB1122

Schnorf, V., Trutnevyte, E., Bowman, G., Burg, V. (2021). Biomass transport for energy: Cost, energy and CO2 performance of forest wood and manure transport chains in Switzerland. Journal of Cleaner Production, 293, 125971. https://doi.org/10.1016/J.JCLEPRO.2021.125971

Springsteen, B., Christofk, T., York, R. A., Mason, T., Baker, S., Lincoln, E., Hartsough, B., Yoshioka, T. (2015). Forest biomass diversion in the Sierra Nevada: Energy, economics and emissions. California Agriculture. 69(3): 142-149., 69(3), 142–149. https://doi.org/10.3733/CA.V069N03P142

Šumarija Vareš, P. J., Halilović, V., Gurda, S., Sokolović, D., Musić, J., Bajrić, M., Ganić, E. (2012). FUEL AND LUBRICANTS CONSUMPTION IN THE PHASE OF HARVESTING AND PROCESSING WOOD IN PUBLIC ENTERPRISE FOREST OFFICES VAREŠ SECTION 37 Potrošnja goriva i maziva u fazi sječe i izrade drveta na području.

Thinning | OregonForests. (2022). Retrieved January 17, 2022, from https://oregonforests.org/thinning

Tubbesing, C. (2020). personal communication.

U.S. Energy Information Administration. (2021a). 1990–2020 Net Generation by State by Type of Producer by Energy Source (EIA-906, EIA-920, and EIA-923). Retrieved December 22, 2021, from https://www.eia.gov/electricity/data/state/

U.S. Energy Information Administration. (2021b). Form EIA-860, Annual Electric Generator Report, U.S. Energy Information Administration, Form EIA-861, Annual Electric Power Industry Report, U.S. Energy Information Administration, Form EIA-923, Power Plant Operations Report and predecessor forms.

U.S. Environmental Protection Agency. (2018). Emission Factors for Greenhouse Gas Inventories. Retrieved from https://www.epa.gov/sites/default/files/2018-03/documents/emission-factors_mar_2018_0.pdf

U.S. Environmental Protection Agency. (2019). Emissions & Generation Resource Integrated Database (eGRID). US Environmental Protection Agency.

U.S. Environmental Protection Agency. (2021). THE EMISSIONS & GENERATION RESOURCE INTEGRATED DATABASE eGRID Technical Guide with Year 2019 Data.

U.S. Forest Service. (2019). HELICOPTER SERVICES, HOURLY FLIGHT RATES, FUEL CONSUMPTION, AND WEIGHT REDUCTION CHART EFFECTIVE. FEBRUARY 16, 2019. FOR CONTRACTS AWARDED 2018-2021 (CWN/Exclusive Use) (For Contracts Awarded 1/1/2018 and After).

U.S. Forest Service. (2020). National Visitor Use Monitoring Survey Results. National Summary Report. Data collected FY 2016 through FY 2020.

U.S. Forest Service. (2021). Silviculture. Retrieved December 19, 2021, from https://www.fs.fed.us/forestmanagement/vegetation-management/silviculture/index.shtml

Xu, H., Latta, G., Lee, U., Lewandrowski, J., Wang, M. (2021). Regionalized Life Cycle Greenhouse Gas Emissions of Forest Biomass Use for Electricity Generation in the United States. Environmental Science and Technology, 55(21), 14806–14816. https://doi.org/10.1021/ACS.EST.1C04301/SUPPL_FILE/ES1C04301_SI_001.PDF

Zambelli, P., Lora, C., Spinelli, R., Tattoni, C., Vitti, A., Zatelli, P., Ciolli, M. (2012). A GIS decision support system for regional forest management to assess biomass availability for renewable energy production. Environmental Modelling & Software, 38, 203–213. https://doi.org/10.1016/J.ENVSOFT.2012.05.016

Zhang, F., Johnson, D. M., Wang, J. (2015). Life-Cycle Energy and GHG Emissions of Forest Biomass Harvest and Transport for Biofuel Production in Michigan. Energies 2015, Vol. 8, Pages 3258-3271, 8(4), 3258–3271. https://doi.org/10.3390/EN8043258

Zhang, F., Johnson, D. M., Wang, J., Yu, C. (2016). Cost, energy use and GHG emissions for forest biomass harvesting operations. Energy, 114, 1053–1062. https://doi.org/10.1016/J.ENERGY.2016.07.086