

Low-carbon forest biofuels in California: state of knowledge, research gaps and near-term priorities
Interim Report to the Joint Institute for Wood Products Innovation

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1 Introduction

California's Forest Carbon Plan (FCP) calls for a significant increase in the level of forest restoration, as well implementing strategies for wood products innovation. Increased levels of forest treatment such as thinning and mechanical harvesting will likely generate millions of new tons of wood waste in California's forests each year. The business-as-usual approaches of utilizing these forest residues include open burning, decomposition or combustion in emissions-controlled biomass power plants. Without advances in wood products innovation, these approaches could result in elevated greenhouse gas emissions that will ultimately undermine the state's aspiration to achieve forest health while meeting its climate goals.

Recent research by the Joint Institute for Wood Products Innovation (Joint Institute, 2020) suggested that California's small-diameter trees and unutilized forest biomass waste from current forestry practices can play an important role to achieve carbon neutrality by 2045 by pursuing innovative wood-based products such as forest biofuels.

Biomass-based fuels have received considerable attention in recent decades, as these biofuels are considered low-carbon or even carbon-negative. Hydrogen and gasoline are two such types of biofuels that can be produced from biomass using thermo-chemical processes. California's abundant underutilized forest biomass resources present an enormous opportunity for the state to produce low-carbon and carbon-negative biofuels. California's climate policy instruments (especially the Low Carbon Fuels Standard, or LCFS) can drive development and deployment of low-carbon and carbon-negative fuels derived from forest biomass.

Biofuels present a promising wood product option for three key reasons. First, is that they are a high-value product in the California' transportation fuels market. Between incentives available via the state's Low Carbon Fuel Standard (LCFS) and the federal government's Renewable Fuel Standard programs, as well as the inherent value of a product like hydrogen, biofuels command a much higher value "per ton" of forest biomass than current wood product options. This can create a reliable income stream to support forest health treatments and a pathway to the state's overall forest treatment goal. Second, is that biofuels are a scalable product. California's liquid fuels end market is extremely large and established. Renewable liquid and gaseous fuels can meet existing demand by displacing fossil fuels in a diversity of hard-to-electrify applications in the coming decades (ClimateWorks Foundation, 2018). Finally, biofuels can provide substantial GHG benefits. The Joint Institute can undertake market formation activities to promote in-state manufacturing. Scale up of innovative processes to produce low-carbon transportation fuels from forest biomass will require additional supportive policy and additional research on feedstock-pyrolysis interactions.

1.1 Objectives

The objective of this report is to synthesize the current state of knowledge in forest-to fuels pathways in California. This report also identifies research gaps for forest biofuels in the context of California, which could be further pursued by the Joint Institute. Answering these questions will inform development and deployment of these fuels in State.

2 Forest biofuels: an overview of the current state of knowledge

The Joint Institute considered forest biofuels as part of its 2020 “**Literature Review and Evaluation of Research Gaps to Support Wood Products Innovation**”. Below, we summarize relevant knowledge from this report. Interested readers are referred to the full report, available at: https://bof.fire.ca.gov/media/9688/full-12-a-jiwpi_formattedv12_3_05_2020.pdf

Liquid and gaseous fuels can be produced from forest biomass, including non-merchantable wood. These fuels can reduce consumption of fossil fuels via substitution of low-carbon or carbon-negative fuels. California stands to benefit significantly from support for innovation in the sector through increased local capacity, strengthened regional collaborations, and increased carbon storage in long-lived wood products. Forest biofuels have sufficient commercial and technical readiness, and potential market size, to justify increased public and private investments in their development. Table 1 shows the most important classes of liquid and gaseous transportation fuels.

Table 1: Liquid and gaseous fuels

| Product Group | Liquid and gaseous fuels |
|--|--|
| Product Types | <ul style="list-style-type: none">• Renewable natural gas• Renewable hydrogen• Fischer-tropsch fuels• Gas fermentation• Fast pyrolysis and hydroprocessing• Lignocellulosic ethanol |
| Purpose | Transportation fuel |
| Carbon storage | Possible (CCS) |
| Range of feedstock required (BDT/year) | 45,000 - 300,000 |
| Technology readiness level (1-9) | 5-8 |
| Commercial readiness level (1-9) | 5-7 |
| Feedstock use | Non-merchantable wood |
| Potential market size | Large |

Resulting low-carbon and carbon-negative fuels can be either gaseous (RNG, H₂) or liquid (ethanol, or other drop-in fuels).

RNG can be produced through the thermal conversation of woody biomass to RNG via gasification and subsequent catalytic conversion. This is broadly known as methanation, or the

Sabatier process. The primary barrier to growth of RNG from forest biomass is the lack of a large-scale demonstration facility operating on woody biomass feedstock.

Another pathway to substantially reduce GHG and criteria pollutant emissions is by expanded use of renewable hydrogen. Hydrogen (H₂) can be produced from a number of processes, such as electrolysis of water or steam-methane reforming of natural gas. Woody biomass can be converted into hydrogen via gasification and subsequent catalytic conversion. This catalytic conversion is known as water-gas shift, which converts carbon monoxide and water vapor to form carbon dioxide and hydrogen. This mixture of hydrogen and carbon dioxide can then be separated into high-purity streams using existing technology. Large-scale hydrogen production from wood via gasification is relatively rare. Nevertheless, gasification of woody biomass is practiced at commercial scale. Proposed hydrogen production plants in CA process agricultural biomass, rather than wood. For instance, Clean Energy Systems plans to develop a facility producing hydrogen from 300 tons per day of orchard wastes near Kimberlina, CA (Clean Energy Systems, 2019). The primary barrier to growth of hydrogen from forest biomass is the lack of a successful demonstration facility operating on woody biomass feedstock. An additional barrier is the lack of enabling infrastructure for hydrogen distribution to vehicles. Future development of hydrogen infrastructure will likely be limited by hydrogen fuel cell vehicle adoption.

Liquid fuels can be produced from forest biomass, including non-merchantable wood. These fuels can reduce consumption of fossil fuels via substitution of low-carbon or carbon-negative fuels. Liquid fuels such as Fischer-Tropsch fuels and gasoline can be derived from biomass through gasification, gas cleaning, and catalytic treatment. Solid biomass is first gasified in oxygen and steam, with subsequent gas conditioning that includes cleaning of the raw synthesis gas and in some cases adjusting the composition of the syngas in preparation for downstream synthesis of Fischer-Tropsch liquids (FTL) or gasoline using methanol-to-gasoline (MTG) pathway. Red Rocks Biofuels has proposed a facility in Lakeview, Oregon in part to serve California markets. This facility will consume 160,000 BDT/yr of biomass to produce 7.2 million gallons a year of jet fuel, 7.2 million gallons a year of diesel fuel, and 3.6 million gallons a year of naphtha (Red Rocks Biofuels, 2018). Liquid fuels plants exhibit large economies of scale, which increases the minimum viable capital investment necessary to construct a commercial facility (Sanchez and Kammen, 2016). Compared to other low-carbon fuels facilities (e.g. RNG, lignocellulosic ethanol), FTL plants face considerably higher capital requirements. Furthermore, large feedstock requirements can create challenges with respect to security of supply of forest biomass in California.

Despite significant potential, commercial production of biofuels faces a number of risks. Issues include:

- **Scale:** biofuel plants are relatively small relative to a pulp mill, are very expensive in terms of capital costs per production volume.
- **Feedstock handling:** Handling and processing biomass at scale presents major logistical challenges.
- **Feedstock-process interactions:** Ash, lignin, and trace contaminant levels in forest biomass can reduce the yield of processes compared to agricultural biomass.
- **Margins:** Fuels have a low margin and are produced at large scale, challenging the profitability of biofuels production. Only with significant subsidies, or a reliable signal sent through climate policy, will allow biofuels to be profitable at scale.

There are currently 13 plants around the world that convert 'biomass' to fuels or chemicals. The Joint Institute Review of Literature report (2020) reported an additional 20 projects in various

stages of development or even initial construction. It is worth noting that many of the underperforming or failed ventures were implemented by large, well-resourced companies who have decades of experience with operating traditional biomass processing plants, e.g., corn dry mills or pulp and paper operations.

Table 2: Partial List of Commercial Biomass to Fuels Production Plants (operating as of 2018)

| Company, Location | Feedstock | Production Capacity (Mil lit/ yr and Mil Gal/yr) | Estimated Biomass Consumption Mt/yr | Technology | Start-up |
|----------------------------|-------------------|--|-------------------------------------|--------------------------------------|----------|
| Borregaard, Norway | Wood | 20/52 | NA - Dilute black liquor sugars | Fermentation of Spent Sulfite liquor | 1938 |
| Domsjo Fabriker AB, Sweden | Wood | 22/58 | NA - Dilute black liquor sugars | Fermentation of Spent Sulfite liquor | 1938 |
| Shandong Longlive, China | Ag Residues | 63/16 | 205,000 | Fermentation of sugars | 2012 |
| Henan Tianguan, China | Ag Residues | 38/10 | 125,000 | Fermentation of sugars | 2012 |
| GranBio, Brazil | Straw and Bagasse | 82/22 | 270,000 | Fermentation of sugars | 2014 |
| Beta Renewables, Italy | Ag Residues | 50/13 | 165,000 | Fermentation of sugars | 2012 |
| Raizen/Logen, Brazil | Straw and Bagasse | 40/11 | 130,000 | Fermentation of sugars | 2014 |
| St1/SOK, Finland | Sawdust | 10/2.5 | 30,000 | Fermentation of sugars | 2014 |
| Enerkem, CAN | MSW | 38/10 | Unavailable | Gasification, chemical catalysis | 2016 |

In the following sections we summarize the state of knowledge of the hydrogen market in California and the potential for producing hydrogen from non-merchantable forest biomass. This market analysis is followed by an economic analysis to evaluate the financial viability of producing renewable hydrogen and gasoline from forest residues, agricultural residues, and municipal solid waste (MSW).

3.1 Hydrogen market analysis

There is much debate on the availability of various biomass sources for bioenergy application in California and the role of biofuels in reducing greenhouse gas emissions. Previous research highlight some of the emerging questions and expectations surrounding the future of low-carbon and carbon-negative fuels in California. Several studies have examined biomass conversion to hydrogen using three main hydrogen conversion platforms, namely gasification to hydrogen, gasification to hydrogen with CCS, and biomass pyrolysis to hydrogen (Larson et al., 2009; Parkinson et al. 2019). These studies provide an insight into the mass and energy balances, costs, emissions, and scale from biomass to hydrogen.

Previous modelling approaches have estimated that hydrogen could play an important role in decarbonization of transportation, as well as buildings and industry sectors, given supporting policy drivers and enabling infrastructure (E3, 2020). Biomass is a potentially remarkable source

for hydrogen as it could provide outsized environmental benefits, including carbon dioxide removal and support for forest restoration, at competitive costs close to those of hydrogen from natural gas or coal.

California is likely to have plentiful biomass resource from forest residues: total biomass availability in California for the year 2025 – estimated at 24 million tons per year – is sufficient to produce 1.7 million tons of hydrogen, or 85% of current State demand and 40% of future 2050 demand of 4 million tons hydrogen per year. Hydrogen production from California’s diverse biomass resource base can be accomplished with gasification, gasification with carbon capture and storage (CCS), and pyrolysis.

The levelized cost of hydrogen from biomass sources using gasification are reported in the range of \$1.48 to 3.00/kg (\$3.15 to 3.6/ kg with CCS), with a mean of \$2.24/kg (\$3.37/kg with CCS). Greenhouse gas emissions of hydrogen produced from biomass are significantly lower than hydrogen produced from natural gas and reported to be in the range of 3 to 72 gCO₂e /MJ, (-97 to -146 gCO₂e /MJ with CCS) with a mean of 22 gCO₂e /MJ (-122 gCO₂e /MJ with CCS). Pyrolysis of biomass for hydrogen production has received insufficient scholarly attention: nevertheless, we expect pyrolysis to have the lowest capital cost and operating costs compared to gasification at a capacity of 2,000 bone dry tons/day of feedstock (~600,000 bone dry tons/year). Biomass gasification demonstrates significant economies of scale in both capital and operational costs. Infrastructure needs for hydrogen distribution in California vary according to the demand and available infrastructure options. In the near-term, California could utilize truck transport for short distances and small volumes, and existing energy infrastructure such as natural gas pipelines, and railroads for the transmission of large amounts of hydrogen for longer distances. California’s robust forest resource base, coupled with supportive climate policy, could play a significant role in the future hydrogen market development in order to meet California’s energy and climate goals.

3.2 Comparative analysis of feedstocks to produce low-carbon or carbon-negative fuels

California’s goal to increase the pace and scale of forest management to one million acres per year presents major implications for forest biomass supply, with the potential of generating hundreds of millions of new tons of forest biomass in the next decade. Current biomass disposal options include open pile burning and decomposition, resulting in significant GHG emissions that could undermine the state’s efforts to achieve its climate goals. Instead, if this waste biomass can be converted into innovative wood products, then these GHG and air quality impacts can be avoided. Moreover, the lifecycle GHG benefits available from wood products (e.g. biofuels) displacing fossil fuels could turn a potentially major carbon problem into a carbon solution.

We performed an economic analysis to evaluate the financial viability of producing renewable hydrogen and gasoline from forest residues, agricultural residues, and municipal solid waste (MSW). To achieve our objectives, first we characterize the costs and performance of biomass gasification and subsequent hydrogen and gasoline production across feedstocks (Table 1). Second, we performed life cycle analysis, consistent with California’s GREET 3.0 model, to calculate average lifecycle carbon intensity of different production processes for hydrogen and gasoline from forest biomass, agricultural residues and municipal solid waste. Finally, we performed a discounted cash flow analysis to estimate the net present value and the internal rate of return of each process. We used Discounted Cash Flow (DCF) analysis to find the net present value and internal rate of return (IRR) for hydrogen and gasoline produced with and without CCS over use a 20-year time period. We evaluated twelve process scenarios for the production of hydrogen and gasoline from forest biomass, agricultural residues and MSW. Table 3 shows the

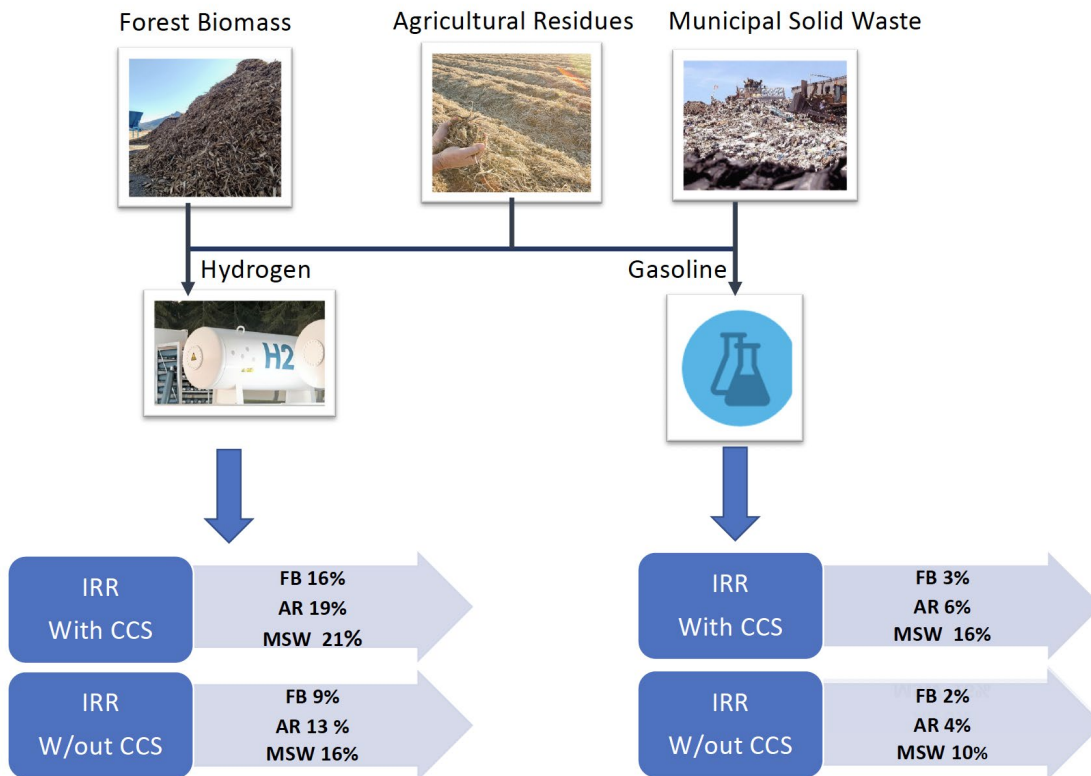
daily feedstock processed in bone dry tons and the total capital cost for each process configuration. Capital costs include the cost of equipment, Engineering, procurement, and construction (EPC), contingency costs and land lease, while the operating costs consist of electricity, labor, maintenance, other operating cost, water, land rent, and natural gas.

Table 3: Feedstock consumption and capital cost for each process configuration

| Process Configuration | Biomass Processed BDT/day | Capital Cost M \$ |
|-----------------------|---------------------------|-------------------|
| FB Hydrogen CCS | 167 | 163 |
| AR Hydrogen CCS | 174 | 161 |
| MSW Hydrogen CCS | 161 | 161 |
| FB Hydrogen | 167 | 185 |
| AR Hydrogen | 174 | 201 |
| MSW Hydrogen | 161 | 188 |
| FB Gasoline CCS | 167 | 130 |
| AR Gasoline CCS | 174 | 134 |
| MSW Gasoline CCS | 161 | 141 |
| FB Gasoline | 167 | 173 |
| AR Gasoline | 174 | 188 |
| MSW Gasoline | 161 | 178 |

A comparison based on the internal rate of returns shows that forest residues is the least profitable feedstock option for both hydrogen and gasoline production. Under existing policy, municipal solid waste is the most profitable route, followed by agricultural residues. The projects can achieve additional returns with the integration of carbon capture and storage.

Under our economic assumptions, all three feedstocks generate a highly positive internal rate of return across technology configurations. This suggests that these would be financially worthwhile enterprises at scale in California. The internal rate of return for hydrogen from MSW is higher (21%) than those of agricultural residues (19%) and forest biomass (16%) with carbon capture and storage. Without CCS, the internal rate of return for hydrogen from MSW is 16%, compared to agricultural residues (13%) and forest biomass (9%). This favorable result for MSW is due its lower lifecycle carbon intensity. MSW feedstock can produce extremely low-carbon and carbon negative fuels, primarily from avoided methane emissions associated with landfilling of waste. This leads to a higher amount of CO₂ tonnes abated per year under the LCFS. MSW generates 60% more LCFS credits than forest residues.



For the gasoline production with carbon capture and storage, MSW yields the highest IRR of 16%. This is followed by agricultural residues with 6% IRR and forest biomass with 3%. When carbon capture and storage is not integrated, the internal rate of return for the three cases drops while still remaining positive. The IRRs for gasoline without carbon capture and storage for forest residues, agricultural residues and MSW are 2%, 4% and 10% respectively. These results indicate that the financial benefit of carbon capture and storage from gasoline production is less pronounced than for hydrogen. While gasoline production yields positive returns across feedstocks, it is less profitable than hydrogen production and yields IRRs less than the weighted average cost of capital for both forest biomass and agricultural residues.

4 Economic impact of potential policy interventions

We assess five policy interventions to support forest residue conversion to fuels in California. These interventions include: 1) adjustments to the LCFS credit price for forest fuels; 2) adjustments to the carbon intensity (CI) of forest fuels; 3) concessionary finance from the state; 4) a subsidy for capital costs; or 5) a subsidy for feedstock delivery. Table 3 shows the range of policy interventions for each of these five recommendations to make forest residues competitive with agricultural residues.

4.1 LCFS credit price

LCFS credits play a vital role in the profitability of biofuels pathways in CA. At the assumed price of \$150 per ton abated, forest biomass remains a financially weaker option than agricultural residues or MSW. This is particularly true because of avoided methane emissions for MSW. Adjusting LCFS credit price for forest-biofuels could increase their profitability. Our analysis for hydrogen shows that at LCFS credit price of \$191.5/tCO₂e, forest biomass would become competitive with agricultural residues with carbon capture and storage, and \$244/tCO₂e without carbon capture and storage. For gasoline, an LCFS credit price of \$250/tCO₂e would make forest biomass competitive with agricultural residues with carbon capture and storage, and \$243/tCO₂e without carbon capture and storage. When considering a LCFS credit value of \$150/tCO₂e, additional LCFS credit price support ranges from \$41-100 t/CO₂e.

4.2 Carbon intensity (CI) score

The CI score of MSW benefits from avoided direct emissions in calculating the CI. Similar full lifecycle assessment to properly account for the GHG benefits provided by fuels derived from forest residues, as discussed in Sanchez et al. (2021), could improve the carbon intensity of these fuels. Our analysis for hydrogen shows that at the CI score of -198 gCO₂e/MJ (initial = -127 gCO₂e/MJ), forest biomass would become competitive with agricultural residues with carbon capture and storage, and -56 gCO₂e/MJ without CCS (initial = 3.1). For gasoline, a CI score of -140 gCO₂e/MJ (initial = -38) would make forest biomass competitive with agricultural residues with carbon capture and storage, and -56 gCO₂e/MJ (initial = 4.4) without carbon capture and storage. When considering the initial CI scores of forest-to-fuel pathways, the range of necessary additional CI decrease is 59 – 102 gCO₂e/MJ.

4.3 Concessionary finance

CA can play an important role by providing concessionary finance in the early stages of deployment, leveraging private capital to achieve scale. This support can take the form of loans, equity investments, or other credit subsidies. We find that for hydrogen production, forest biomass become competitive with agricultural residues at 7% and 6 % weighted-average cost of capital (WACC) with and without carbon capture and storage, respectively. For gasoline production, we find a 6% WACC with carbon capture and storage, and 7% WACC without carbon capture and storage. When considering the initial WACC of 10%, the range of concessionary debt or equity is 3 – 4%. In our discounted cash flow analysis, we assumed a mix of 50% debt and 50% equity. However, the additional debt will impact both the equity and debt investors because additional leverage makes it riskier for equity investors. In other words, as the total debt percentage increases, the interest rate on the debt also increases as the lenders will demand higher rate of interest because of higher risk. As a result, the, the cost of debt and the cost of equity both increases due to changes in the capital structure and therefore the weighted average cost of capital (WACC) also increases.

4.4 Capital cost subsidy

To improve financial outcomes for forest fuel production systems, the state could provide grants for systems located in CA. Our analysis shows that for hydrogen production a capital cost of \$132 million (initially \$152 million) allows forest biomass to deliver the same IRR as agricultural residues with carbon capture, and \$107 million (initial = \$130 million) without carbon capture and storage. For gasoline, a capital cost of \$145 million (initial = \$185 million) makes forest biomass

competitive with carbon capture, and \$143 million (initial = \$173) without carbon capture. As a % of base capital costs, necessary capital cost subsidies range between 13-21%.

4.5 Feedstock subsidy

Forest biomass faces direct competition from other biogenic feedstock, notably from agricultural residues, for biofuel production. Competition may be further exacerbated through the introduction of new regulations that restrict or a complete phase-out of agricultural burning e.g. by January 1, 2025 in San Joaquin Valley. In addition, due to its proximity to urban centers, agricultural residues are relatively easier to mobilize than forest residues, which is heterogeneous and need to be transported to a centralized infrastructure for conversion. Production costs of biofuels are dependent on the feedstock cost. Forest biomass is roughly 60% more expensive than agricultural residue in our base case. This reduces the profitability of forest-to-fuel pathways. One potential policy intervention is a feedstock subsidy. Our analysis shows that for hydrogen production a feedstock price of \$-21 per dry ton allows forest biomass to deliver the same internal rate of return (IRR) as agricultural residues with carbon capture and storage, and \$-13 without carbon capture and storage. For gasoline, a feedstock price of \$-20 per dry ton makes forest biomass competitive with agricultural residues with carbon capture and storage, and \$5 without carbon capture and storage. When including the assumed cost of biomass of \$50 per dry tonne, subsidies from the state will need to range from \$45 – 71 per dry tonne.

5 Research gaps

Forest biofuel production faces a number of remaining challenges prior to its successful commercialization in California. These can be classified, broadly, as economic challenges, technical challenges, financing and insurance, and attitudes and perceptions of relevant stakeholders. Today there is a large amount of empirical data available for biomass availability, feasibility of forest-to-fuels pathways, policy analysis and technology developments. It is now time to move from analyses of individual studies to analyses of larger materials, in order to generate specific knowledge in the context of California by analyzing key questions on project finance, feedstock supply, supportive policy, infrastructure needs, and equity and development. The key barriers for the expansion of the cellulosic biofuels in California are related to economic viability and project finance. The industry is considered as a high-risk investment due to technical barriers and uncertainty about the projects' profitability. Addressing these barriers will support the development and commercialization of forest-to-fuels pathways in California. Here, we list key considerations identified by forest biofuels working group in each of the five areas with relevant research questions that need to be addressed to develop a forest biofuels industry in California. The full findings of the forest biofuels working group will be published in the Final report to the Board of Forestry and Fire Protection.

5.1 Project finance

Construction of large-scale forest biofuels infrastructure often relies on project finance, a non-recourse financial structure. Central to project finance is the execution of long-term contracts from credit-worthy counterparties in: 1) engineering, procurement and construction (“EPC”), 2) technology operations and maintenance (“O+M”), 3) feedstock supply, and 4) product offtake (agreement in which a third party that has signed a contract guaranteeing that they will buy the project owner’s output for a certain length of time in the future. Several relevant questions arise in this context:

- Which companies can procure, construct, and construct sufficiently de-risked, commercially mature, or guaranteed forest biofuel technologies?
- What is a sufficient feedstock “guarantee” that will satisfy commercial lenders?
- How is state funding best deployed to support forest biofuels?
- How willing are fuels purchasers to enter long-term offtake contracts? How are policy-supported revenues distributed?

We expect that the final report to the BOF will answer these questions to the extent feasible. No further research questions have arisen during the course of investigation.

5.2 Feedstock supply

Wood products businesses are unable to obtain reliable, long-term supply of woody biomass from forested lands in California due to high transportation costs, limited USFS contracting approaches and private landholder forest management challenges. These barriers, as well as lengthy government approval processes slows down the removal of biomass from forest fuel reduction and restoration projects, impede wood products business development.

One approach to solving these issues is the development of public institutional arrangements, such as a Joint Powers Authority or special districts that could serve as brokers for these biomass materials. Due to regional variability in California, the solution to improving feedstock supply will likely look differently in different areas, and depend on how industry professionals and community leaders relate to the following three main topics: (1) existing and envisioned involvement of public entities that choose to coordinate feedstock mobilization, (2) community stakeholder involvement (including private industry and current non-profit partners that engage with the USFS), and (3) financing for such efforts. The Governor’s Office of Planning and Research (OPR) is expected to allocate roughly \$2.5 million for planning and outreach efforts needed to pilot models that target feedstock supply chain improvements. Over the course of the next several years, regions will be addressing several fundamental questions to ensure reliable feedstock supply chain logistics at a smaller, regional scale.

Given the strong policy support to expand the forest biofuels market, providing constancy to forest biomass feedstock supply will be a priority, and long-term research will be needed to enable this sector at this larger scale of feedstock supply. The following research questions can be answered concomitantly:

- What are the organizational structure and financial variables that change when moving to contracting with large scale facilities (meaning scaling from small to large scale wood product business partners)?
- Can these entities provide enough contract stability to entice private lenders and equity investors for projects of this value?

- How will forest biomass best be combined with agricultural and urban wood waste in order to support these larger scale projects?
- How can we ensure that at this scale the demand for wood waste will not drive forest practices, ensuring that waste and residues are used for fuels?

5.3 Supportive policy

California has set an ambitious goal to increase the pace and scale of forest treatments to one million acres per year by 2025 to reduce wildfire risk and improve forest health. Currently, the state treats about 200,000 acres per year, excluding commercial timber harvest. An expansion to this level of forest treatments is expected to generate *hundreds of millions* of new tons of waste forest biomass over the course of the next 1-2 decades. Collecting and converting this biomass into renewable liquid and gaseous fuels, which are high-value, scalable, and can be carbon-negative when coupled with carbon capture and storage (CCS), presents a robust solution that could support the state’s ambitious goal. Collecting and converting forest residues into wood products like biofuels is a key strategy for California to achieve its forest health, wildfire risk reduction, and long-term climate goals. California’s world-leading climate policies, along with federal policies, are important potential drivers of forest biofuels deployment in the state. Notwithstanding available incentives under the state’s Low Carbon Fuel Standard (LCFS) and federal government’s Renewable Fuel Standard (RFS) programs, there are currently a number of real-world barriers to demonstrating and scaling carbon-negative forest biofuels pathways in California. Policy intervention can help overcome these barriers. To support and inform the nature of this policy intervention, some select, outstanding research questions need to be answered, including:

- What is the lifecycle greenhouse gas emissions profile of forest biomass to biofuels pathways in California? Can this be developed into a simplified calculator for adoption under CA-GREET?
- What is the (quantified) CI and NPV impact of additional incentives, in the form of a credit carve-out or credit multiplier, on alternate forest biofuels pathways under the LCFS? What are the possible implications to the broader program if such additional incentives are adopted? Is there a possible exposure to interstate commerce clause obligations?
- What is an alternative and contemporary interpretation of California’s “areas at risk of wildfire” (for the purpose of Title 2, Subtitle A, Section 201 of the Energy Independence and Security Act of 2007) compared to an historic, and now arguably outdated quantitative assessment performed by University of Wisconsin-Madison in 2010 to inform the RFS program?
- What are the public health implications to Californians of alternate forest biomass management strategies at the scale of treating one million acres per year?
- What sequence of policy recommendations and commercialization roadmap could support the demonstration and deployment of carbon-negative forest biofuels pathways in California?

5.4 Infrastructure

Large-scale deployment of forest biofuels will involve a complex supply between forests and fuel consumers. The infrastructure of low-carbon and carbon-negative gaseous and liquid fuels in California may include large-scale production facilities in Western Sierra and the Central Valley, a fuels distribution network, and a large fueling station infrastructure network.

An infrastructure to transport and store gaseous fuels is already in place, including SoCalGas's 20,000 square-mile service territory and connecting remote utility-scale solar producers with urban centers (CAFCEP 2021). This existing infrastructure could be leveraged to enable hydrogen distribution and long-term energy storage opportunity. A mature network of on-site hydrogen production and fueling infrastructure is expanding to meet higher hydrogen demand. Blending hydrogen in natural gas pipeline networks may provide a solution to the problem of hydrogen distribution from remote or centralized production facilities in Western Sierra and the Central Valley of California. To better understand the infrastructure needs and implications of a blended infrastructure, the following research questions are suggested:

- What is the distribution cost for hydrogen blended into natural gas pipelines and how does it compare to other distribution options?
- What are the necessary modifications to natural gas pipelines that would allow hydrogen blending at various percentages?
- What are the effect of various blend percentages on end-use equipment?
- How can we repurpose existing infrastructure and biopower facilities for forest biofuels production?
- How do siting decisions intersect with economic development and social equity?
- What are siting considerations based on (1) transport cost of supply and various offtakes (e.g., hydrogen) and (2) demand/supply
- How will fuel offtake contracting affect addressable market size (e.g. refineries have long term-offtakes for SMR H₂, making it hard to break in)?

5.5 Development and equity

The working group assigned to consider the topics of environmental and economic equity as it relates to the development of a biofuels industry in California has three primary recommendations for the Advisory Council to consider in its future funding.

First, to encourage the consideration of environmental burden (both historic and predicted), economic impact, rural resilience, and wildfire vulnerability in future research as a critical aspect of the work, five guiding principles are proposed:

1. Ensure that sustainable forest restoration, economic feasibility and environmental and social equity are weighted equally in recommendations.
2. Ensure rural, community-scale economic development alongside sustainable forest management.
3. Ensure source communities are beneficiaries of biofuels production and sustainable research management.
4. Ensure projects are compatible with surrounding land use and communities.
5. Enable restorative outcomes for under-resourced and under-served communities.

Second, there is a research gap in understanding the overlay of three factors: vulnerability to wildfire, economic resilience, and environmental burden associated with forest management and biofuels industries. At present, there are not useful tools which shows us where to invest in forested areas for sustainable forest management scaling with an equity and economic resilience lens. Rather, our most commonly used tool is the CalEnviroScreen tool, which was established to identify regions with significant historic environmental burden and does not account for economic and environmental vulnerability (such as wildfire). With more accurate research we might be able to more effectively identify those communities where sustainable restoration projects should be prioritized and/or where the positive economic benefit of biofuels industry development should be prioritized.

Third, further research on the full distributional impacts of forest biofuel supply chains will improve prioritization of end-market technologies. For example, the use of biomass for liquid biofuel generation may have the impact of shifting the burden of combustion pollution to urban populations with greater density of vehicles - thus adding to the pollution burden for historically over-burdened communities. It is important that the full down-stream impact of any technology be understood in order to enable the state to effectively support those technologies which provide for the most equitable economic and environmental outcomes for the State and its populations.

6 Summary

Development and deployment of low-carbon and carbon-negative fuels can help the State of California increase the pace and scale of forest management and restoration efforts, build local capacity, strengthen regional collaboration, support innovation, and promote carbon storage in long-lived products, including geologically sequestered CO₂.

Previous researchers have focused on biomass logistics and supply chain in California and the potential to use this biomass in biofuels production, however the potential for hydrogen production using forest biomass has received scant scholarly attention. Nevertheless, the current state of knowledge in forest biofuels in the State of California is rapidly evolving. California is likely to have plentiful biomass resource from forest residues: total biomass availability in California for the year 2025 – estimated at 24 million tons per year – is sufficient to produce 1.7 million tons of hydrogen, or 85% of current State demand and 40% of future 2050 demand of 4 million tons hydrogen per year. Hydrogen production from California’s diverse biomass resource base can be accomplished with gasification, gasification with carbon capture and storage (CCS), and pyrolysis. The state could promote these efforts though increased investment in research and development.

Our economic analysis to evaluate the financial viability of producing renewable hydrogen and gasoline from forest residues, agricultural residues, and municipal solid waste (MSW) showed that each of these feedstocks can generate positive financial returns, in large part due to incentives available under policies like the Low Carbon Fuel Standard (LCFS). We also find that these financial returns can be substantially enhanced when coupled with carbon capture and storage (CCS). Forest-to-fuels pathways (internal rate of return (IRR) between 2-16%) are the least competitive biomass-based pathway option. As a result, it is unlikely that these pathways will be commercialized on par with agricultural residue (4-19%) and MSW (10-21%) pathways.

Leveraging the LCFS to provide additional support for forest-to-fuels pathway and ensuring that forest-to-fuels pathways can be coupled with CCS, are two key actions that could create a reliable market to sustain investments in forest biofuels in California. To build further knowledge in the

area of forest-to-fuels pathways, it is critical for the state agencies, technology providers, financiers, and industry stakeholders to engage in a dialogue which aims to address barriers in development and commercialization of forest biofuels in California. The most important unanswered questions arise in project finance, feedstock supply, supportive policy, infrastructure, social equity, and economic development.

Based on feedback from our working group, we believe the Joint Institute is most able to answer the following unresolved research questions:

- **[Policy]** What is the lifecycle greenhouse gas emissions profile of forest biomass to biofuels pathways in California? Can this be developed into a simplified calculator for adoption under CA-GREET?
- **[Policy]** What is the (quantified) CI and NPV impact of additional incentives, in the form of a credit carve-out or credit multiplier, on alternate forest biofuels pathways under the LCFS? What are the possible implications to the broader program if such additional incentives are adopted? Is there a possible exposure to interstate commerce clause obligations?
- **[Policy]** What is an alternative and contemporary interpretation of California's "areas at risk of wildfire" (for the purpose of Title 2, Subtitle A, Section 201 of the Energy Independence and Security Act of 2007) compared to an historic, and now arguably outdated quantitative assessment performed by University of Wisconsin-Madison in 2010 to inform the RFS program?
- **[Policy]** What are the public health implications to Californians of alternate forest biomass management strategies at the scale of treating one million acres per year?
- **[Policy]** What sequence of policy recommendations and commercialization roadmap could support the demonstration and deployment of carbon-negative forest biofuels pathways in California?
- **[Infrastructure]** What is the distribution cost for hydrogen blended into natural gas pipelines and how it compares to other distribution options? What are the necessary modifications to natural gas pipelines that would allow hydrogen blending at various percentages? What are the effect of various blend percentages on end-use equipment?
- **[Infrastructure]** How can we repurpose existing infrastructure and biopower facilities for forest biofuels production? How do siting decisions intersect with economic development and social equity? What are siting considerations based on (1) transport cost of supply and various offtakes (e.g., hydrogen) and (2) demand/supply?
- **[Equity and Development]** How can we understand the overlay of three factors: vulnerability to wildfire, economic resilience, and environmental burden associated with forest management and biofuels industries? At present, there are not useful tools which show us where to invest in forested areas with an equity and economic resilience lens.
- **[Equity and Development]** What are the fill distributional impacts of forest biofuel supply chains? For example, the use of biomass for liquid biofuel generation may have the impact of shifting the burden of combustion pollution to urban populations with greater density of vehicles - thus adding to the pollution burden for historically over-burdened communities.
- **[Feedstock]** Can FRAME entities provide enough contract stability to entice private lenders and equity investors for large-scale projects?
- **[Feedstock]** How will forest biomass best be combined with agricultural and urban wood waste in order to support these larger scale projects?

Finally, to encourage the consideration of environmental burden, economic impact, rural resilience, and wildfire vulnerability in future research, we propose five guiding principles:

1. Ensure that sustainable forest restoration, economic feasibility and environmental and social equity are weighted equally in recommendations.
2. Ensure rural, community-scale economic development alongside sustainable forest management.
3. Ensure source communities are beneficiaries of biofuels production and sustainable research management.
4. Ensure projects are compatible with surrounding land use and communities.
5. Enable restorative outcomes for under-resourced and under-served communities.

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