November 5, 2020

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Re: Feedback and Comments related to the Low Carbon Fuel Standard Public Workshop to Discuss Potential Regulation Revisions (October 14-15, 2020).

To the Air Resources Board team,

Thank you for the opportunity to provide feedback related to potential regulation revisions for the Low Carbon Fuel Standard (LCFS). **With this letter, we primarily aim to highlight recent research findings related to the mobilization of forest biomass residues to support California's forest health, wildfire risk reduction, and carbon sequestration goals, and how the LCFS could play an important role to support these goals.** We hope this letter can be informative for California Air Resources Board (CARB) staff as they explore potential revisions to the LCFS and would gladly provide further information on these recent research findings if this would be of interest.

This letter is composed of two key parts. First, we highlight California's recent commitments to increase the pace and scale of forest treatments, and the potential GHG emissions and air quality impacts that may result from these commitments. We highlight how CARB could overcome some of these impacts, as well as obtain significant emissions reductions through the displacement of fossil fuels, by prioritizing the development of competitive forest-to-fuels pathways under the LCFS. Second, we highlight the opportunity to obtain "negative emissions" by adding carbon capture and storage (CCS) as part of forest-to-fuels and other biomass-to-fuels pathways in California. Due to the state's large industrial and agricultural sectors, negative emissions will likely be an important strategy for California to compensate for hard-to-decarbonize sources and maintain a viable pathway to carbon neutrality by 2045.

The LCFS is a world-leading climate change mitigation program that has initiated the process of diversifying and growing the alternative fuels pool in California. We are strong supporters of the LCFS program, and believe that it is now time for the program to take next steps that are even more impactful. We stand ready to help CARB staff where it may be appropriate.

Kind Regards,

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If CARB staff are interested in further discussion or a briefing, please direct correspondence to Sam Uden (sam@csgcalifornia.com), who can also assist with coordinating the relevant researchers as part of this comment letter.

1. Potential GHG implications from California forest policy

California's commitment to treating one million forested acres per year for wildfire risk reduction will create substantial GHG emissions and air quality impacts unless a strategy is developed to ensure that forest biomass waste is collected and processed in a carbon-beneficial way. Our research shows that renewable liquid and gaseous transportation fuels are a promising option for biomass conversion based on commercial and technological readiness. CARB could prioritize the development of competitive forest-to-fuels pathways under the LCFS to support and enable this opportunity.

California's dense and overstocked forests, resulting from a century of fire suppression policies, is a key driver of recent catastrophic fire events[1]. In response, the state has set an aspirational goal to increase the pace and scale of forest treatments, including primarily thinning and prescribed fire fuels reduction treatments, to one million acres per year by 2025[2]. This presents a significant increase from current treatment levels, which are estimated to be 250,000 acres per year[3]. The goal of increasing forest treatments is to return California's forests to their healthy, resilient, and historical baseline.

One implication of increasing forest treatments is the potential for a substantial increase in GHG emissions, driven in large part by approaches to biomass waste disposal[4]. It is estimated that treating one million forested acres per year will result in 15 million new bone dry tons (BDTs) of forest residues per year, and *hundreds of millions* of new BDTs over a 20-year period (Figure 1)[5]. Currently, forest residues are commonly disposed of via open pile burning, resulting in significant GHG and PM 2.5 emissions, or are left to decompose in large piles on the forest floor. While this is already a problem today, to the extent California achieves its forest treatment goals, it presents a potentially significant GHG emissions problem going forward. It is true that increased forest treatments are anticipated to progressively reduce wildfire emissions and increase nature-based carbon storage, however, these carbon benefits are generally not anticipated to offset treatment-induced losses until *after* midcentury[6]. As a result, California's forests (and, by extension, Natural and Working Lands) will present a net source of GHG emissions on the 2045 time-scale; although these emissions can be minimized, and feasibly offset on a lifecycle basis, if a strategy to mobilize the biomass waste is developed.

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[1] Little Hoover Commission, 2018, "Fire on the Mountain: Rethinking Forest Management in the Sierra Nevada", https://lhc.ca.gov/sites/lhc.ca.gov/files/Reports/242/Report242.pdf; *See also* Kelsey, R (The Nature Conservancy), 2019, "Wildfires and Forest Resilience: the case for ecological forestry in the Sierra Nevada", https://www.scienceforconservation.org/assets/downloads/WildfireForestResilience_2019_Kelsey_2.pdf.

[2] "Agreement for Shared Stewardship of California's forest and rangelands", 2020, https://www.fs.usda.gov/sites/default/files/CA-Shared-Stewardship-MOU-8-12-20.pdf.

[3] Executive Order B-52-18, 2018, https://www.ca.gov/archive/gov39/wp-content/uploads/2018/05/5.10.18-Forest-EO.pdf.

[4] B. Cabiyo, J.S. Fried, B.M. Collins, B. Stewart, J. Wong, D.L. Sanchez, 2020, "Innovative wood use can enable carbon-beneficial forest management in California", *In Review at PNAS*.

[5] California has 33 million acres of forest. It is estimated that approximately half of these acres require multiple rounds of forest treatments. A 20-year period is therefore a reasonable (if not conservative) estimate of the amount of time California needs to be performing forest treatments at the scale of one million acres per year.

[6] Cabiyo et al. 2020.

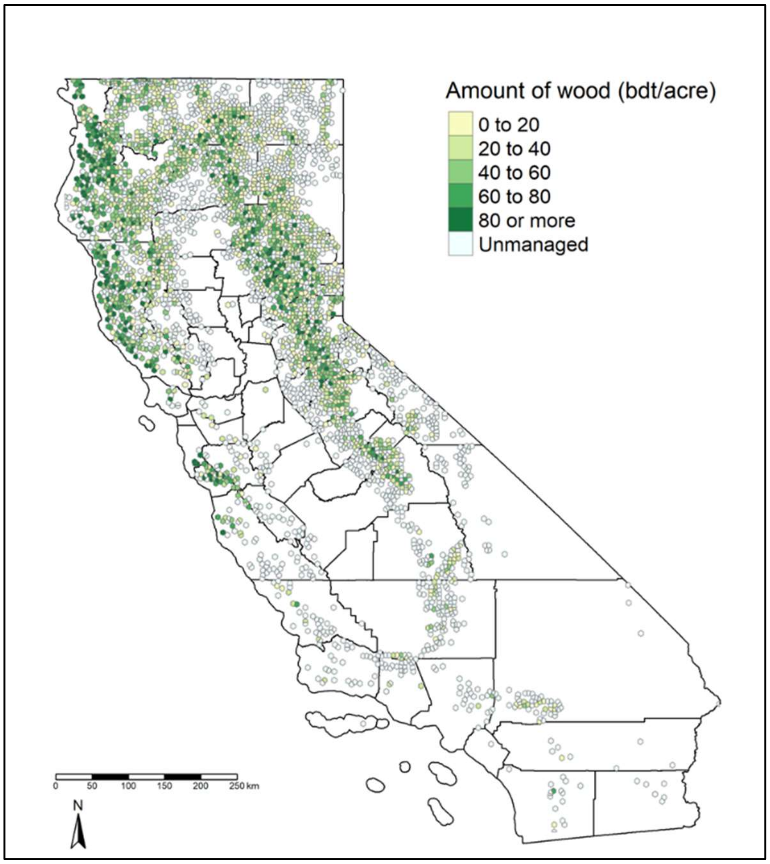

Figure 1: *This figure shows the results of BioSum modeling performed by Cabiyo et al. 2020. The authors modeled anticipated forest biomass removal volumes of treating one million acres per year over a 20-year period (i.e. Forest Carbon Plan implementation). The average removal volumes across all acres is 15 million BDTs/year.*

Recently, the Joint Institute for Wood Products Innovation (JIWPI), which is a research entity that sits within the Board of Forestry, completed a comprehensive assessment of options for converting forest residues into various wood products[7]. Converting forest residues into wood products presents an opportunity to avoid open pile burning and decomposition, and to realize carbon benefits. In addition, it also presents an opportunity to create an income stream to fund forest treatments. JIWPI found that the most promising wood product conversion option for small-diameter forest residues (such as those resulting from fuels reduction treatments), on the bases of commercial readiness and technological feasibility, are liquid and gaseous transportation fuels (biofuels). Biofuels can displace fossil fuels and, on a lifecycle basis, including estimates for changes in forest carbon stocks, minimize treatment-induced carbon losses and feasibly result in net-negative emissions on an annual basis by 2040[8,9]. In addition, biofuels are a highly valuable wood product, and could provide a strong income stream to support the

[7] Joint Institute for Wood Products Innovation, 2020, "Literature Review and Evaluation of Research Gaps to Support Wood Products Innovation", https://bof.fire.ca.gov/media/9688/full-12-a-jiwpi_formattedv12_3_05_2020.pdf.
[8] Cabiyo et al. 2020.
[9] We note how this solution can be enhanced even further with the addition of carbon capture and storage (CCS). We explore this further in the next section.

state's one million acres per year forest treatment goal[10]. Currently, it is not yet clear how the state intends to fund this forest treatment goal, which we estimate will cost at least $2 billion per year[11]. In 2019-20 budget, California appropriated only $200 million towards forest health and fire prevention[12]. with more and more funds having to be redirected towards fire-fighting each year. Developing a strategy to pay for forest treatments to reduce wildfire, while not CARB's responsibility, is a crucial task for the state[13].

If CARB develops a forest-to-fuels pathway under the LCFS, it could potentially address a number of key challenges. For one, it could provide financial support for expensive forest treatments, which can serve to progressively reduce wildfire and increase nature-based carbon storage overtime. In addition, it could turn what would otherwise be a substantial carbon problem (presented by the increasing amounts of forest biomass waste) into a carbon solution for the purpose of achieving 2045 carbon neutrality. Finally, CARB would be adopting a substantial leadership role in terms of addressing what is one of California's major public health and safety challenges, which is the threat of catastrophic wildfire.

CARB might also consider additional options to ensure forest-to-fuels pathways are competitive, so that developers have sufficient incentives to pursue these pathways alongside alternatives (e.g. agricultural waste[14]), where feedstock costs are lower. Given the broader social benefits on offer (i.e. wildfire risk reduction) which are not easily captured by the market, it seems reasonable that the state might adopt additional incentives on this basis for forest-to-fuels pathways[15]. Below we've outlined a number of ideas for CARB's consideration. We provide these ideas primarily to stimulate discussion, and would welcome the opportunity to explore these further with CARB[16]:

- Ensure forest pathways account for the full emissions profile of woody biomass utilization pathways, including avoided emissions from the counterfactual fate of feedstocks:
    - It is not possible to assign a robust carbon intensity (CI) to fuel derived from forest residues without accounting for the counterfactual fate of those residues. That fate is a combination of prescribed burn, decay, and exposure to wildfire.
    - Emissions from each of these are variable by species, residue type, and climatic characteristics, and CI calculations must account for this variation to avoid failing to capture potential benefit or creating an incentive for detrimental activities.

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[10] Preliminary estimates indicate that, for an nth-scale plant, converting forest residues into renewable hydrogen (wholesale revenue + LCFS credits) could support a feedstock cost of greater than $70/BDT. Adding CCS could support a feedstock cost of greater than $100/BDT. At 15 BDTs/acre, a hydrogen+CCS pathway could feasibly generate $100/BDT * 15 BDTs/acre = $1,500/acre in revenue to support forest health and wildfire risk reduction treatments. Daniel Sanchez and Haris Gilani (UC Berkeley) are currently developing a discounted cash flow analysis which evaluates these potentials more fully, including for smaller gasification/pyrolysis plant sizes. It is anticipated that this analysis will be completed by 30 November, 2020.

[11] Assuming it costs $2,000 to treat one acre: $2,000 * 1,000,000 acres = $2 billion.

[12] California State Budget 2019-20, http://www.ebudget.ca.gov/2019-20/pdf/Enacted/BudgetSummary/FullBudgetSummary.pdf.

[13] Public Policy Institute of California, 2020, "Paying for forest health projects", https://www.ppic.org/blog/paying-for-forest-health-projects/?utm_source=rss&utm_medium=rss&utm_campaign=paying-for-forest-health-projects?utm_source=ppic&utm_medium=email&utm_campaign=blog_subscriber.

[14] In this case we are referring to woody agricultural waste that is usually regularly harvested, like almond trees.

[15] Conceptually, CARB adopted this same policy prioritization approach for hydrogen via fueling infrastructure capacity credits.

[16] For a more comprehensive summary of ideas, see Appendix A: Fingerman et al., 2020, "Policy Options for Deep Decarbonization and Wood Utilization in California's Low Carbon Fuel Standard".

    - The California Biopower Emissions Characterization (C-BREC) model, developed through a $1 million Electric Program Investment Charge (EPIC) grant, robustly characterizes these variable impacts and could be a useful tool in establishing CI values for fuels from woody residues.
- Create additional, targeted incentives for woody biomass residuals from forest management activities as appropriate, such as:
    - Volumetric carve-outs: For example, blenders must procure a certain portion of their fuel from woody forest biomass;
    - Co-benefits recognition: For example, additional credit is provided on the basis of air quality benefits and/or wildfire risk reduction.

CARB, in partnership with other agencies, will need to develop strong environmental safeguards as the cornerstone of competitive forest-to-fuels pathways. CARB might consider qualification requirements such as chain-of-custody certifications, or integrated resource planning to ensure that forest biomass is utilized at an appropriate scale. These are just two ways in which CARB can prevent LCFS incentives being available to potential bad actors, especially out-of-state fuel providers. CARB could also feasibly develop its own standards which set a strong environmental benchmark and clear guidelines for potential applicants.

In summary, our research has highlighted the importance of mobilizing forest residues to reduce potential GHG emissions from business-as-usual biomass disposal options, as well as to provide an income stream to support the state's ambitious forest treatment goals. While CARB might otherwise be the unfortunate recipient of these GHG emissions challenges, with the LCFS as an available policy tool, CARB has an opportunity to preempt these emissions impacts. CARB could develop competitive forest-to-fuels pathways under the LCFS, and aim to promote and expand these pathways over time. This is an important first step for California to begin to navigate the complex forest-wildfire-climate challenge.

2. Opportunity to achieve negative emissions for carbon neutrality

In a landmark report released in January 2020, Lawrence Livermore National Laboratory (LLNL) and its partners highlighted how California could cost-effectively obtain 125 Mt of negative emissions to achieve carbon neutrality by 2045[17]. Approximately two-thirds of this solution comes from BECCS opportunities: with the state's vast forest, agricultural, and municipal solid waste streams converted into biofuels with CCS. In addition to supporting the mobilization of forest waste, CARB could also seek to provide increased incentives for negative emissions pathways under the LCFS to achieve 2045 carbon neutrality goals.

Negative emissions refer to the physical removal of carbon dioxide from the atmosphere[18]. There is a limited number of ways to obtain negative emissions. In general, there are three key strategies: nature-based solutions (e.g. reforestation/afforestation); conversion of waste biomass to transportation fuels with CCS (BECCS); or DAC with carbon storage (DACCS). In their report, *Getting to Neutral: Options for Negative Carbon Emissions in California*, LLNL explored California's potential to achieve negative emissions via each of these strategies[19]. LLNL found that California could theoretically obtain 125 Mt of negative emissions, which, based on current GHG emissions reduction projections, would enable California to achieve carbon neutrality by 2045.

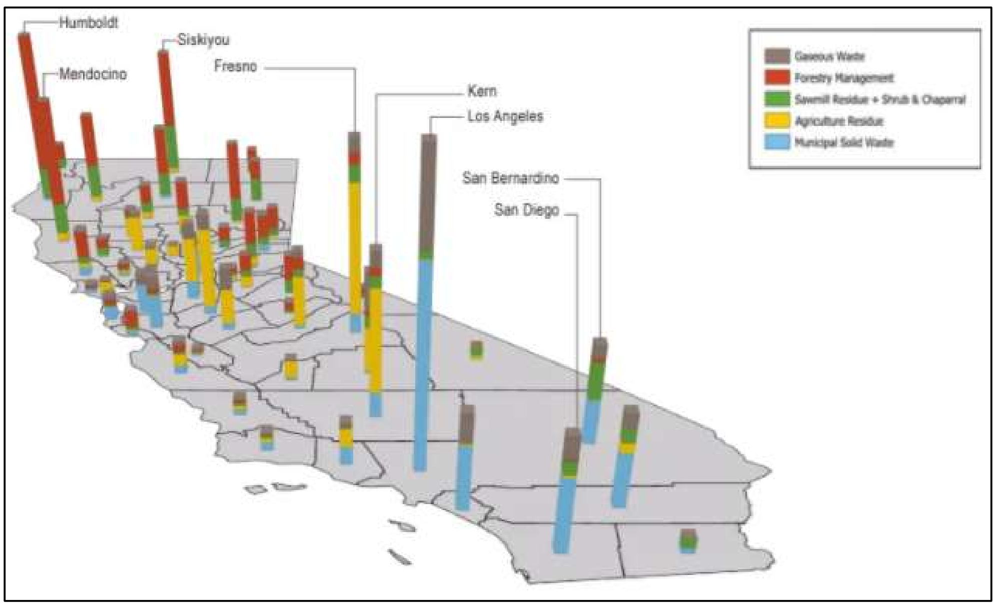

Figure 3: *This figure highlights California's significant biomass waste resources on a per-county basis. Significant volumes of forest waste are available in Northern California, while the Central Valley provides a lot of agricultural waste, and Southern California provides substantial municipal solid waste.*

[17] LLNL, 2020, "Getting to Neutral: Options for Negative Carbon Emissions in California", https://www-gs.llnl.gov/content/assets/docs/energy/Getting_to_Neutral.pdf.

[18] Note that this is different to the "net-negative" reference in the previous section, which referred to the situation where avoided emissions (i.e. biofuels offsetting fossil fuels) outweigh total GHG emissions from lifecycle forest treatment effects. Net-negative emissions are effectively GHG emissions reductions. "Negative emissions" here refers to when CO_2 is directly removed from the atmosphere, such as via vegetation or man-made machines, and prevented from returning into the atmosphere. Both GHG emissions reductions and negative emissions achieve climate change mitigation.

[19] For further information, see: https://www-gs.llnl.gov/content/assets/docs/energy/Getting_to_Neutral.pdf.

The most significant opportunity highlighted by LLNL for California to obtain negative emissions is conversion of waste biomass to transportation fuels. By diverting forest, agricultural, and municipal biomass waste streams in the state that would otherwise be pile burned, landfilled or left to decompose into the production of biofuels with CCS, California could obtain 84 Mt of negative emissions (Figures 3 and 4). Forest waste, consisting primarily of the byproducts of the treatments we describe above, presents the most significant opportunity, accounting for approximately half of this total 84 Mt, and also yielding the co-benefits described above, including wildfire risk reduction, air quality benefits, and more.

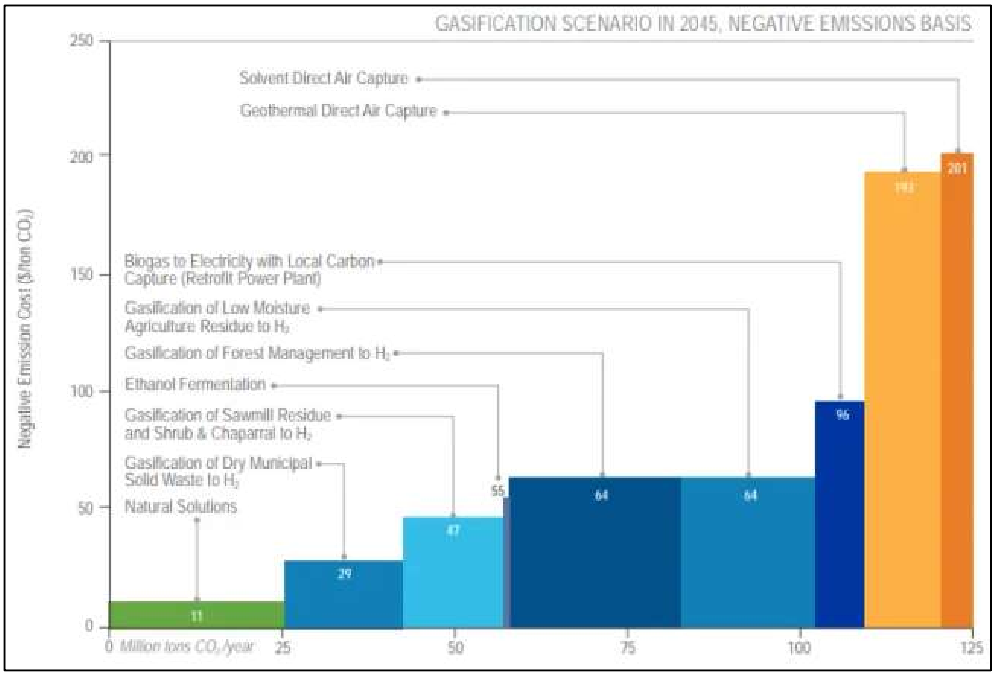

Figure 4: *This figure presents a marginal abatement cost curve (MACC) of negative emissions options for California. Nature-based solutions are highlighted in green, BECCS in blue, and DACCS in orange.*

CARB could consider added incentives under the LCFS to support negative emissions pathways. As a market-based tool, the LCFS is designed to deliver the cheapest CI reductions in the transportation fuel system. This is an efficient outcome, but may come at the expense of promoting technologies that would be poised to offer *deeper* decarbonization, such as negative emissions fuel pathways. Given the importance of achieving negative emissions to achieve carbon neutrality by 2045, one option that CARB could consider is to provide a **credit multiplier** for either negative CI or negative emissions fuel pathways. This credit multiplier could be applied on a sliding scale, so that the deeper the negative, the greater the incentive. Figure 5 provides an illustrative take on this idea.

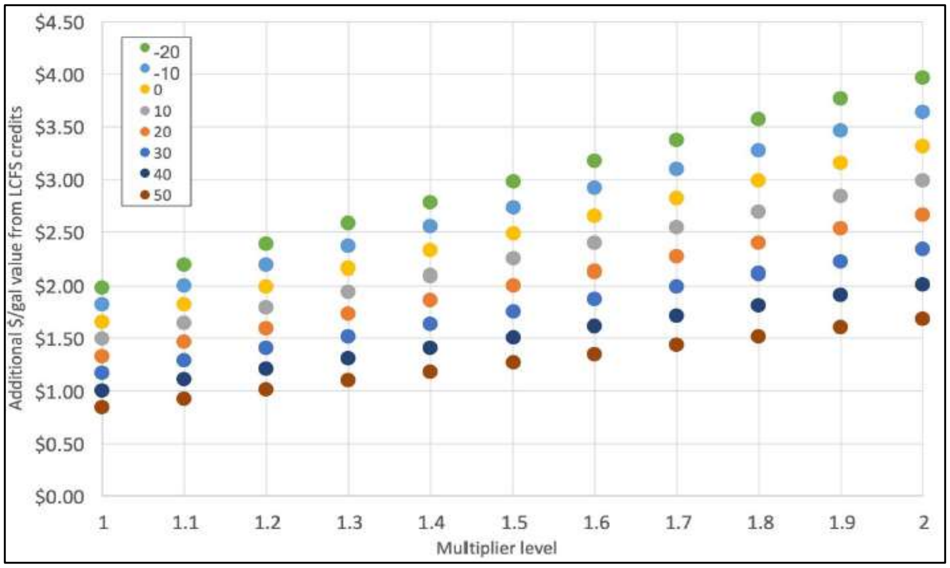

Figure 5: *This figure provides an illustration only of how a negative CI credit multiplier on a sliding scale could function.*

Applying CCS on biofuels production can substantially enhance the carbon benefit provided by mobilizing biomass waste, and catapult California towards its 2045 carbon neutrality goal. While each of forest, agricultural, and municipal solid waste streams can provide a pathway to negative emissions, we believe that demonstrating the forest-to-fuels with CCS pathway is vital. This is because forest waste is the most abundant feedstock in the state, but also the hardest to collect. It is important that sufficient incentives are in place for project developers to action this opportunity. Between targeted incentives to mobilize forest waste, and incentives to support negative emissions, the LCFS can support this idea.

Appendix A

Find attached: Memorandum prepared by K. Fingerman, D. Sanchez, C Herbert, 2020, “Policy Options for Deep Decarbonization and Wood Utilization in California’s Low Carbon Fuel Standard”.

Policy Options for Deep Decarbonization and Wood Utilization in California's Low Carbon Fuel Standard

February 19, 2020

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Executive Summary

California's Low Carbon Fuel Standard (LCFS) is designed to deliver the cheapest carbon intensity (CI) reductions possible in the transportation fuel system. This is an efficient outcome but may come at the expense of promoting technologies that would be poised to offer *deeper* decarbonization or other ancillary benefits to California's people and environment. This report contemplates how the LCFS might be administered to further stimulate the commercialization of promising low-carbon and carbon-negative fuels. To do so, we examine promising technical pathways, their barriers to commercialization, and recent administrative actions by the CA Air Resources Board (ARB) under the LCFS to promote novel lower-carbon fuels. We propose several actions that ARB could undertake to promote commercialization within existing authorities.

Numerous fuel pathways could satisfy California's demand for low-carbon and carbon-negative fuels. Notable pathways include:

Biofuels from Forest Residues, including biofuels with CCS. Low-carbon and carbon-negative fuels derived from non-merchantable forest biomass ("forest residues") 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. Targeted mobilization of non-merchantable woody biomass could reduce catastrophic wildfire, promote sustainable forest practices, and improve air quality in California.

Low-carbon fuels from Direct Air Capture. In addition to biomass-based processes, it is possible to create low-carbon and carbon-negative fuels using CO_2 captured directly from the air. These processes integrate direct air capture (DAC) technologies. The US National Academy of Sciences recently reported the levelized costs of DAC to be uneconomical in current policy environments. Despite their immaturity, two pathways have been proposed for low-carbon and carbon-negative transportation fuels based on DAC. Notably, Carbon Engineering and Occidental Petroleum have both signaled that the LCFS will be driver for DAC-EOR projects.

Despite the large financial incentives for low-carbon and carbon-negative fuels in California, these fuels may require additional support to be successfully commercialized.

Through examination of academic literature, recent operating experience, and interviews with entrepreneurs, we identify the following reasons for this outcome:

1. **Low technical and commercial maturity**
2. **High capital costs.** Low-carbon and carbon-negative fuels facilities have capital costs ranging from several hundreds of millions to billions of dollars.
3. **Feedstock supply uncertainty for forest biomass**, including
    a. Lack of access to long-term wood supply
    b. Dramatic supply variability from year to year
    c. High cost compared to other sources of biomass given its sourcing from remote, dispersed, and difficult to access landscapes
4. **Stability** of revenues given policy uncertainty in the LCFS
5. **Permitting challenges**, many of which are outside of the scope of the LCFS, but within the purview of the Air Resources Board and CalEPA

Prior administrative changes to the LCFS have ensured that California can meet climate policy goals and remain on the path to carbon neutrality.

In 2018, CARB board members amended the LCFS to broaden the program's focus and move closer to a negative emissions goal. Taking effect January 1, 2019, the re-adoption of LCFS extended the program to 2030 with a targeted 20 percent decrease in average fuel carbon intensity (AFCI) from 2010 levels. The re-adoption expanded credit generating opportunities to include non-alternative fuel pathway crediting, encompassing Carbon Capture and Sequestration (CCS), low-carbon electricity generation, and infrastructure deployment for Zero Emissions Vehicles. The decision to extend the market to 2030 signaled CARB's commitment to LCFS, and the market has priced in this certainty.

There is a precedent for using LCFS credits to incentivize activities not strictly within the bounds of the LCFS market. For example, the allocation of credits for hydrogen fueling and fast EV charging infrastructure on a capacity rather than a delivery basis enables ARB to leverage the LCFS program to achieve broader ZEV goals. Further, the requirement that utilities invest their holdback credits in ZEV purchase rebates and fueling infrastructure in disadvantaged communities is another example of leveraging the LCFS system to achieve broader state goals.

To commercialize low-carbon and carbon negative fuels—including those derived from forest residue feedstocks—the Air Resources Board could consider numerous administrative actions within the LCFS

Ensure that the LCFS accurately accounts for the emissions benefits offered by every fuel pathway, including avoided emissions from the counterfactual fate of feedstocks. Many forest-to-fuels pathways may be competitive within the LCFS system if properly credited for the emissions avoided. Several parameters should be taken into consideration here:

- Ensure that C accounting takes into account counterfactual emissions including avoided emissions of methane from biomass decomposition and combustion in either prescribed burns or wildfire.
- Reduce key uncertainties in fuel CI by pursuing targeted research to improve empirical evidence where it is lacking, and using revised estimates to better parameterize LCAs.

Update global warming potential values used for calculating fuel CI. Updating to the more recent AR5 global warming potentials would mean crediting avoided methane 30:1 using the 100-year values and 85:1 over 20 years, thereby improving the calculated CI of fuels offering significant avoided methane emissions. This change would raise some interesting and important issues:

- It would affect the CI of every fuel in the LCFS system, including the petroleum baseline fuels and would also bring the LCFS out of step with other carbon accounting systems at use in the state.
- This disruption could be minimized by allowing operators to opt into updating their pathways to reflect new GWP values.
- Consideration of 20-year GWP values raises some larger questions of climate policy in the state and the relevant timelines for action.

Create additional, targeted incentives for very low-C fuels or those offering priority ancillary benefits. The LCFS is structured to deliver fuel CI reduction as efficiently as possible, and it is doing this well. However, its design only enables it to deliver the least expensive near-term mitigation, so it may not optimally promote deeper decarbonization technologies. Furthermore, its robust market and high carbon price could be leveraged to simultaneously deliver *other* state goals such as fire risk reduction, air quality improvement, or development of CCS technology. Such an incentive could take several forms within the LCFS system:

- A volumetric technology carve-out could be applied to a target fuel, such as one achieving a very low or negative CI score or one made from biomass that would otherwise have been burned in the field, leading to significant air quality impairments. A carve-out could require blenders to procure some fraction of their fuel from that source (or pay someone else to do so). Similar carve-outs are commonly used in RPS policies to deliver priority goals. While policy design for this carve-out requires future work, estimation of the following parameters would help ensure that this policy has its intended impact:

    a. Volume of fuels available
    b. Time frame for commercialization
    c. Phase out, based on expected facility lifetimes

  The key challenge posed in this case is that such a “quantity” measure does not control cost. If a very small set of facilities are able to produce qualifying fuel, the cost of these credits could rise rapidly. A carve-out could be more appropriate once the industries in question have matured in order to use the LCFS system to drive further commercialization of already proven and operational technologies.

- **A credit multiplier** would deliver a similar stimulous to targeted fuel types. If a certain type of fuel or feedstock source is found to deliver priority goals, this mechanism would offer additional LCFS credits to manufacturers of that fuel. Specific multiplier values would be determined based on current market conditions and cost of production.
- **A credit multiplier could also be applied on a sliding scale** based on CI score to further incentivize very low carbon fuels.

Specifically target woody biomass residuals with the added incentives discussed above. Making fuels from woody residuals of forest management activities in California can in many cases offer climate, fire risk, and/or air quality benefits when compared to the alternative fate of those same materials. In particular, it is very clear that mobilizing woody biomass that would otherwise be burned in open piles leads to a significant reduction in health-harming particulate emissions. As a result, ARB should consider offering targeted incentives for fuel pathways making use of woody residuals from fire management or forest restoration activities, especially where this means diverting woody residues that would otherwise have been burned in nonattainment airsheds and/or those near disadvantaged communities.

Similarly, ARB could consider **modifications to the structure of the price ceiling within the Credit Clearance Market to promote production of very-low CI fuels.** Where the current mechanism borrows future credits to maintain its price ceiling while promoting EV uptake, the same type of system could be used to promote very low-carbon fuels or those diverting residues from sustainable forestry by allocating some LCFS credit revenue up-front to enable facility construction.

Extending the 2019 amendments to the LCFS would offer needed policy certainty to drive significant investment in the alternative fuels space. In particular, ARB could extend the policy to 2040 or beyond with further signals of increased target stringency. The 2019 amendments solidified CARB’s commitment to the LCFS, and a 20 year policy runway would facilitate the industrial development necessary in this low carbon fuels space.

Make sure that the LCFS is stimulating only the best performing fuels across a variety of parameters. Concerns abound regarding bioenergy feedstock sourcing and its impacts on ecosystems, biodiversity, water resources, soil erosion, and other metrics of concern. Safeguards should be put into place to avoid perverse outcomes from these policy supports. Examples could include:

- Specific geographic or ecologically-driven feedstock sourcing restrictions, constraining support schemes to other targeted feedstock types or locations rather than the easiest-to-access woody biomass.
- Limitations to residue removal and requirement of forestry best practices to ensure that ecosystem integrity and soil structure are not compromised.
- Consider third-party certification by entities such as the Forest Stewardship Council and the Roundtable on Sustainable Biomaterials to ensure best practices are followed in feedstock sourcing.

1. Deep Decarbonization and California's Low Carbon Fuel Standard

California's Low Carbon Fuel Standard (LCFS) is one of the most important policies to develop low-carbon and carbon-negative fuels. The year 2019 saw the announcement of numerous commercial-scale cellulosic biofuel, bioenergy with carbon capture and sequestration (BECCS), and direct air capture (DAC) projects, many of which explicitly cited revenues from CA's LCFS as a motivation.[1] These fuels play a pivotal role in California, national, and international action to address climate change.[2] Yet successful commercialization of low-carbon and carbon-negative fuels is far from certain, despite policy support from the LCFS. Commercial-scale cellulosic biofuels, for instance, have faced several high-profile failures in recent years. Further, negative emissions technologies face both technical and commercial immaturity. Without changes to the LCFS, these promising technologies might be locked out by more established and cheaper alternatives.

The transportation sector represents 41% of total GHG emissions in California, and recently surpassed electric power to become the largest emissions sector nationwide.[3] This is because emissions from electric power generation, long the most significant sector, are comparatively easy and inexpensive to reduce. Emissions reductions from transport, on the other hand, are comparatively challenging to achieve. Necessary change in this sector is inhibited by market barriers such as technology lock-in, the low price elasticity of fuel demand, and the need for coordination among fuel producers, distributors, and consumers. Furthermore, the marginal abatement cost of transportation emission reductions—especially through fuel switching—is comparatively high, meaning an economy-wide carbon price, while an economically efficient approach to emission abatement, is unlikely to achieve significant near-term reductions from transport at politically-acceptable carbon prices.[4,5] U.S. government analysis of the American

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[3] California Air Resources Board. (2019). California Greenhouse Gas Emissions for 2000 to 2017. https://ww3.arb.ca.gov/cc/inventory/pubs/reports/2000_2017/ghg_inventory_trends_00-17.pdf

[4] Lutsey, N., Sperling, D. (2009). Greenhouse gas mitigation supply curve for the United States for transport versus other sectors. Transp. Res. Part Transp. Environ. 14, 222–229.

[5] van der Zwaan, B., Keppo, I., Johnsson, F., 2013. How to decarbonize the transport sector? Energy Policy 61, 562–573.

Clean Energy and Security Act of 2009 determined that its proposed nationwide GHG emissions trading scheme would generate almost no emission abatement from the transport sector, leading transport to account for over 50% of total emissions nationwide in 2050.[6]

The above challenges in spurring emission reductions from transportation fuel switching are the reason the LCFS is necessary. The current credit price on the CA C&T system is $17 where the market clearing price for LCFS credits in January 2020 was $200 per metric ton[7] and could well have been higher if not for cost-containment measures imposed by ARB. This implies that the changes being spurred by the LCFS would indeed not come about through the economy-wide carbon price alone. The LCFS and other sector-specific policies are necessary to spur the development of technologies and markets that will ultimately be necessary for the deeper emissions cuts that will get us to 2030, 2040, and 2050 targets. As has been shown before in the renewable energy space, these near-term costs can ultimately stimulate technology development leading to cost reductions such that these targeted policies are no longer needed. One key element in the pursuit of deep emissions cuts from transportation will be the deployment of low-carbon alternative fuels, an outcome that is the direct target and result of California's LCFS.

The authors Vogt-Schilb and Hallegatte described this challenge as a conflict between what they refer to as "cheap" and "deep" abatement options.[8] A carbon price will typically deliver the cheapest mitigation. However, as the authors point out *"the measures required to achieve ambitious emission reductions cannot be implemented overnight, the optimal strategy to reach a short-term target depends on longer-term targets. For instance, the best strategy to achieve Europe's -20% by 2020 target may be to implement some expensive, high-potential, and long-to-implement options required to meet the -75% by 2050 target. Using just the cheapest abatement options to meet the 2020 target can create carbon-intensive lock-in and make the 2050 target too expensive to reach."* **This is the reason the LCFS exists at all; it will help spur early action on deeper abatement pathways that will be necessary in the long run.**

However, this problem also exists *within* the LCFS ecosystem, as that system is also designed to deliver the cheapest fuel carbon intensity reductions possible.

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[6] U.S. EPA. (2010). Supplemental EPA Analysis of the American Clean Energy and Security Act of 2009 H.R. 2454 in the 111th Congress. Office of Atmospheric Programs, U.S. Environmental Protection Agency, Washington, D.C.

[7] California Air and Resources Board. (2019). CA-QC Joint Auction Summary Results Report. https://ww3.arb.ca.gov/cc/capandtrade/auction/nov-2019/summary_results_report.pdf; California Air and Resources Board (2020). Weekly LCFS Credit Transfer Activity Report, https://ww3.arb.ca.gov/fuels/lcfs/credit/lrtweeklycreditreports.htm

[8] Vogt-Schilb, A., Hallegatte, S., 2014. Marginal abatement cost curves and the optimal timing of mitigation measures. Energy Policy 66, 645–653.

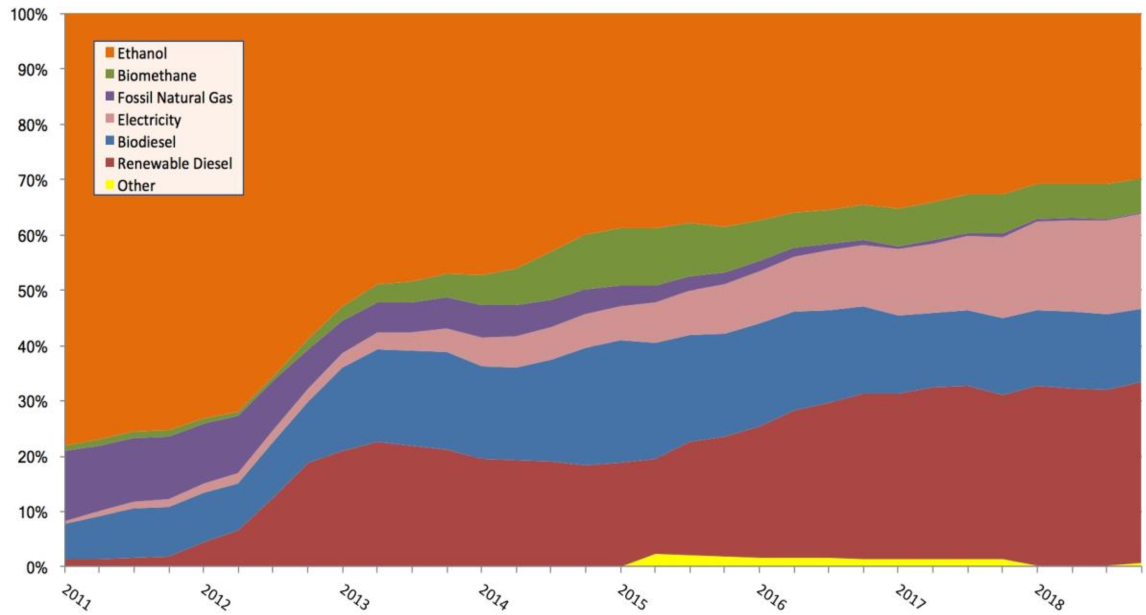

Figure 1: Yearly rolling average percentage of credits by fuel type from Q1 2011 to quarter 3 (Q3) 2019. Total credits generated grew more than 10-fold over this period from 328,000 metric tons in quarterly in 2011 to 3.48 million metric tons quarterly.[9]

Just as we need the LCFS policy to stimulate action in the transportation fuels space - action that will eventually be necessary to reach deep mitigation targets, we may also need action within the LCFS system to spur development of technologies capable of deeper mitigation than those that are emerging naturally from the LCFS carbon market. It is also worth considering whether the LCFS can be leveraged to achieve broader state goals beyond only fuel CI reduction.

Put more plainly, the LCFS has not yet led to wide-scale commercialization of cellulosic biofuels. Instead, early targets were met by blending conventional crop-based biofuels that were able to deliver 1-5% average fuel CI reductions but do not have a low enough carbon footprint to contribute to reaching a 10-20% targets. Compliance has shifted to lower carbon fuels such as biodiesel and renewable diesel from recycled vegetable oils, but these are supply-limited, hampering their ability to drive deep decarbonization.[10] As demand for these costly fuels has increased, credit prices have risen dramatically.

[9] California Air Resources Board. (2020). *Low Carbon Fuel Standard Reporting Tool Quarterly Summaries*. https://ww3.arb.ca.gov/fuels/lcfs/lrtqsummaries.htm

[10] Christensen, A. & Hobbs, B. (2016). *A model of state and federal biofuel policy: Feasibility assessment of the California Low Carbon Fuel Standard.* Applied Energy. https://doi.org/10.1016/j.apenergy.2016.01.121

2. The low-carbon fuel landscape in California

California has numerous commercial-scale low-carbon and carbon-negative fuels production facilities in various stages of development (Table 1). We break these here into two major categories: those making biofuels from very low carbon biomass feedstocks—especially residues from sustainable forest management—and those using direct air capture or other carbon capture and sequestration (CCS) technologies to make low carbon and carbon-negative fuels.

Table 1: Characterization of low-carbon and carbon-negative pathways proposed in California.

Product	**Feedstock required**	**Example**	**Carbon removal**	**TRL**[i] (1-9)	**CRL**[ii] (1-9)	**Project location**	**Capital cost** ($ million)
Biofuels from woody biomass, including biofuels with CCS							
Fischer-Tropsch Fuels	68,000 (BDT/year)	Red Rock Biofuels	Possible (CCS)	7	6-7	Lakeview, OR	>200[11]
Gas Fermentation	133,000 (BDT/year)	Aemetis Inc.	No	8	6	Riverbank, CA	158[12]
Fast Pyrolysis and Hydroprocessing	300,000 (BDT/year)	SPI Camino site	Yes (char)	6	5	Camino, CA	429[13]
Lignocellulosic Ethanol	100,000 (BDT/year)	Axens/ Anderson Biomass	Possible (CCS)	8	6	Anderson, CA	Unknown
Renewable Natural Gas	250,000 (BDT/year)	GTI Stockton	Possible (CCS)	6	5	Stockton, CA	340[14]

[11] Dihn, M. & Manternach, J. (2019). DOE Bioenergy Technologies Office 2019 Project Peer Review. Red Rock Biofuels. [Powerpoint Slides] Retrieved from: https://www.energy.gov/sites/prod/files/2019/04/f61/Woody%20Biomass%20Biorefinery%20Capability%20Development_EE000DPA2.pdf

[12] Lane, J. (2018). Commercial time: Aemetis embarks on $158 million cellulosic ethanol project in California. Biofuels Digest. https://www.biofuelsdigest.com/bdigest/2018/03/08/commercial-time-aemetis-embarks-on-158-million-cellulosic-ethanol-project-in-california/

[13] Estimated at commercial scale of 2000 tons/day, in Brown, T., Thilakaratne, R., Brown, R.C., Hu, G. (2013). Techno-economic analysis of biomass to transportation fuels and electricity via fast pyrolysis and hydroprocessing. Fuel. https://lib.dr.iastate.edu/cgi/viewcontent.cgi?article=1052&context=imse_pubs

[14] Gas Technology Institute (GTI). (2019). *Low-Carbon Renewable Natural Gas (RNG) from Wood Wastes*. Retrieved from https://www.gti.energy/wp-content/uploads/2019/02/Low-Carbon-Renewable-Natural-Gas-RNG-from-Wood-Wastes-Final-Report-Feb2019.pdf

Renewable Hydrogen	45,000 (BDT/year)	Clean Energy Systems	Possible (CCS)	5	5	Kimberlina, CA	>100
			Low-carbon fuels from Direct Air Capture				
DAC Electrofuels	Unknown	N/A	No	5	3	N/A	N/A
DAC - EOR	500,000 (tCO_2/yr stored)	Carbon Engineering + Occidental Petroleum	Possible	6	6	West Texas	~500[15]

i: Technology Readiness Level
ii: Commercial Readiness Level

2.1. The forest/fuel nexus in California

California's forest management crisis has important implications for public safety, biodiversity conservation, water resource management, air quality, climate change, and the state's economy[16]. Wildfires in California during the 2018 fire season released about 68 million tons of CO_2 equivalent (US Department of the Interior, 2018). This accounts for 15% of California's total carbon footprint and is comparable in magnitude to emissions from the state's electricity generation in the same year. The 2018 Camp Fire alone is estimated to have cost $16.5 billion in economic losses.[17]

Because of these cross-cutting impacts, especially in the wake of two years of severe wildfires, significant political will and economic resources are now being mobilized in Sacramento to promote sustainable management of California's forests. Historically, restoration treatments have been "carried" economically by the concurrent harvest of merchantable sawlogs as part of the management plan. Where this is not feasible, other sources of funding must be applied to support forest management. Forest restoration and fire management activities typically cost between $500 and $2000 per acre treated[18].

[15] Estimate based on 500,000 tCO2/yr capacity and capital costs given in: Keith, D. W., Holmes, G., Angelo, D. S., & Heidel, K. (2018).
[16] Little Hoover Commission. (2018). *Fire on the Mountain: Rethinking Forest Management in the Sierra Nevada*. Report #242, https://lhc.ca.gov/sites/lhc.ca.gov/files/Reports/242/Report242.pdf
[17] Löw, P. (2019). *The natural disasters of 2018 in figures: Losses in 2018 dominated by wildfires and tropical storms*. Munich RE. *https://www.munichre.com/topics-online/en/climate-change-and-natural-disasters/natural-disasters/the-natural-disasters-of-2018-in-figures.html*
[18] Sierra Institute. (2019). *Paying for Forest Health: Improving the Economics of Forest Restoration and Biomass Power in California.* Produced under California Energy Commission contract EPC-16-047.

Recent research by the Board of Forestry's Joint Institute for Wood Products Innovation has found that the LCFS could be an important source of revenue for forest restoration in California.[19] In short, innovative wood products, including low-carbon and carbon-negative fuels, hold the potential to support carbon-beneficial, sustainable forest management in California. Innovative wood products can support the state of California in increasing the pace and scale of forest management and restoration efforts, building local capacity, strengthening regional collaboration, supporting innovation, and promoting carbon storage.

Modeling work performed by Dr. Sanchez's research group at the University of California-Berkeley indicates that increased delivered feedstock prices can drive increased production and delivery of wood chips that would otherwise be left in the forest. At the same time, increased chip price does not drive large increases in merchantable wood production. These results indicate that increased revenues can promote residue mobilization from the forest (Figure 2).

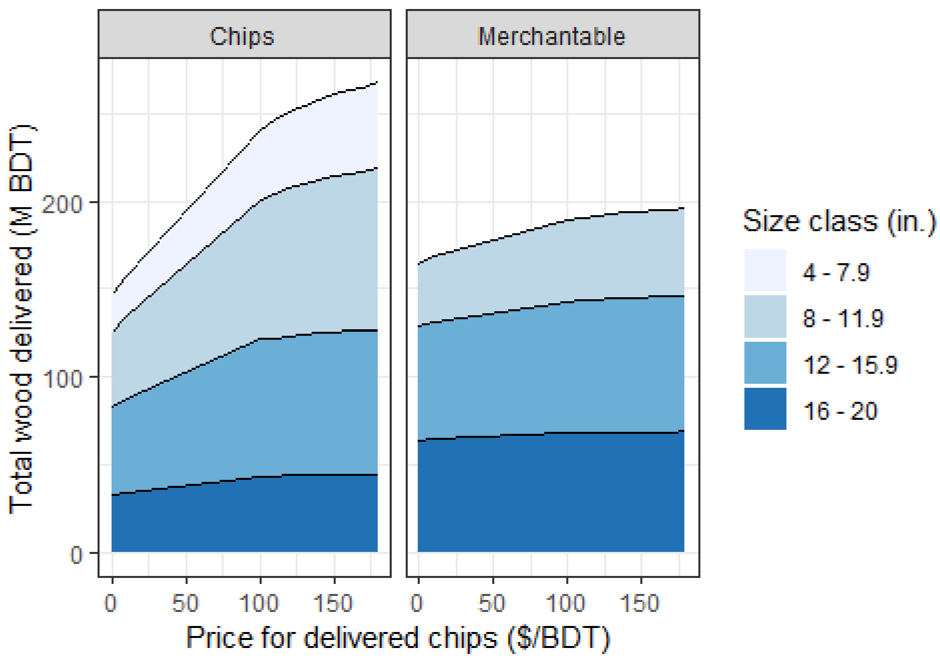

Figure 2: Modeled residue mobilization volumes at varying delivered chip prices. Figure from Cabiyo et al. (Manuscript in Preparation).

In Annex 1, we briefly review promising technologies for gaseous and liquid fuels production from forest biomass. We focus on proposed commercial-scale facilities that employ these technologies in or near California, their commercial and technical readiness, and ability to produce net-negative emissions. Readers seeking more information are directed towards the draft Joint Institute report.[20] It is important to note that most of these technologies can employ woody agricultural biomass, such as orchard and vineyard wastes, in addition to forest biomass. Agricultural biomass has numerous economic and logistical advantages over forest biomass: it

[19] Sanchez, D., et al. (2020). *Joint Institute for Wood Products Innovation: Evaluation of Literature,Research Gaps, Partnerships, and Priorities.* Board of Forestry and Fire Prevention. https://bof.fire.ca.gov/media/9512/1-draft_jiwpi-report_152020_ada.pdf
[20] Sanchez, D., et al. (2020)

is often cheaper, closer to existing infrastructure, and co-located with suitable geology for geologic CO_2 sequestration.

The air quality benefit of diverting otherwise-burned biomass

From 2005-2012, open burning of agricultural residue in the San Joaquin Valley had been reduced by over 80%, but drought and the shutdown of six biopower facilities in the region led to a significant increase in open burning, bringing it back above 2005 levels. Most of this increase is from open burning of biomass from pruning and removal of orchard trees. Under business-as-usual projections, open burning of agricultural residues—and the resultant emissions of health-harming air pollutants—are expected to increase, as indicated in Figure 3 below.

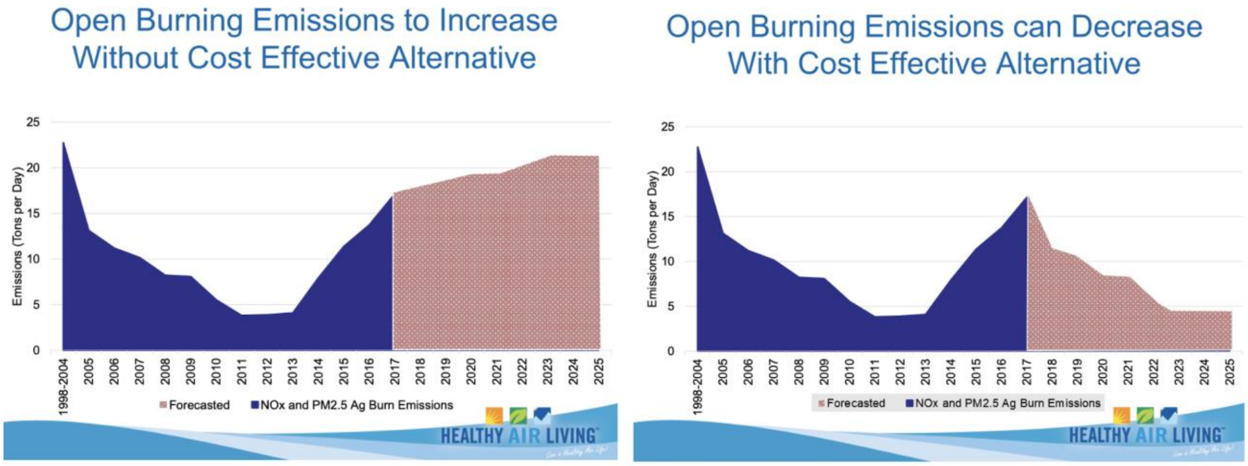

Figure 3: Expected emissions of key health-impacting air pollutants from agricultural burning. Source: Olsen, J. San Joaquin Valley Air Pollution Control District. Presentation at the Central Valley Summit on Alternatives to Open Burning of Agricultural Wastes, November 2017

Working to find alternatives to open burning of agricultural waste is a major stated priority for the San Joaquin Valley Air Pollution Control District.[21] Not only is this a public health concern, but it is also a significant environmental justice consideration, as recognized disadvantaged communities are disproportionately exposed to the emissions from these open burns.[22] Open burning of forestry residuals, as well as exposure to wildfire smoke, are similarly significant public health concerns, but under the current LCFS structure, there is no way to support pathways that offer reductions in criteria pollutant emissions.

2.2. DAC and CCS technologies

In addition to biomass-based processes, it is possible to create low-carbon and carbon-negative fuels using carbon capture and sequestration (CCS) on fuels production processes. Opportunities include carbon capture and sequestration of existing CO_2 emissions from fuels production or by making fuels using CO_2 captured directly from the air. When CARB announced

[21] San Joaquin Valley Air Pollution Control District. (October 2018). *Report to the Community 2017-18. https://www.valleyair.org/General_info/pubdocs/2017-18-Annual-Report.PDF*

[22] California's Office of Environmental Health Hazard Assessment. (2020). *SB 535 Disadvantaged Communities.* https://oehha.ca.gov/calenviroscreen/sb535

its 2019 changes to the LCFS, they pointed out that the CCS protocol would be particularly useful for ethanol producers, allowing producers to reduce CI by up to 40%.[23] To date, there is one CCS project submitted to CARB for approval. This project is part of an existing starch ethanol facility in North Dakota that will capture about 181,000 metric tons of CO_2 annually from starch fermentation and inject into a geologic formation 6500 ft below the ethanol facility.[24]

Two leading direct air capture (DAC) technology platforms employ liquid solvents and solid sorbents.[25] Several companies are currently commercializing technologies that use these platforms, including Carbon Engineering, which uses a liquid alkaline solvent for thermal energy-driven calcium looping,12 and Global Thermo- stat and Climeworks, which use solid-supported amine sorbents for thermal energy-driven adsorption/desorption.[26] The advantages of using DAC for engineered CO_2 removal include flexibility in site location, low land footprint, and potentially limitless scale. However, DAC technologies suffer from high costs, substantial energy requirements, and commercial immaturity.[27] The US National Academy of Sciences recently reported the levelized costs of CO_2 removal via DAC to be uneconomical in current policy environments.[28] Despite their immaturity, two pathways have been proposed for low-carbon and carbon-negative transportation fuels based on DAC. As with forest biomass, we briefly review promising DAC technologies in Annex 1.

2.3. Barriers to commercialization

Despite the large financial incentives for low-carbon and carbon-negative fuels in California, these fuels may require additional support to be successfully commercialized. This is because low-carbon and carbon-negative fuels have not overcome the so-called “commercialization valley of death” (Figure 4).

Through examination of academic literature, recent operating experience, and interviews with entrepreneurs, we identify the following reasons for this outcome:

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[23] California Air Resources Board. *CARB amends Low Carbon Fuel Standard for wider impact.* September 27, 2018. https://ww2.arb.ca.gov/news/carb-amends-low-carbon-fuel-standard-wider-impact

[24] California Air Resources Board. *Staff Summary Application No. D0005.* February 04, 2020. https://ww3.arb.ca.gov/fuels/lcfs/fuelpathways/comments/tier2/d0005_summary.pdf; Red Trail Energy, LLC. *Red Trail Energy Low Carbon Fuel Standard (LCFS) Design-Based Pathway Application – Carbon Capture and Storage Integrated with Ethanol Production.* November 20, 2019. https://ww3.arb.ca.gov/fuels/lcfs/fuelpathways/comments/tier2/d0005_report.pdf

[25] Sandalow, D., Friedmann, J. & McCormick, C.. (2018). Direct Air Capture of Carbon Dioxide: ICEF Roadmap. https://www.icef-forum.org/pdf2018/roadmap/ICEF2018_Roadmap_Draft_for_Comment_20181012.pdf; Sanz-P´erez, E.S., Murdock, C. R., Didas, S. A., & Jones, C. W. (2016). Direct Capture of CO_2 from Ambient Air. Chem. Rev., 2016, 116, 11840–11876. https://pubs.acs.org/doi/pdf/10.1021/acs.chemrev.6b00173

[26] P. Eisenberger and G. Chichilnisky, (2015). US Pat., No. 2015/0283501 https://patents.justia.com/patent/20150283501

[27] Sandalow, D., Friedmann, J. & McCormick, C.. (2018).

[28] National Academy of Sciences. (2018). Negative Emissions Technologies and Reliable Sequestration: A Research Agenda, Natl. Acad. Press, pp. 131–171. https://www.nap.edu/resource/25259/Negative%20Emissions%20Technologies.pdf

1. **Low technical and commercial maturity**
2. **High capital costs.** Low-carbon and carbon-negative fuels facilities have capital costs ranging from several hundreds of millions to billions of dollars.
3. **Feedstock supply uncertainty for forest biomass**, including
    a. Lack of access to long-term wood supply
    b. Dramatic supply variability from year to year
    c. High cost compared to other sources of biomass
4. **Stability** of revenues given the policy uncertainty in the LCFS space
5. **Permitting challenges**, many of which residue outside of the scope of the LCFS, but within the purview of the Air Resources Board and CalEPA

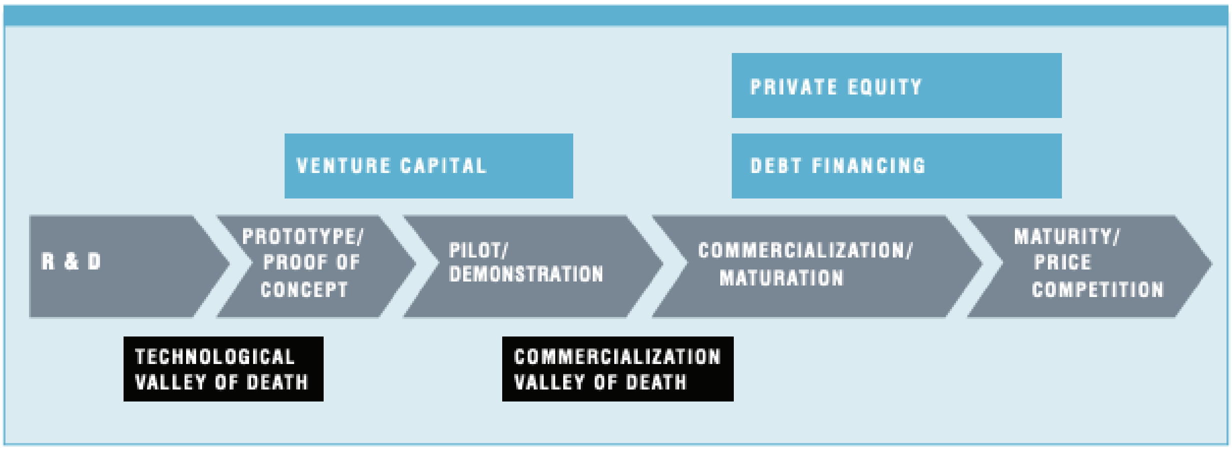

Figure 4: Energy technology commercialization and "valleys of death."[29]

Low technical and commercial maturity:

CDR technologies lack both technical and commercial maturity.[30] According to the IPCC Fifth Assessment Report, 'the availability and scale of [CDR] technologies and methods are uncertain and CDR technologies and methods are, to varying degrees, associated with challenges and risks (high confidence)'.[31] Research and development (R&D) to address such challenges and risks has been endorsed by a number of prominent organizations, including the US National Academy of Sciences, the Energy Futures Initiative, and most environmental organizations.

Innovative technologies are often too risky to attract development capital and long-term investment. Technologists, developers, and investors frequently struggle with how to finance energy projects deploying innovative technologies. Potential solutions include:[32]

[29] Jenkins, J.,& Mansur, S. (2011). Bridging the Clean Energy Valleys of Death Helping American Entrepreneurs Meet the Nation's Energy Innovation Imperative. Breakthrough Institute. https://s3.us-east-2.amazonaws.com/uploads.thebreakthrough.org/legacy/blog/Valleys_of_Death.pdf
[30] Lomax G, Lenton, T. M., Adeosun, A. & Workman, M. (2015). Investing in negative emissions Nat. Clim. Change 5 498–500, https://www.nature.com/articles/nclimate2627
[31] Intergovernmental Panel on Climate Change.(2014). IPCC WGIII Fifth Assessment Report—Mitigation of Climate Change, http://mitigation2014.org/
[32] Reicher, D., Brown, J., Fedor, D., Carl, J., Seiger, A., Ball, J., Shrimali, G. (2017). Derisking Decarbonization: Making Green Energy Investments Blue Chip. Stanford Steyer-Taylor Center for Energy Policy and Finance &

1. Partial government grant funding of a project to cut overall project capital costs;
2. A government loan or loan guarantee to cut borrowing costs lengthening repayment schedules; A buy-down of the generally above-market cost of energy produced at a project deploying a new technology (e.g. “contract for differences”);
3. Tax-related incentives including tax credits, tax-exempt financing, and other tax-advantaged vehicles;
4. Government procurement of a FOAK plant.

High capital costs:
Low-carbon and carbon-negative fuels facilities have capital costs ranging from several hundreds of millions to billions of dollars. In Table 1, we document estimated of capital costs for proposed commercial-scale facilities, which range from $100-500 million.

Costs may be even higher based on estimates from existing cellulosic biorefineries producing ethanol, many of which were constructed in the United States in the past decade.[33] High capital costs are an impediment to the cost-competitiveness and replication of pioneer cellulosic biofuels facilities. For example, while the capital cost per annual gallon of capacity averages $13.81/annual gallon for the first six commercial-scale lignocellulosic ethanol facilities; the corresponding value for corn ethanol plants is on the order of $2/gallon.

LCFS Credit Price:
Even a facility with a low enough projected levelized cost to generate an attractive ROI can be difficult to finance due to uncertainties surrounding the LCFS credit price, and other critical factors. In the first years of compliance, LCFS credits traded for an average of $17/T to $55/T as CI averages were high and many regulated entities were able to generate their credits through shifting sourcing and practices. Credit prices remained stable around $30/T from the end of 2013 through 2015 because of a court-ordered target freeze at 1% and ongoing lawsuits that caused market uncertainty. Once these lawsuits resolved, staff at CARB released this temporary target cap and credits in 2016 traded for an average of $101/T.[34] Since the announcement of the extension of the market to 2030 in 2018, the average credit price in 2018 and 2019 was around $155/T to $192/T, respectively.[35] As CI averages decline, there are growing deficits and a shrinking credit bank that are expected to keep credit prices close to the credit cap, above $200/T.

Stanford Precourt Institute for Energy and Hoover Institution. https://www-cdn.law.stanford.edu/wp-content/uploads/2017/11/stanfordcleanenergyfinanceframingdoc10-31_final.pdf

[33] Lynd, L. R., Liang, X., Biddy, M. J., Allee, A., Cai, H., Foust, T., ... & Wyman, C. E. (2017). Cellulosic ethanol: status and innovation. Current opinion in biotechnology, 45, 202-211.

[34] Stillwater Associates, LLC. (May 2019). Low Carbon Fuel Standard Monthly Newsletter, May 2019. https://www.stillwaterpublications.com/wp-content/uploads/2019/06/Stillwater_LCFS_Mly_1905-dja892.pdf

[35] California Air Resources Board. *Weekly LCFS Credit Transfer Activity Reports.* February 11, 2020. https://ww3.arb.ca.gov/fuels/lcfs/credit/lrtweeklycreditreports.htm

Feedstock supply uncertainty:

Forest biofuels in California face the following barriers compared to agricultural biomass, which hinder commercial development:[36]

1. Lack of access to long-term wood supply
2. Dramatic supply variability from year to year
3. High cost compared to other sources of biomass

Many of these issues are outside of the control of the ARB and CalEPA.

[36] Sanchez, D., et al. (2020)

3. Relevant Administrative Actions under LCFS

In 2018, CARB board members amended the LCFS to broaden the program's focus and move closer to a negative emissions goal.[37] Taking effect January 1, 2019, the re-adoption of LCFS extended the program to 2030 with a targeted 20 percent decrease from 2010 levels. Additionally, the re-adoption imposed a CI gasoline and diesel standard for all post-2030 years that keeps the CI from increasing over time.[38] Along with extending the timeline for LCFS, the re-adoption expanded credit generating opportunities to include non-alternative fuel pathway crediting, encompassing Carbon Capture and Sequestration (CCS), low-carbon electricity generation, and building infrastructure for Zero Emissions Vehicles. The decision to extend the market to 2030 signaled CARB's commitment to LCFS, and the market has priced in this certainty.[39]

3.1. Inclusion of Carbon Capture in LCFS

The first non-fuel credit-generating pathway added in 2018 is the Project Based Crediting for CCS.[40] Prior to this official change, CARB reports indicated interest in integrating CCS with state climate policies for years, affirming the importance of supporting the development and deployment of CCS to meet 2050 state climate goals.[41] To qualify for this protocol, a project can be part of a low carbon fuel pathway (Tier 2 pathway), a refinery investment (e.g. steam methane reforming), innovative crude (e.g. co-gen at oil field), or direct air capture.[42] CCS projects must inject the carbon into a saline reservoir, depleted oil and gas reservoirs, or oil and gas reservoirs used for CO_2-enhanced oil recovery and secure the carbon belowground for at least 100 years, meeting the permanence requirement.[43] Before credits are issued, a permanence certification needs to be issued, which includes a sequestration site certification and a CCS project certification. Both of these certifications require third-party review, and take an estimated six months for crediting.[44] This reporting and review may be a barrier for CCS implementation.

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[37] California Air Resources Board. (September 2018). CARB amends Low Carbon Fuel Standard for wider impact. https://ww2.arb.ca.gov/news/carb-amends-low-carbon-fuel-standard-wider-impact
[38] California Air Resources Board. Low Carbon Fuel Standard. [powerpoint] Retrieved from: https://ww3.arb.ca.gov/fuels/lcfs/background/basics-notes.pdf
[39] Extrapolating the trend in historic weekly averages of LCFS credits prices leading up to the announcement of the market extension (5/2/2016-9/17/2018) to forecast the price a year from the announcement for linear forecasting, the expected value is $169 and the actual market value was $195.
[40] Townsend, A, & Havercroft, I. *The LCFS and CCS Protocol: An overview for policymakers and project developers.* Global CCS Institute. 2019. https://www.globalccsinstitute.com/wp-content/uploads/2019/05/LCFS-and-CCS-Protocol_digital_version.pdf
[41] California Air Resources Board. *Carbon Capture and Sequestration Program: 2016 Progress and Future Plans*. https://ww2.arb.ca.gov/sites/default/files/2018-12/CCS_Summary_Paper_April_2017.pdf
[42] California Air Resources Board. *Public Workshop to Discuss Implementation LCFS*. November 28, 2018. [powerpoint, slide 33] https://ww3.arb.ca.gov/fuels/lcfs/lcfs_meetings/112818presentation.pdf
[43] California Air Resources Board. *Carbon Capture and Sequestration Project Eligibility*. September 2019. https://ww2.arb.ca.gov/sites/default/files/2019-09/ccs_project_eligibility_faq_9-12-19.pdf
[44] California Air Resources Board. *Public Workshop to Discuss Implementation LCFS*. November 28, 2018. [powerpoint] https://ww3.arb.ca.gov/fuels/lcfs/lcfs_meetings/112818presentation.pdf

The LCFS CCS protocol promotes flexibility on where projects can occur and allows stacking tax credits to promote maximum development and deployment of CCS technologies. Projects can occur anywhere in the world, but non-DAC projects must be associated with fuel sold in California. Projects can stack LCFS credits with 45Q tax credit that increases the dollar subsidy for CCS projects. Stacking LCFS credits with 45Q increases the price of carbon by up to $35/ton for projects injecting in EOR sites and $50/ton for other geologic formations.

3.2. Zero Emissions Vehicle Infrastructure Capacity

Prior to the 2018 amendments, electric utilities could opt-in to participating in the LCFS, producing electricity as a transportation fuel and supporting electric vehicles (EV). Utilities were eligible as Regulated Entities to generate LCFS credits for electricity they provided to charge EVs, and used credit revenue to provide a one-time, post-purchase rebate to utility customers who had purchased an EV. The 2019 amendments expanded the role of electricity providers and support for EVs, by expanding credit-generating opportunities based on supporting no-tailpipe car charging infrastructure and purchase. The 2019 amendments did not change how LCFS counts utility electricity generation, but it does have two notable contributions to changing LCFS credit generating opportunities: awarding credits for capacity rather than dispensed fuel, and further prioritizing deployment of EVs through a point-of-purchase EV rebate.[45]

The zero emissions vehicle (ZEV) amendments to LCFS cover Hydrogen Refueling Infrastructure (HRI) and Direct Current Fast Charging Infrastructure (FCI) per Executive Order B-48-18 and Board Resolution 18-17.[46] By December 2019, 43 sites have been approved for ZEV infrastructure credits, including 49 hydrogen stations and 454 DC fast chargers.[47] This protocol differs from other credit-generating opportunities under the LCFS because it awards credits based on capacity built, rather than dispensed fuel.[48] As the number of stations reach full utilization, credits decrease in value, creating some first mover advantage.[49] By the end of 2025, these credits will sunset and, throughout its lifetime, are not to exceed 5% of program deficits.[50]

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[45] Zheng, S. *Is California's Low Carbon Fuel Standard Incentivizing Electric Vehicle Deployment?* Clean Energy Finance Forum. May 29, 2019. https://www.cleanenergyfinanceforum.com/2019/05/29/is-californias-low-carbon-fuel-standard-incentivizing-electric-vehicle-deployment

[46] California Air Resources Board. *2018 Proposed Amendments to the Low Carbon Fuel Standard Regulation and to the Regulation on Commercialization of Alternative Diesel Fuels.* [powerpoint] September, 27, 2018. Retrieved from: https://ww3.arb.ca.gov/board/books/2018/092718/18-7-4pres.pdf

[47] California Air Resources Board. LCFS ZEV Infrastructure Crediting. https://ww3.arb.ca.gov/fuels/lcfs/electricity/zev_infrastructure/zev_infrastructure.htm

[48] California Air Resources Board. *2018 Proposed Amendments to the Low Carbon Fuel Standard Regulation and to the Regulation on Commercialization of Alternative Diesel Fuels.* [powerpoint] September, 27, 2018. Retrieved from: https://ww3.arb.ca.gov/board/books/2018/092718/18-7-4pres.pdf

[49] California Air Resources Board. *2018 Proposed Amendments to the Low Carbon Fuel Standard Regulation and to the Regulation on Commercialization of Alternative Diesel Fuels.* [powerpoint] September, 27, 2018. Retrieved from: https://ww3.arb.ca.gov/board/books/2018/092718/18-7-4pres.pdf

[50] Witcover, J. (2018). Status Review of California's Low Carbon Fuel Standard, 2011–2018 Q1 *September 2018 Issue* . *UC Davis: Institute of Transportation Studies*. Retrieved from https://escholarship.org/uc/item/445815cd

The point-of-purchase rebate is still under development but is intended to further incentivize Californians purchasing EVs, now better supported by EV charging infrastructure.[51]

3.3. Credit Clearance Market

Staff at CARB create price certainty through the Credit Clearance Market (CCM). The CCM is used to create a price cap, creating an annual market that allows deficit holders to trade at a set maximum ($200 in 2016 dollars) with credit holders that have agreed to participate.[52] This CCM prevents daily trades from exceeding too far above this $200/T ceiling because deficit holders have either the CCM or deficit banking opportunities at the end of the compliance year to settle deficits. As CI averages decline and it becomes more difficult to comply with LCFS fuel averages, the CCM will become increasingly important. Staff at CARB has indicated that the CCM should be used for cost containment to prevent demand-driven price spikes.

The price cap is maintained through granting electric utilities LCFS credits in the current year that are "borrowed" from that utility's future EV charging credit generation. The utilities are then obligated to sell these credits in the CCM and to invest proceeds from these "holdback" credits into subsidies for new EV purchase (the Clean Fuel Rewards program) and in the installation of EV charging infrastructure in disadvantaged communities.[53]

3.4. Changes to Target Stringency and End Date

Another policy design impacting price certainty is target stringency—or the ambition of CI targets—and the rate of ratcheting down CI averages. To encourage large capital investments and changes in supply-chains necessary for decarbonizing transportation, it is important for the policy to have high target stringency so that regulated entities have the necessary market certainty to stimulate investment. In 2018, CARB made minor changes to the short-term CI targets leading up to 2020 and signaled major commitment to the LCFS by extending the market to 2030.

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[51] Zheng, 2019

[52] Stillwater Associates LLC. *The LCFS Credit Clearance Market: What Might Happen?* 2018. https://www.stillwaterpublications.com/wp-content/uploads/2018/11/CCM-Analysis-11-2018-hfw9723k.pdf; California Air Resources Board. (2019). 2018 LCFS Compliance Information and Credit Clearance Market Information. https://ww3.arb.ca.gov/fuels/lcfs/2018compliance-ccm_051519.pdf

[53] California Air Resources Board. (2019) Low Carbon Fuel Standard Workshop, July 31, 2019, Sacramento, CA. [powerpoint] https://ww3.arb.ca.gov/fuels/lcfs/lcfs_meetings/073119presentation.pdf

4. Recommendations:

Ensure that the LCFS accurately accounts for the emissions benefits offered by every fuel pathway, including avoided emissions from the counterfactual fate of feedstocks. This has the benefit of not requiring any fundamental shifts in the LCFS structure, but instead works within that structure to make sure it delivers cost-effective mitigation. Many forest-to-fuels pathways may be competitive within the LCFS system if properly credited for the emissions avoided. There are several parameters that should be taken into consideration here:

- *Ensure that C accounting takes into account counterfactual emissions.* The LCFS carbon accounting framework currently does not account for emissions of biogenic carbon. While appropriate for agricultural biofuels for which the time period of carbon sequestration is short (i.e. <1year), it raises concerns when applied to woody biomass which may sequester that carbon for decades. It also therefore fails to account for emission of black carbon from prescribed burn or wildfire as well as any methane that may result from field decay large biomass if not mobilized. These emissions should be quantified in pathway CI calculations in order to appropriately incentivize fuel pathways that can lead to significant reductions in counterfactual emissions. This creates a new challenge of ascertaining the fraction of woody biomass that would be burned in the counterfactual since any operator would benefit from claiming their feedstock would otherwise be burned. ARB would need to conduct a study to estimate burned fraction on a county-by-county basis to be used as a default value for any operator unable to show a specific history of burn permits for its feedstock supplier prior to policy adoption.
- *Reduce key uncertainties in fuel CI.* As discussed above, proper accounting for the emissions intensity of woody biomass counterfactuals is not straightforward and involved several uncertainties. ARB should pursue research internally and externally to identify and reduce these uncertainties. For example, the frequency with which forestry residuals are being burned in the field is not currently being tracked despite its obvious importance to fire risk, carbon budget, air quality and other key concerns. Better tracking the business-as-usual fate of woody residuals will aid in accurate accounting for the emissions avoided by their utilization and better targeting that removal where it can offer the most benefit. Furthermore, there is very little empirical data on methane emission from biomass piles stored in the field. Given methane's importance as a GHG, this question warrants empirical study in the California context in order to accurately account for the net emissions impact of residue mobilization.

Update global warming potential values used for calculating fuel CI. Currently, the only global warming potential (GWP) values that can be used for carbon accounting are the 100-year GWPs laid out in the IPCC's fourth assessment report (AR4). This 2007 report represents the best available science as of 2005 or 2006. This means that any methane that is avoided by diverting woody material that would otherwise have been exposed to uncontrolled combustion of decomposition is credited on a 25:1 CO_2 equivalency basis. If the 20-year AR4 values were used, this would instead be a 75:1 credit. Updating to the more recent AR5 global warming potentials would mean crediting avoided methane 30:1 using the 100-year values and 85:1 over

20 years. These values are all present in the CA-GREET model, but are not admissible in formal pathway calculations

Figure 5 below shows the results of a preliminary investigation into the impact of such a structural change on broad categories of fuels certified under the LCFS. The biofuel and electricity pathway changes were calculated using the CA-GREET model version 3.0 where the fossil fuel pathways were calculated based on values reported in the ARB's lookup table pathway documents for fossil fuels and the woody biomass pathways characterized based on proprietary data shared with the authors by a California wood-to-fuels operator. *Note that avoided emissions of CH_4 and N_2O from open combustion of residues is included in the woody biomass pathway, though no such credits have to date been approved by CARB.* Sources of avoided CH_4 and N_2O emissions may also be present in some other pathways but are not characterized here as these are modeled using CA-GREET baseline pathways.

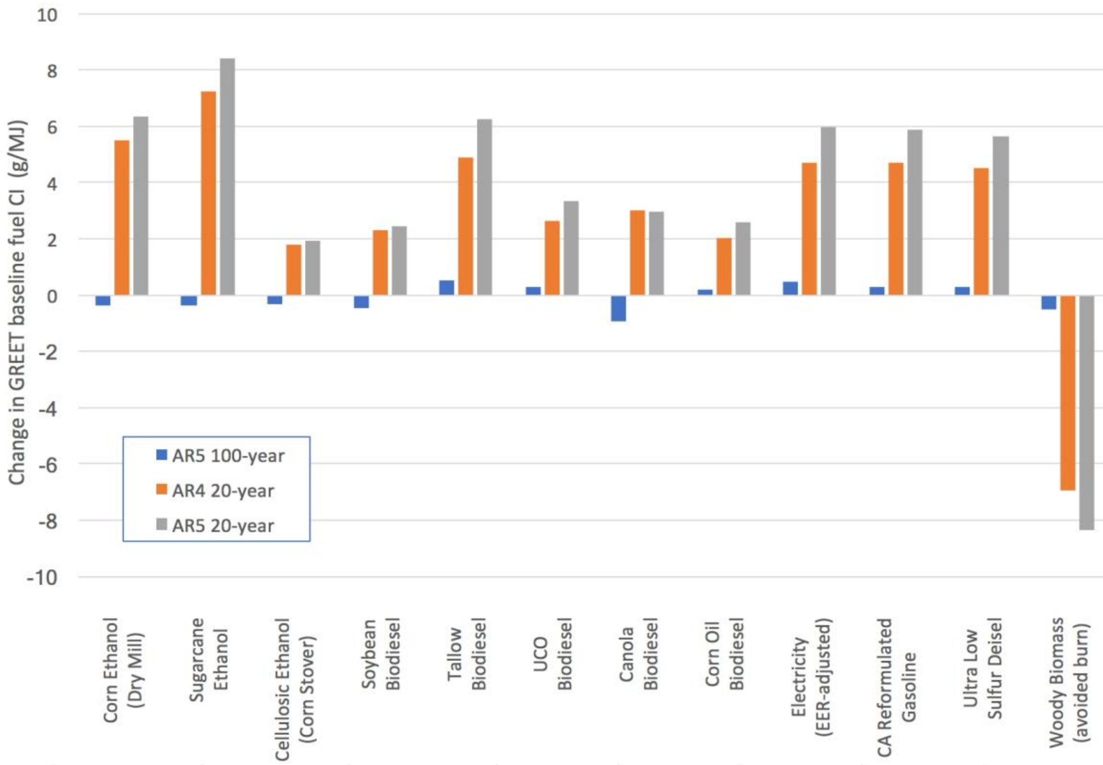

Figure 5: Approximate change in default fuel CI by fuel type caused by altering the fuel CI calculation methodology to reflect the Global Warming Potentials for CH4 and N2O in the 5th IPCC Assessment Report and/or those for climate forcing over a 20-year period.

This change would raise some interesting and important issues:

- It would affect the CI of every fuel in the LCFS system, including the petroleum baseline fuels and would also bring the LCFS out of step with other carbon accounting systems at use in the state. Of concern is that it would introduce uncertainty as to whether the calculation methodology will change again in the future (AR6 is expected in 2022). Policy uncertainty is a key barrier to project development in the alternative fuels space, so this change *could* lead to some perverse outcomes.

- This disruption could be minimized by allowing operators to opt *into* updating their pathways to reflect new GWP values. This means that the change to any one pathway would only be a reduction in calculated CI. This would reduce resistance from regulated entities, but would not eliminate their concerns, since the relative CIs of competing pathways would change, impacting the market for LCFS credits. Pathways that offer diversion of waste products - especially those that emit methane in their counterfactual fate - would benefit strongly. This would likely include pathways using MSW, landfill gas, and manure feedstocks. First generation agricultural biofuels would not be significantly affected.
- In particular, this change would elevate the importance of methane in the LCFS system. The GWP of N_2O has not changed much between AR4 and AR5 and also is not nearly as different between 20 and 100-year calculation timelines (since the lifetime of N_2O in the atmosphere is longer than 100 years where that of CH_4 is much shorter). *This means that any fuel pathway with either significant life-cycle methane emissions (such as natural gas pathways) or significant avoided methane emissions (such as dairy biogas pathways) could be substantially affected by this change.*
- Consideration of 20-year GWP values raises some larger questions of climate policy in the state and the relevant timelines for action. 20 and 100-year GWPs are both “correct” and there is no objective basis upon which to determine which should be used for LCFS calculations.
- It’s also notable that this finds common cause with some other hot-button topics such as fugitive methane from natural gas infrastructure and hydraulic fracturing. There is a nexus of parties interested in this sort of shift in carbon accounting, which could create both risks and opportunities.
- Of concern is the possibility that restructuring the CI calculations could make the significant gains made in the LCFS program to date look less impactful relative to efforts to address SLCPs.

Create additional, targeted incentives for very low-C fuels or those offering priority ancillary benefits. The LCFS is structured to deliver fuel CI reduction as efficiently as possible, and it is doing this well. However, its design only enables it to deliver the least expensive near-term mitigation, so it may not optimally promote deeper decarbonization technologies. Furthermore, its robust market and high carbon price could be leveraged to simultaneously deliver *other* state goals such as fire risk reduction, air quality improvement, or development of CCS technology. Such an incentive could take several forms within the LCFS system.

- *A volumetric technology carve-out* could be applied to a target fuel, such as one achieving a very low or negative CI score or one made from biomass that would otherwise have been burned in the field leading to significant air quality impairments. A carve-out could require blenders to procure some fraction of their fuel from that source (or pay someone else to do so). Similar carve-outs are commonly used in RPS policies to deliver priority goals. Where an RPS is generally designed to be technology-neutral like the LCFS, such carve-outs require regulated entities to procure a set percentage or amount of their power from operators of a certain type. This allows policymakers to use the RPS to achieve goals such as the development of off-shore wind or local manufacture of solar panels. A similar approach could be implemented in the LCFS.

For example, if the state identifies some priority such as creation of a renewable hydrogen industry, diversion of woody biomass that would otherwise have been open pile burned, or avoided flaring of landfill gas, the LCFS could mandate some fixed and rising number of MJ of fuel be generated from this source annually, obligating parties to purchase their “share” of these fuels or credits. The key challenge posed in this case is that such a “quantity” measure does not control cost. If a very small set of facilities are able to produce qualifying fuel, the cost of these credits could rise rapidly. A carve-out could be more appropriate once the industries in question have matured in order to use the LCFS system to drive further commercialization of already proven and operational technologies. Allowing deficit banking of these carve-out credits would limit this problem, smoothing the market over time and creating more market transparency for prospective operators.

While policy design for this carveout requires future analytical work, estimation of the following parameters would help ensure that this policy has its intended impact:

I. Volume of qualifying fuel available
II. Time frame for commercialization
III. Phase out, based on expected facility lifetimes

➢ *A credit multiplier* could also drive uptake of target pathways. If a certain type of fuel or feedstock source is found to deliver priority goals, this mechanism would offer additional LCFS credits to manufacturers of that fuel - for example: 1.2 or 1.5 MJ of credit for every MJ of fuel delivered. Specific multiplier values would be determined based on current market conditions and cost of production. One down-side of such a policy is that it reduces the actual GHG reductions delivered by the LCFS, since it would in effect create credits for low-carbon fuels that were not delivered.

This is not a novel concept. For example, the US Corporate Average Fuel Economy (CAFE) Standard is designed to increase the fuel economy of the vehicles sold in the US. However, the policy has also been leveraged to incentivize fuel switching. Electric vehicles sold into US markets are counted as 1.5 vehicles in calculating a manufacturer’s average fuel economy. This means that a car maker would need to sell 50% more conventional vehicles than EVs with the same fuel economy to reach their target in a given year. This mechanism has been successful in driving more alternative fuel vehicles into US markets.

This credit multiplier could also be applied on a sliding scale within LCFS to further incentivize very low carbon fuels. An operator could receive, for example, 1.1x credit value per MJ for fuels from 30g CO_2e/MJ down to 20g/MJ, 1.2x from 20 down to 10, 1.3x from 10 down to 0, and 1.5x for any negative C pathway. This would both accelerate the production and uptake of very low C fuel pathways that will be critical for meeting future goals while still retaining the LCFS model of CI-dependant subsidy level.

The level of multiplier necessary to achieve the intended uptake of target fuel types would need to be determined through further study. It would be necessary to conduct a detailed technoeconomic analysis of operator profitability at different multiplier levels to assess the multiplier necessary to drive significant uptake. Figure 6 presents the de facto per gallon subsidy created by the LCFS at different fuel CI values and different multiplier levels.

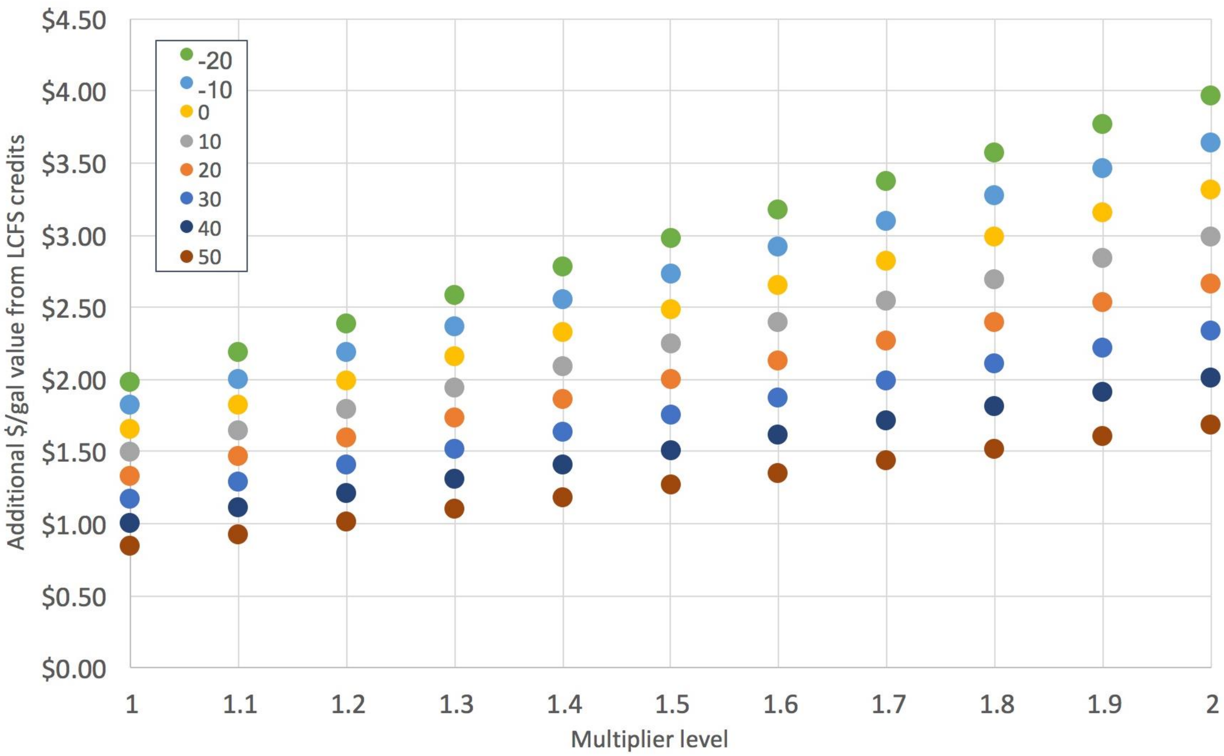

Figure 6: value of LCFS credits for delivery of a gallon of fuel as a function of that fuel's CI and the multiplier level applied to that fuel type.

Implementing these additional incentives would mean reaching beyond the direct LCFS policy structure to achieve broader state goals. There is precedent, however, for using LCFS credits to incentivize activities not strictly within the bounds of the LCFS market. For example, the allocation of credits for hydrogen fueling and fast EV charging infrastructure on a capacity rather than a delivery basis enables ARB to leverage the LCFS program to achieve broader ZEV goals. Furthermore, as with the concern raised at the top of this section, this existing credit allocation also reduces the level of GHG reduction actually delivered by the LCFS program.

Specifically target woody biomass residuals with the added incentives discussed above. Making fuels from woody residuals of forest management activities in California can in many cases offer climate, fire risk, and/or air quality benefits when compared to the alternative fate of those same materials. In particular, it is very clear that mobilizing woody biomass that would otherwise be burned in open piles leads to a significant reduction in health-harming particulate emissions. As a result, ARB should consider offering targeted incentives for fuel pathways making use of woody residuals from fire management or forest restoration activities, especially where this means diverting woody residues that would otherwise have been burned in nonattainment airsheds and/or those near disadvantaged communities.

- ➢ These supports could be structured to draw residues from priority landscapes, determined based on high-hazard zone designation and/or the calculated climate and air quality impacts of mobilizing residues from these locations.
- ➢ As fuels made from woody biomass become increasingly common, the Air Resources Board will be faced with challenges in rigorously calculating the significant and variable climate benefit offered by avoided combustion of this material in prescribed burns and/or wildfires. The climate forcing of the black carbon component of particulate emissions in particular is a very complex, uncertain, and evolving science. The proposed approach facilitates reduction in PM emissions—in line with the state's SLCP plan—while avoiding assignment of a global warming potential (GWP) to black and brown carbon emissions.
- ➢ The Air Resources Board states its mission as "protecting the public from the harmful effects of air pollution and developing programs and actions to fight climate change." LCFS is structured to achieve the latter goal, but this concept leverages it to support the former as well. Unlike GHGs, where the location of emissions is not a significant concern, the impact of criteria pollutant emissions varies by location. As such, ARB could target these incentives to avoid open burning of woody biomass specifically in degraded, California airsheds. *However*, there is a risk that doing so may violate California's interstate commerce obligations and/or create international trade barriers actionable under the WTO. This might be avoidable if the incentive were applied directly to wood mobilization rather than as a multiplier or carve-out within LCFS. These questions would need to be further investigated or resolved before creating a woody biomass utilization incentive that is geographically limited.

Offer further long-term certainty to low carbon fuel markets. Building upon some of the amendments to the LCFS made in 2019 would offer needed policy certainty to drive significant investment in the alternative fuels space. In particular:

- ➢ Extend the policy to 2040 or beyond with further signals of increased target stringency. The 2019 amendments solidified CARB's commitment to the LCFS, and a 20 year policy runway would facilitate the industrial development necessary in this low carbon fuels space. This would most likely require legislative rather than administrative action, but Air Board staff are well positioned to facilitate this development if it would support the ongoing operation and effectiveness of the LCFS.
- ➢ Consider implementing a price floor to go along with the ceiling created by the CCM amendments. This would give operators more confidence to enter the market. This floor could take the form of a put option or contract for differences at a price determined via reverse auction as proposed in a 2018 ARB white paper.[54] Under current market conditions, a price floor does not appear obviously necessary. However, the tight market

[54] CARB. DRAFT-SB 1383 Pilot Financial Mechanism Concept Paper May 2018
https://ww3.arb.ca.gov/cc/dairy/documents/05-23-18/pilot-financial-mechanism-white-paper.pdf

for LCFS credits to date could stem in large part from the inability of the electric vehicle market to keep pace with average fuel CI reductions. If the EV market continues to grow at its recent rate, it is possible that LCFS credits generated by electric utilities and owners of public charging infrastructure could outstrip deficits generated by fossil fuel blenders. In that scenario, credit prices could fall. However, even in that circumstance, very low-carbon liquid fuels would remain an important component of meeting future climate goals as they would offer alternatives for heavy-duty transport, aviation, and an offtake for waste biomass. Offering price certainty to the market - or specifically to operators of very low-C fuel manufacturing facilities could enable those facilities to be built.

Consider adapting the price control mechanisms within the LCFS to support other targeted low-carbon fuels technologies. The price cap in the CCM must be maintained through awarding credits beyond those “earned” via low carbon fuel production in a given compliance year. This creates an opportunity since the allocation of these credits can be used to strategically promote desirable activity in California’s low carbon fuels system. The current approach has been to grant electric utilities LCFS credits that are “borrowed” from future EV charging credit generation. Proceeds from the sale of these “holdback” credits must be invested in promoting EV uptake through both vehicle purchase and EVSE installation. If very low-carbon biofuels or fuels made from woody residues of fire management are considered similarly desirable, the same structure could be used to loan money (without cost to the state) to developers of targeted low carbon fuel technologies to be paid back via foregone future credit generation. This would give these operators low-cost capital to construct facilities that could otherwise lack sufficient financing.

Make sure that the LCFS is stimulating the best performing fuels across a variety of parameters. Biofuels incentivized by the LCFS can offer significant environmental benefit, but this can’t be taken as a given. Concerns abound regarding feedstock sourcing and its impacts on ecosystems, biodiversity, water resources, soil erosion, and other metrics of concern. Many of these considerations may be captured via the rigorous supply chain traceability already applied in the LCFS and the woody biomass GHG accounting approaches proposed here. However, others may not be tied to—or may even be inversely correlated with—life-cycle CI. Safeguards should be put into place to avoid perverse outcomes from these policy supports. Examples could include:

- ➢ Specific geographic or ecologically-driven feedstock sourcing restrictions, constraining support schemes to other targeted feedstock types or locations rather than the easiest-to-access woody biomass. The policy could require, for example, that any operator claiming a particular LCFS support or pathway must source some set fraction of feedstock from non-merchantable biomass in defined High Hazard Zones or from fire risk reduction treatments around critical infrastructure.
- ➢ Limitations to residue removal and requirement of forestry best practices to ensure that ecosystem integrity and soil structure are not compromised. The policy could include a minimum residue retention level to ameliorate compaction and erosion concerns as well as a requirement that foliage be retained on site to minimize nutrient removal.

- ➢ Best practice guidelines could ensure biodiversity, soil conservation, and watershed stewardship goals are met on any landscapes from which residues are sourced, and third-party certification by entities such as the Forest Stewardship Council and the Roundtable on Sustainable Biomaterials can be an effective tool for providing these assurances.

Annex 1: Promising pathways for deep decarbonization of transport fuels and their status in California

Product: Fischer - Tropsch Fuels

Fischer-Tropsch fuels are 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). Prior to synthesis, CO_2 and sulfur compounds are removed in the acid gas removal step. The CO_2 may be vented or captured and stored underground. Fischer-tropsch liquids typically contain a mixture of hydrocarbons, including gasoline and diesel substitutes.[55]

There is a long history of attempts to commercialize Fischer-Tropsch fuels and other processes employing gasification, gas cleaning, and catalytic treatment. There have been several notable failures, alongside a few successes. For instance, Range Fuels was unable to successfully commercialize ethanol production from southern pine via gasification and catalysis. In contrast, Emerkem has successfully produced ethanol via gasification of municipal solid waste (MSW).

Red Rocks Biofuels has proposed a facility in Lakeview, Oregon in part to serve California markets. This facility will consume 68,000 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.[56] This facility has not yet been placed in service. Numerous observers have questioned the technical viability of Red Rocks Biofuels' gasification technology.

Velocys plans on taking woody biomass forest residue from lumber industries and convert using proprietary Fischer Tropsch processes into aviation or heavy duty road transportation fuels. Of particular interest is Velocys integration of carbon capture utilization and storage (CCUS) technology into the process, generating net negative carbon intensity fuels.[57]

Product: Gas Fermentation

Low-carbon cellulosic ethanol can be produced from lignocellulosic biomass through gasification, gas cleaning, and gas fermentation. The resulting syngas from gasification and gas

[55] Kreutz, T. G., Larson, E. D., Liu, G., & Williams, R. H. (2008, September). Fischer-Tropsch fuels from coal and biomass. In 25th annual international Pittsburgh coal conference (Vol. 29, p. e2). Princeton University Pittsburg

[56] Red Rock Biofuels. (n.d.). Lakeview Site. Retrieved December 4, 2019, from https://www.redrockbio.com/lakeview-site.html.
[57] Stratmann, P. (n.d.). From waste woody biomass to carbon negative transportation fuels via CCUS. Retrieved December 4, 2019, from http://www.biofuelsdigest.com/bdigest/2019/12/02/from-waste-woody-biomass-to-carbon-negative-transportation-fuels-via-ccus/.

cleaning is converted into cellulosic ethanol using gas fermentation technologies. Gas fermentation typically employs engineered bacteria to biologically process syngas into ethanol.

Lanzatech has successfully commercialized syngas fermentation processes. Their technology has been used in multiple demonstration projects at varying scales.[58]

Aemetis has proposed a facility in Riverbank, CA that will produce 12 million gallons per year of cellulosic ethanol from 133,000 BDT/yr of agricultural wood waste from orchards, using Lanzatech's gas fermentation processes. This facility has successfully secured a USDA loan guarantee, a 20-year feedstock supply agreement, and a 55-year land lease.[59] Aemetis plans to open the facility in 2020 and an integrated demonstration unit has operated for 120 days. Future expansion at 3 other locations would bring total production to 160 million gallons of cellulosic ethanol.[60]

Product: Fast Pyrolysis and Hydroprocessing

Fast pyrolysis and upgrading is a thermochemical pathway that produces pyrolysis oil that can be upgraded via hydroprocessing into hydrocarbon-based transportation fuels.

This process includes fast pyrolysis of biomass at high temperatures, decomposing biomass feedstock into gas (syngas), solid (char), and liquid (pyrolysis oil) products. Pyrolysis oil is a viscous, oxygenated, and corrosive mixture of polymeric chemical compounds that has little immediate commercial value. Pyrolysis oil must be upgraded via a combination of hydrotreating and either hydrocracking or fluid catalytic cracking before high-value biobased hydrocarbons can be derived from it. Char can serve as a low-value coal substitute, soil amendment agent, or used for long-term carbon sequestration.

Kior represents a high-profile failure to commercialize transportation fuels production via fast pyrolysis of woody biomass. As noted above, catalyst deactivation at Kior's facility was blamed on very low levels of sulfur, chlorine and alkaline earth minerals that are present in even the cleanest of wood.

Lawrence Livermore National Laboratory, Sierra Pacific Industries (SPI), and Frontline Bionergy are in the process of testing a 50 ton per day autothermal pyrolysis unit operating on forest biomass at SPI's Camino mill in El Dorado County, CA.[61] The project is supported by the California Energy Commission.

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[58] Holmgren, J (2018). Developing a Research Agenda for Utilization of Gaseous Carbon Waste Streams. http://nas-sites.org/dels/files/2018/02/2-1-HOLMGREN-Lanzatech.pdf
[59] Shaver, K. (2018, March 6). Aemetis Completes Operation of Cellulosic Ethanol Integrated Demonstration Unit, Produced Record Yields. Retrieved from http://www.aemetis.com/aemetis-completes-operation-of-cellulosic-ethanol-integrated-demonstration-unit-produced-record-yields/.
[60] Aemetis. (2019). Commercializing Below Zero Carbon Advanced Biofuels Production. Retrieved from http://www.aemetis.com/wp-content/uploads/2019/01/Aemetis-Corporate-Presentation-2019-01-18.pdf
[61] McCoy, S. (2018). Wood-to-fuel for California's Transportation Sector using Autothermal Pyrolysis [Powerpoint Slides]. Retrieved from http://sofarcohesivestrategy.org/wp-content/uploads/2017/06/McCoy-Wood-to-Fuel-pilot.pdf

Product: Lignocellulosic Ethanol

Ethanol derived from forest biomass is a second generation cellulosic biofuel that can be used as a transportation fuel. Production generally occurs in the following steps:

1. Size reduction and pretreatment to increase the porosity of biomass particles and to increase the accessibility of cellulose and other polysaccharides to enzymes
2. Hydrolysis to produce sugars, typically catalyzed by enzymes that can collectively hydrolyze cellulose and hemicellulose to free sugars
3. Fermentation of sugars to ethanol, typically by yeast

Several pioneer facilities producing ethanol from lignocellulosic agricultural residues with capacity >10 million gallons per year have been built over the last few years. These include facilities in both Kansas and Iowa (Carroll, 2009).

Currently, there are no commercial scale facilities producing bioethanol from cellulosic biomass in California. The proposed Axens/Anderson project will utilize the existing infrastructure at the Anderson, CA complex. The facility will be capable of processing 100,000 BDT of feedstock per year.

Woody biomass is more recalcitrant to microbial and enzymatic actions than non woody biomass. This is particularly true for softwood species.[62] Particular attention needs to be paid to (1) the effectiveness of pretreatment for complete wood cellulose saccharification and (2) the energy consumption for woody biomass pretreatment, in particular for wood-size reduction to the level for effective enzymatic saccharification.

Product: Renewable Natural Gas

One pathway to substantially reduce GHG and criteria pollutant emissions is by expanded use of renewable natural gas (RNG). RNG can be produced from many sources, such as digesters, wastewater treatment facilities, landfills, and thermal conversion of renewable carbonaceous materials like woody biomass. Here, we target the thermal conversation of woody biomass to RNG via gasification and subsequent catalytic conversion. This is broadly known as methanation, or the Sabatier process. Commercial suppliers of these technologies include Andritz and Haldor Topsoe A/S.[63]

We are not aware of any existing demonstrations of this technology using forest biomass. However, there have been at least two proposals for facilities producing RNG in California:

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[62] Zhu, J.Y., & Pan, X.J. (July 2010). "Woody biomass pretreatment for cellulosic ethanol production: Technology and energy consumption evaluation" Bioresource Technology Vol 101, Issue 13, Pages 4992-5002. https://doi.org/10.1016/j.biortech.2009.11.007

[63] Gas Technology Institute (GTI). (2019). Low-Carbon Renewable Natural Gas (RNG) from Wood Wastes. Retrieved from https://www.gti.energy/wp-content/uploads/2019/02/Low-Carbon-Renewable-Natural-Gas-RNG-from-Wood-Wastes-Final-Report-Feb2019.pdf

1. The Gas Technology Institute has produced an engineering design for RNG production in Stockton, CA. The facility would operate at the DTE biomass power plant in Stockton, producing 3 BCF/yr RNG and displacing approx 170,000 tons of CO2/yr.[64]
2. San Joaquin Renewables has announced intentions to develop a RNG production facility employing methanation on agricultural wood waste in McFarland, California.[65]

Product: Renewable Hydrogen

Hydrogen (H_2) can be produced from a number of processes, such as electrolysis of water or steam-methane reforming of natural gas. Here, we target the thermal conversation of woody biomass to 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. Gasification, catalytic conversion, and gas separation is widely practiced at commercial scale in ammonia, hydrocarbon, methanol, and hydrogen production.

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.[66] Clean Energy Systems hopes to retrofit a number of existing biomass power plants to produce hydrogen for use as a transportation fuel.

There has been at least one demonstration of hydrogen and electricity production from forest biomass in California. Unfortunately, this demonstration proved unsuccessful. Blue Lake Rancheria, in Humboldt County, CA, aimed to produce hydrogen from mill residues, for electricity generation via fuel cells (West, 2015). The fuel cell system had stringent gas quality standards that were not met.

Hydrogen must be sold as a transportation fuel in order to qualify for subsidies through the LCFS. Thus, future development of hydrogen infrastructure will likely be limited by hydrogen fuel cell vehicle adoption. As of December 2019, there are 44 open hydrogen fueling stations in California.[67] There are over 10,000 retail fuel stations in California.

Product: Air-to-fuels

Air-to-fuels pathways convert CO_2 captured from the air into transportation fuels. While we are not aware of any planned air-to-fuels facilities to serve California markets. Two primary methods have been proposed: 1) thermochemical conversion via reverse water-gas shift, and 2) electrochemical conversion in aqueous media.

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[64] Gas Technology Institute (GTI). (2019).
[65] San Joaquin Renewables. (2019, August 23). About San Joaquin Renewables. Retrieved from https://sjrgas.com/about-san-joaquin-renewables/.
[66] Clean Energy Systems. (2019). “Site Locations” Accessed February 2020 http://www.cleanenergysystems.com/site-locations
[67] California Fuel Cell Partnership (2019). “List of Hydrogen Fueling Stations” https://cafcp.org/sites/default/files/h2_station_list.pdf

Thermochemical conversion of CO_2 to fuels is considered more technically mature.[68] Carbon Engineering is developing air-to-fuel systems in which the hydrogen required as feedstock for the fuel synthesis step is produced by electrolysis of water. The production of hydrocarbons from CO_2 and H2 feedstock is a high-pressure catalytic process where the choice of catalyst, operating pressure, and temperature affects the reaction products.[69]

These fuels roughly carbon neutral if the carbon capture, hydrogen production, and fuel synthesis processes are powered by essentially carbon-free electricity, such as wind, solar, and nuclear. Both electrofuel production and DAC are capital-intensive processes, creating an incentive for a high capacity factor. Variable renewable electricity is a relatively inexpensive source of very low-carbon electricity. Thus, there is a tension between capacity factor, capital cost, electricity cost in DACS and electrofuel production. Recent work has estimated the cost of carbon-neutral air-to-fuels at ~$9/gallon of gasoline equivalent, which is accomplishable at a carbon price of ~$1000 / tCO_2.[70]

Product: Direct air capture and enhanced oil recovery

Instead of converting CO_2 into transportation fuels, CO_2 could be used for enhanced oil recovery (EOR) to produce low-carbon transportation fuels. CO_2-EOR is the extraction of crude oil from an oil field that cannot be extracted otherwise via injection of CO_2. The United States has been using CO_2 EOR for over 30 years: for instance, oil fields in the Permian Basin of Texas have implemented CO_2 EOR using naturally sourced CO_2 from New Mexico and Colorado.

CO_2-EOR could also be a powerful strategy to reduce emissions from oil consumption until the world completes the transition to clean energy. Under the right conditions it is even possible to achieve net CO_2 removal from the atmosphere by combining direct air capture with CO_2-EOR.

There is one announced DAC-EOR facility in the United States.[71] Carbon Engineering and Occidential Petroluem aim to build a large-scale plant that will capture and sequester 500,000 metric tons of carbon dioxide from the air each year. The plant, which will be operational in three years, is to be located in the Permian Basin, where Occidental Petroleum has multiple depleted oil fields that need carbon dioxide injections to recover more oil.

We expect this facility to reduce net emissions by 30-40% compared to conventional petroleum. As James Mulligan and Dan Lashof explain: “Carbon Engineering's technology captures as much as half a ton of CO_2 from natural gas combustion for every one ton removed from the atmosphere. In this case, one ton of air-captured CO_2 goes into the oil field, along with half a ton

[68] Keith, D. W., Holmes, G., Angelo, D. S., & Heidel, K. (2018). A process for capturing CO_2 from the atmosphere. Joule, 2(8), 1573-1594.
[69] Zeman, F. S., & Keith, D. W. (2008). Carbon neutral hydrocarbons. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 366(1882), 3901-3918.
[70] Sherwin, Evan. (2018). Aviation and Freight Transportation: A Techno-Economic Analysis. [Powerpoint Slides]. Retrieved from: http://www.usaee.org/usaee2018/submissions/Presentations/Sherwin_DC18.pdf
[71] Rathi, A. (2019). The Story behind the World’s First Large Direct Air Capture Plant. Quartz, https://qz.com/1638096/the-story-behind-the-worlds-first-large-direct-air-capture-plant/

of gas-captured CO_2, and 2.25 tons come out. *This diminishes the net emissions reduction to 40% compared to conventional oil production*. The other critical question is how much oil produced with CO_2-EOR will displace oil that would have been produced elsewhere. The International Energy Agency estimated that eight of every 10 barrels of CO_2-EOR oil will displace oil that would have been produced anyway. The other two barrels would not have been produced otherwise, further r*educing the net emissions reduction from 40% to one-third*."[72]

To produce lower-carbon or carbon-negative oil via DAC and EOR, two things must change. First, DAC technologies would need to reduce the consumption of natural gas or other fossil fuels as a source of energy for their processes. Second, the ratio of CO_2 injected to oil produced, which depends both on technology and economics, would need to increase.[73] These improvements raise the prospect of "carbon-negative oil" production in the United States.[74]

[72] Mulligan, J., and Lashof, D. (2019) "A CO_2 Direct Air Capture Plant Will Help Extract Oil in Texas. Could This Actually Be Good for the Climate? | World Resources Institute." World Resources Institute, https://www.wri.org/blog/2019/07/co2-direct-air-capture-plant-will-help-extract-oil-texas-could-actually-be-good-climate.
[73] Benson, S. & Duetch, J. (2018). "Advancing Enhaced Oil Recovery as a Sequestration Asset." Joule, e 2, 1386–1389, https://www.cell.com/joule/pdf/S2542-4351(18)30337-4.pdf
[74] Hornafius, K.Y. & Hornafius, J.S. (2015). "Carbon Negative Oil: A Pathway for CO2 Emission Reduction Goals." International Journal of Greenhouse Gas Control, vol. 37, Elsevier Ltd, Dec. 2015, pp. 492–503, doi:10.1016/j.ijggc.2015.04.007.